INVESTIGATIONS ON FINE FINISHING OF SURFACES USING ELASTIC ABRASIVES

A thesis submitted

in partial fulfillment for the degree of

Doctor of Philosophy

by

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CERTIFICATE

This is to certify that the thesis titled **INVESTIGATIONS ON FINE FINISHING OF SURFACES USING ELASTIC ABRASIVES**, submitted by **Mr. Sooraj V. S.**, to the Indian Institute of Space Science and Technology, Thiruvananthapuram, in partial fulfillment for the award of the degree of **Doctor of Philosophy**, is a *bona fide* record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Place: Thiruvananthapuram
Date: February 2014

DECLARATION

I declare that this thesis titled **INVESTIGATIONS ON FINE FINISHING OF SURFACES USING ELASTIC ABRASIVES** submitted in partial fulfillment of the Degree of Doctor of Philosophy is a record of original work carried out by me under the supervision of **Prof. V. Radhakrishnan**, and has not formed the basis for the award of any degree, diploma, in this or any other Institution or University. In keeping with the ethical practice in reporting scientific information, due acknowledgments have been made wherever the findings of others have been cited.

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ABSTRACT

Surface roughness is an important factor deciding the tribological behaviour and functional performance of a manufactured component. To meet the stringent requirements in precision and meso/micro engineering, ultra fine finishing of surfaces without altering its form is needed. State-of-the-art methodologies and practices adopted for the generation of fine finished surfaces exhibit the successful use of abrasive grains in their loose as well as bonded form. Polymer-abrasive medium in abrasive flow finishing, magnetic-abrasive medium in magnetic abrasive finishing, magnetorheological medium in magnetorheological finishing and ice-abrasive tool in ice bonded abrasive polishing are representative examples. But many of these approaches are applicable for specific surface geometries, and do require special care in the preparation of abrasive carrier media. Degree of sophistication, tooling requirement and cost of finishing are also of great concern. Therefore, development of a multiple application oriented micro/nano finishing approach that can be applied to a wide range of surface geometries is of great practical relevance.

The main highlight of the present research is the introduction of such a finishing approach by means of *elastic abrasives*. The abrasive embedded elastomeric balls of average diameter in meso/micro scale are referred to as elastic abrasives in this thesis. The unique feature of elastic abrasive projected in this work is the elastomeric action, facilitating the refinement of surface profile without altering the basic form of surface. In addition, the elastic abrasives in the shape of balls can be re-configured easily in accordance with the finishing requirements and can be utilized for both abrasion as well as erosion based finishing systems. Size of the proposed balls, their elastic behaviour, and the characteristics of embedded abrasive grains are easily adjustable, thus making the approach more versatile. Simple and cost effective methods of preparing elastic abrasives are proposed in this thesis, followed by a detailed characterization study. The reusability of elastic abrasive balls is another important feature, substantiated through specific wear tests.

In this thesis, the usage of elastic abrasives are well demonstrated for internal as well as external surface finishing, both using abrasion as well as erosion principles. Dedicated experimental setups developed as a part of this thesis include *elastic abrasive-internal finishing setup* (with and without workpiece rotation), *internal circumferential groove finishing system*, *fluidized elastic abrasive finishing setup*, and *elasto-magnetic abrasive finishing setup*. The experimental setup and methodologies described in this thesis clearly illustrates the simplicity, effectiveness and convenience of using the proposed elastic abrasive balls. The range of work materials used for the experiments reported include magnetic as well as non-magnetic materials, both of ductile and brittle in nature, covering difficult-to-cut materials such as hardened steel and tungsten carbide. Experimental studies have been well substantiated through

theoretical study of the fundamental mechanisms involved as well as by the analysis of experimental data.

Among these, fluidized elastic abrasive finishing system use low velocity impact of proposed balls to get controlled erosion and fine finishing of surfaces. The problems associated with the fluidization of fine abrasive powders are fully resolved through the application of elastic abrasive balls, and can be used effectively further for the fine finishing of intricate free form surfaces. Elasto magnetic abrasive finishing is a variant of magnetic abrasive finishing performed using magnetic elastic abrasive balls (referred to as *elasto-magnetic abrasives* in this thesis).

Significant improvement in surface finish is achieved through the application of elastic abrasives, with a remarkable improvement in average roughness, peak to valley roughness and peak height. The average roughness obtained in accordance with the selected experimental conditions in this thesis is of the order 15 to 40 nanometres, from an initial range of 150 to 250 nanometres, after a processing time of 40 to 60 minutes. Simple, flexible and convenient application of elastic abrasive balls, minimal cleaning after processing, finishing of surfaces without altering the form, absence of liquid carrier medium, simple and cost effective experimental setups, etc. are the key operational features of the proposed approach.

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ABBREVIATIONS

AFF	Abrasive Flow Finishing
AJM	Abrasive Jet Machining
AWJM	Abrasive Water Jet Machining
BMA	Bonded Magnetic Abrasive
CIP	Carbonyl Iron Particles
CMP	Chemo-Mechanical Polishing
CNC	Computer Numerical Control
EDM	Electric Discharge Machining
EEM	Elastic Emission Machining
ELID	Electrolytic In process Dressing
FB-AJM	Fluidized Bed Assisted Abrasive Jet Machining
FMAB	Flexible Magnetic Abrasive Brush
MAF	Magnetic Abrasive Finishing
MCP	Mechano-Chemical Polishing
MRF	Magneto Rheological Finishing
RSM	Response Surface Methodology
SPDT	Single Point Diamond Turning
TAM	Turbo Abrasive Machining
UMA	Unbounded magnetic abrasive

NOTATIONS

$A_{c(def)}$	Area of contact of elastic abrasive ball with work surface during its radial deformation, m^2
$A_{c(g)}$	Area of contact during the penetration of an embedded abrasive grain, m^2
A_p	Projected area of penetration, m^2
$A_{p(ea)}$	Area of penetration of elastic abrasive ball, m^2
$A_{s\text{-}(ea)}$	Surface area of elastic abrasive, m^2
$A_{s(w)}$	Surface area of workpiece, m^2
B	Magnetic flux density, T
d_{ea}	Diameter of elastic abrasive ball, m
d_g	Diameter of embedded abrasive grain
d_w	Diameter of cylindrical flat work specimen, m
E	Elastic Modulus, N/m^2
E_{eq}	Equivalent Elastic Modulus, N/m^2
e_p	Coefficient of restitution, dimensionless
F	Ratio of fluidized bed height to static bed height
F_a	Axial force acting on embedded abrasive grain, N
$F_{a(ea)}$	Axial force on elastic abrasive ball, N
$F_{c(i)}$	Contact force during impact of an elastic abrasive sphere, N
F_N	Total normal force (Mechanical +Magnetic), N
F_r	Radial force on embedded abrasive grain, N

F_t	Tangential force acting on embedded abrasive grain, N
$F_{t\,(ea)}$	Tangential force component acting on elastic abrasive ball, N
F_T	Total tangential force (Mechanical +Magnetic), N
H_w	Brinell Hardness of work specimen
h	Depth of penetration of embedded abrasive grain, m
h_e	Depth of penetration of elastic abrasive ball during impact, m
k	Radius of gyration of spherical abrasive ball
L_p	Packing length, m
L_w	Length of work piece, m
M	Total mass of elastic abrasive balls filled inside the fluidized chamber, kg
m_{ea}	Mass of elastic abrasive ball, kg
N	Rotational speed of work specimen (rpm)
N_B	Rotational speed of elasto-magnetic abrasive brush (rpm)
$N_{g/b}$	Number of abrasive grains in a single elastic abrasive
$N_{g/b/c}$	Number of active grits in an elastic abrasive corresponding to the contact area Ac
N_p	Number of active grains in the filled packing of elastic abrasives
n_t	Number of elastic abrasives hitting the workpiece per second
n_v	Number of elastic abrasive balls per volume of bed (particle number density)
P_a	Radial Stress, N/m^2
P_C	Maximum contact pressure, N/m^2
P_r	Axial Stress, N/m^2

P_y	Limiting value of contact stress, N/m^2
$\mathbf{R_a}$	Average roughness, µm
$\mathbf{R_p}$	Maximum peak height, µm
$\mathbf{R_{pb}}$	Radius of polymer bead, m
$\mathbf{R_{pk}}$	Peak height from bearing ratio curve, µm
$\mathbf{R_t}$	Peak to Valley roughness, µm
R_{wi}	Internal diameter of tubular work specimen, m
S	Distance between spindle axis and workpiece, m
T	Processing time, s
U	Energy available for erosion during the impact of an elastic abrasive ball (considering only the normal velocity component), J
V_a	Velocity of impingement, m/s
V_c	Axial (longitudinal) velocity in elastic abrasive-internal finishing system
$V_{embedded}$	Filled volume of abrasives, m^3
V_s	Volume swept by the workpiece during rotation, inside the fluidized bed, m^3
$V_{w(e)}$	Volume of material eroded by the impact of a single elastic abrasive, m^3
$V_{w/g}$	Volume of material removed by a single abrasive grain, m^3
$V_{w/p}$	Volume of material removed per packing of elastic abrasives, m^3
$V_{w/s}$	Volume of material removed per stroke, m^3
$V_{w(T)}$	Volume of material removal corresponding to a processing time of 'T' seconds, m^3

$v_{f(g)}$	Volume fraction of abrasive grains
$v_{f(pb)}$	Volume fraction of polymer bead
v_{ax}	Axial velocity of elastic abrasive (in the internal finishing system with work rotation), m/s
v_R^*	Resultant velocity of elastic abrasive (in the internal finishing system with work rotation), m/s
v_{tan}	Tangential velocity of elastic abrasive (in the internal finishing system with work rotation), m/s
W_e	Work done during the impact and penetration of elastic abrasive, J
$\mathbf{Z}$	Number of cycles
α	Angle of tilt given to workpiece (angle of impingement)
δ	Elastic deflection of polymer bead, m
ρ_{ea}	Density of elastic abrasive ball, kg/m^3
ρ_{pb}	Density of polymer bead, kg/m^3
$\rho_{b(f)}$	Density of bed in the fluidized state, kg/m^3
$\rho_{b(s)}$	Density of bed in its static state, kg/m^3
ρ_g	Density of abrasive grain, kg/m^3
σ_w	Flow strength of work material, N/m^2
τ_{sw}	Shear strength of work material, N/m^2
υ	Poisson's ratio, dimensionless
ω	Angular velocity of elastic abrasive rotation

Subscript

ea	Elastic abrasive
g	Embedded abrasive grain
pb	Polymer bead
w	Work piece material

NOMENCLATURE

SiC	Silicon Carbide
Al_2O_3	Aluminium Oxide
CBN	Cubic Boron Nitride

CHAPTER 1

INTRODUCTION

1.1 Background and Significance of Research Area

Surface finish of manufactured parts is critical to their function, and our understanding of this requirement has led to many research studies covering various functional aspects of surfaces, application related specification of surface finish, and the development of manufacturing processes capable of achieving the required finish and topography. Investigations into the influence of process variables on the finish achieved in various processes as well as fast and reliable assessment of surfaces that can be of assistance in monitoring the processes are also covered in these studies. Functional behaviour of parts used in engineering applications, in additional to their material properties, depends on the surface that plays a major role in wear behaviour, lubrication, load bearing capacity, fluid flow resistance, optical characteristics, bio-compatibility, heat transfer, corrosion resistance, fatigue resistance, etc. (Komanduri et al., 1997; Jain, 2013; Singh et al., 2012a). However, achieving the required finish on many of the complex parts that are currently used in technologically advanced products still pose major challenges. In many situations, the order of surface roughness is a critical parameter deciding the product quality and acceptance. Precision engineered products such as spool valves, sleeves, bearings, and fuel injection pumps are representative examples. Further, in many cases, finishing is a major bottleneck often involving labour intensive, time consuming, expensive and least controllable sequence of operations (Jain, 2013). With the advent of meso, micro, and nano scale manufacturing, new challenges are in the offing (Radhakrishnan, 2013). Micro/nano finishing of advanced materials including hardened steels, titanium alloys, nickel alloys, ceramics and glass, which falls into the category of difficult-to-cut materials, is yet another example. In addition to the above, nano scale finishing of complex free form surfaces, internal grooves, pockets, high aspect ratio holes and micro features on parts often encountered in die and mold manufacturing, automotive, aerospace, electronics, semiconductor and optical industries need consistency and uniformity in surface finish. The complexity and cost of finishing operations shoot-up sharply as the requirement moves to nano scale roughness, of the order 50 nm or less (Sankar et al., 2009a). Controlling and maintaining the mechanical forces involved in finishing without damaging the sub surface and without altering the surface form is again a technical challenge. The traditional route of lapping, polishing and associated finishing methodologies alone are incapable of achieving these goals. A series of advanced fine finishing methodologies employing micron/sub micron sized abrasive grains in their loose or fixed form has been reported in the last decade to address these issues (Jain, 2010). Abrasion and erosion, often classified as the undesirable tribological effects, are viewed in a promising and positive way in many of these techniques. Abrasive flow finishing, Magnetic abrasive finishing, Magnetorheological finishing, Magnetorheological jet finishing, Ice bonded abrasive polishing, etc. are few of the examples. Detailed reviews of traditional and advanced methodologies of fine finishing are presented, and discussed systematically in the following section of this thesis. While discussing these advanced processes many have reported on process limitations and technical issues that need to be addressed to make these processes practically viable (Singh et al., 2012a ; Mohan and Ramesh Babu, 2010; Singh et al., 2012b). Some of these significant points and scope of refinement that have been reported are mentioned below:

- ✓ Many of the advanced finishing operations are limited only to specific surface geometries and typical class of materials
- ✓ Many of the fixed abrasive methodologies pose accessibility limitation
- ✓ Many of the loose abrasive methods use a slurry or liquid carrier medium, making them inconvenient in some specific applications
- ✓ Each of these new approaches requires a specially designed abrasive-carrier medium that can be applied only to their domain of applications, and not multi-application oriented.

The aforementioned points are discussed methodically in the third section of this chapter with a detailed description on the objectives of present research. But it can be summarized that the development of a multi-application oriented finishing approach that can create a common platform for achieving fine finish on various types of surfaces, of various class of materials, without altering the surface form is of great research interest and of significant industrial relevance.

1.2 State-of-the-art

Finishing of surfaces using abrasives is well accepted in a wide range of precision engineering applications. Abrasive grits that are relatively harder than the work material are good for the generation of high quality surfaces in terms of form accuracy and finish, especially for hard materials or hardened surfaces. Traditional methodologies of abrasive finishing mainly include precision grinding, honing, lapping and polishing, developed with an emphasis based on the requirements. As an example, honing is generally used for finishing bores by imparting form accuracy and generating cross hatched surface topography to enhance lubrication. Whereas polishing of metallographic specimens is for removing the scratches and surface damages prior to the study of the micro structure. Sometimes, lapping and polishing techniques are used for removing the micro cracks, voids, etc., caused by the previous manufacturing operation such as grinding or Electric Discharge Machining (EDM) (Komanduri et al., 1997). These techniques typically illustrate the application of abrasive grits in precision finishing processes.

State-of-the-art abrasive finishing methodologies and practices mainly include the application of abrasives either in a fixed (bonded) or loose (free) form (Komanduri et al., 1997). Ultra precision grinding and honing are typical examples of using abrasives in a bonded form to impart fine finish on surfaces. The abrasives are in the form of a rigidly bonded wheel for grinding and in the stick form in honing. Research reported in this area mainly include the usage of various abrasive materials, new methods of bonding them, strategies of lubricant supply and improvisation of machine tools for different applications (Komanduri, 1997; Malkin and Guo, 2008; Shaw,1996). Conventional abrasives like aluminium oxide (Al_2O_3), silicon carbide (SiC), zirconium dioxide (ZrO_2), B_4C, super abrasives like diamond, Cubic Boron Nitride (CBN) and soft abrasives such as MgO, CeO_2, fumed silica, are also used extensively for fine finishing. Grinding wheels bonded with clay, resin, glass and metal are used by many researchers (Komanduri, 1996; Malkin and Guo, 2008; Marinescu et al., 2007a). A cast iron bonded diamond wheel developed by Nakagawa et al. (1986) for finishing ceramics and hard work materials, which can be continuously dressed using Electrolytic In-process Dressing (ELID) is a typical example. ELID is a hybrid approach developed by Ohmori and Nakagawa (1995) for fine finishing of silicon wafers, in which a continuous dressing of grinding wheel is occurring at a slow rate through electrolysis, simultaneously with the grinding action. Ultrasonic assisted grinding is also reported as a hybrid approach, well suited for brittle and hard materials (Marinescu et al., 2007a), combining the features of ultrasonic machining and abrasive action of the grinding wheel.

In the experimental work published by Cho et al. (2002), a specially made flexible abrasive tool was used in a three-axis machining centre for automatic finishing of rough milled surfaces. In this study, a cylindrical shaped tool of diameter 40 mm and length 50 mm with a half doughnut bottom (similar to a form grinding wheel) was prepared by pressure mounting the abrasives over the cast polymer form. By nature, this method is similar to a contour grinding operation suitable to finish well defined curved surfaces and will not fit perfectly in the category of fine finishing techniques addressed in this paper.

Micro machining approaches such as diamond turning (Dornfeld et al. 2006; Liu et al., 2004), abrasive impregnated brush deburring (Matahi et al., 2013), electrical discharge diamond grinding (Koshy et al., 1996) and abrasive assisted wire EDM (Menzies and Koshy, 2008) are some of the examples to demonstrate the usage of abrasives in their bonded form. Single Point Diamond Turning (SPDT) uses a single crystal diamond as a cutting tool to remove material. Even though the mode of using abrasive (diamond) in this case is not similar to ultra precision grinding operations, material is removed in smaller quantities and the chips are of same size or even smaller as in precision grinding (Komanduri et al., 1997; Shaw, 1996). Diamond turning is categorized as a hard loop finishing technique which needs same accuracy on the guidance of the tool as it requires on the surface (Balasubramanium and Suri, 2010), demanding a highly accurate and rigid machine tool. Mechanism of material removal during diamond turning of ductile materials is shearing and cutting, and the process is capable of yielding optical quality surface. However, crack propagation and sub surface damage is a serious technical concern in brittle materials. Brittle materials can be machined on diamond turning machine with single crystal diamond tool or by diamond grinding using an improvised methodology referred as *Ductile Regime Machining* (Balasubramanium and Suri, 2010; Venkatesh and Izman, 2007; Dornfeld et al.,2006), in which the crack propagation is restricted by controlling the depth of cut.

Mathai et al. (2013) reported an experimental and theoretical study on the application of a nylon brush impregnated with 100µm ceramic aluminium oxide grits for the deburring of micro milled grooves. Cost effectiveness, ease of automation and low brushing forces leading to reduced distortion of micro parts are projected as the advantages of abrasive brush deburring. Even though it is not strictly falling under fine finishing category, these studies showed an effective application of abrasives in their bonded form for burr removal.

A combination of abrasive action and electric discharge machining has been attempted by several researchers to overcome the limitations of traditional approaches, especially for advanced engineering materials that are difficult to machine by plunge grinding and drilling. Electrical discharge diamond grinding is a typical example which integrates electrical discharge machining and diamond grinding for machining electrically conducting hard materials (Koshy et al., 1996). Grinding force in this case is reduced by the thermal softening effect of work material created by electric discharge, followed by an abrasive action of *metal bonded diamond wheel* to get reasonably good surface quality. Abrasive assisted wire EDM is another hybrid approach, a combination of wire electric discharge machining and slow speed wire sawing, in which abrasives are used for improving the wire EDM performance (Menzies and Koshy, 2008). In both these cases, abrasives are used in a *rigid bonded* form. For example, experiments by Menzies and Koshy (2008) used a wire with synthetic diamond abrasives of 50 μm nominal diameter retained in an electroplated nickel layer covered over a high tensile strength steel core.

Micro grinding, the mechanical micro manufacturing technique reported as a miniaturized grinding operation, is also utilizing abrasive grains in its bonded form to generate high quality surfaces in micro parts. Electroplated metal bond, epoxy or polyester resin bond and sintered metal bond are typical form of bonding in this case, used for silicon wafer grinding, precision die grinding etc. (Rao and Ghosh, 2013). Size effect, higher ploughing forces and grinding wheel deformation are reported as some of the predominant effects in micro grinding. Requirements of high precision machine spindle and miniaturized grinding wheels are challenging technical requirements in micro grinding.

Discussions so far were mainly on fixed abrasive techniques. On the other hand, abrasives in its loose or free form can be used effectively for facilitating more accessibility to complex profiled work surfaces and can be used for a wide range of applications including finishing, patterning, roughening, deburring and other surface modifications (Komanduri et al., 1997; Marinescu et al., 2007b; Mathai and Melkote, 2012). Lapping and polishing are classical examples of traditional loose abrasive finishing techniques in which the material is removed through two-body or three-body abrasion (Marinescu et al., 2007b; Marinescu et al., 2004; Evans et al., 2003). Hard abrasive grits are introduced between the work material and a compliant lap in the case of lapping, whereas a conformable pad or soft cloth is used for polishing. Many of these lapping/polishing techniques use abrasives mixed in a carrier liquid, slurry medium or carrier paste to finish surfaces with the support of rotating or relatively moving lap/pad. Fine abrasives suspended in paste or liquid carrier are supplied initially to the plate or supplied during the process at specific intervals. At times abrasives embedded onto the lapping plate or pad, are also used allowing material removal through micro cutting (Marinescu et al., 2007b). Conventional pitch polishing show an example of this embedded type pad, which according to Komanduri et al. (1997) may fit in the category of fixed type abrasive polishing. Similar to metallurgical polishing and wax polishing, conventional pitch polishing is also categorized as a close contact operation (Kasai et.al., 1988). In general, it can be summarized that material removal in lapping and polishing is by rolling or sliding of free abrasive grits in the working gap or through an associated ultra-micro cutting action. The amount of material removal and finishing speed are relatively lower in lapping and polishing, with a less concentration of energy in the contact area. Because of this, the average temperature tends to be lower than that of in grinding, but the specific cutting energy will be higher. Since the volume of material removal is very low, it is not considered to be significant (Marinescu et al., 2004).

The characteristics of the lapping/polishing pad highly influence the movement of abrasive grains in the slurry (Marinescu et al., 2007b). A variety of lapping techniques using flexible laps have been reported in literature (Komanduri et al., 1997). Synthetic fabric laps with diamond paste (Parks and Evans, 1994) used for polishing optical surfaces, metal backing plate covered with a non-woven synthetic fabric (pellon) used for finishing nickel plated optics, teflon laps with aluminium oxide or silicon carbide abrasives for finishing glass or silicon etc. (Leistner, 1993), are typical examples of flexible laps. A 'rapidly renewable lap' introduced by Evans and Parks (1995) and Parks et al. (1997) discussed another mode of applying abrasives in lapping operation. Ultrasonic assisted lapping, vapour lapping using abrasive liquid jet etc. are some of the hybrid approaches in this category (Marinsacu et al., 2007b)

Similar to this, ultra precision polishing methods using ultra fine free abrasives are also investigated in detail (Marinescu et al., 2007b; Komanduri et al., 1997). Semi-contact polishing methods like chemical mechanical polishing of silicon wafers and non-contact polishing operations such as float polishing, Elastic Emission Machining (EEM) are some of the interesting examples. In float polishing, free abrasives mixed in a carrier fluid or polishing slurry is used with a soft diamond turned tin plate to generate optical quality surfaces in brittle as well as ductile materials (Namba and Tsuwa, 1977; Namba et al., 1987; Komanduri et al.,1997; Marinesu et al., 2007b). The floating condition in this case is achieved through the hydroplaning phenomenon under suitable tool rotation and slurry supply (Marinescu et al., 2007b). The cavitation in the slurry layer can make the abrasive grains undulate with the fluid medium, facilitating an additional erosion effect in the working gap along with the abrasion effect (Komanduri et al., 1997; Marinescu et al., 2007b). However, if the rough surfaces are not floating enough to the required level, the mirror-cut tin plate will change to muddy surface by the friction with the work surface and thereby polishing will not be effective (Marinescu et al., 2007b).

Elastic Emission Machining (EEM) enables a non-contact state between the workpiece and polishing tool using a rotating rubbery sphere. As the sphere rotates the abrasive slurry introduced in the working gap is forced out and the collision of abrasive grits results in atomic scale fracture and material removal (Mori et al., 1988; Mori and Yamauchi, 1987; Komanduri et al., 1997; Marinescu et al., 2007b; Kanaoka et al., 2007; Yamauchi et al., 1999). The above studies reported that the material removal process in EEM is a surface energy phenomenon in which each abrasive particle removes a number of atoms after coming into contact with the surface. It is also found that the type of abrasives have a very critical role in the material removal efficiency (Komanduri et al., 1997, Mori et al., 1988). Pressure between the spherical lap and workpiece in EEM is of the order of 5 bar, about three orders higher than that in float polishing (Komanduri et al., 1997).

Mechano-Chemical Polishing (MCP) is another class of technique characterized by the use of powders softer than the work surface (typically S_iO_2, Fe_2O_3 or MgO) and which can react with the work material. Solid-phase reactions will be generated in the contact zone between the low hardness abrasives and work material, producing various solid solutions. Further, the reacted spots are removed at nano scale by the frictional forces (Marinescu et al., 2007b; Komanduri et al., 1997). The mechano-chemical polishing is attempted both in dry and wet conditions using proper solutions. MCP of sapphire with S_iO_2 grains having hardness below 50% of work material was reported to have high polishing efficiency in dry condition, compared to wet MCP as well as mechanical polishing with diamond abrasives (Marinescu et al., 2007b). Chemical Mechanical Polishing (CMP) is defined as a wet type MCP in which the material is removed through chemical action followed by mechanical interaction (Jain, 2010; Komanduri et al., 1997; Marinescu et al., 2007b). In this process, slurry composed of chemicals and submicron sized abrasives is used as polishing medium and a typical example is colloidal silica suspension. Chemical reaction between the chemicals and work metal layers result in a thin, non-dissolving, chemically passivating surface film that is removed gradually by the mechanical interaction of abrasive particles (Jain, 2010). Sapphire, silicon wafer, glass, silicon nitride, quartz, etc. are typical range of work materials used in the research works reported in these chemical-mechanical techniques, with SiO2, Fe_3O_4, MgO, $CaCO_3$, $BaCO_3$, CeO_2, etc. as abrasive particles (Komanduri et al., 1997, Yuan et al., 2002).

Even though chemo-mechanical polishing is capable of producing high quality surfaces, the performance will be affected if the chemical reaction products diffuse into work material or remain on the surface. So it is very crucial to ensure that the chemical reaction products are completely removed from the surface and sub surface of work material. Since a multi-phase complex chemical reaction is involved, proper control of chemical reaction rate is also a critical and challenging requirement in CMP. Delamination, micro scratches, erosion, corrosion and inefficient post-CMP cleaning are some other technical issues associated with this chemical mechanical technique (Jain, 2010; Komanduri et al., 1997).

Electro abrasive mirror polishing and Progressive Mechanical and Chemical Polishing (P-MAC) are similar techniques falling in the aforementioned loose abrasive category. Electro abrasive polishing is developed for mirror polishing of metals using abrasive-$NaNO_3$ solution, and an electrode covered with nylon fabric or polymer pad. The polishing process includes electrolysis at the surface peaks (elevated surface regions) producing passive oxide film, followed by rubbing action of abrasives (Marinescu et al., 2007b). P-MAC technique reported by Kasai et al. (1988) involves a polishing mechanism altered progressively from mechanical to chemical action. Along with the methodologies, interesting research and developments in polishing and lapping machines, including ultra-precision CNC machines, are also reported in various literatures (Komanduri et al., 1997; Marinescu et al., 2007b).

As mentioned above, abrasives are applied in the form of slurry in lapping and polishing, where loose abrasives like aluminium oxide, cubic boron nitride or diamond are dispersed in a liquid media or paste. The abrasive slurry can be water-soluble, oil-based or oil-water emulsion type, with additives like corrosion inhibitors, suspension agents, viscosity enhancement agents, lubricants etc. Oil based slurry is expensive to use, difficult and expensive to dispose. Moreover the oil to be disposed is a hazardous waste, according to industrial regulations (Marinescu et al., 2007b). Water based slurry is an alternative and promising choice, but rust inhibitors and other additives are very essential in this case. The oil-water emulsion can also be used; but shorter shelf life and variation of viscosity during operation are the disadvantages. Difficulty in suspending super abrasives, break up of liquid film during operation are some other challenges (Marinescu et al., 2007b). The composition and volumetric concentration of slurry, properties of carrier medium, mode and quantity of slurry supply and the size of abrasive grains are critical parameters influencing the surface finish. For example, too high slurry supply in lapping may produce an aquaplaning effect and at the same time low quantity slurry may deteriorate the material removal. If the slurry film is broken, cold welding of lapping plate and work surface may happen (Marinescu et al., 2007b). Inconvenience in handling, cost factor and environmental/health considerations are some of the serious challenges associated with this wet medium.

Table 1.1: State-of-the-art advanced finishing methodologies
(Jain, 2013; Jain, 2010; Singh et al., 2012a)

- Micro/Nano finishing with flexible flow of abrasive
  - Abrasive Flow Finishing
    - One-Way Abrasive Flow Finishing
    - Two-Way Abrasive Flow Finishing
    - Orbital Abrasive Flow Finishing
    - Micro Abrasive Flow Finishing
    - Hybrid and Allied approaches in AFF
      - Electrochemical Assisted Abrasive Flow Machining
      - Ultrasonic Flow Polishing
      - Spiral Polishing
      - Centrifugal Force Assisted Abrasive Flow Machining
      - Drill bit guided Abrasive Flow Finishing
      - Rotational Abrasive Flow Finishing

- Magnetic Field assisted abrasive Finishing
  - Magnetic Abrasive Finishing
  - Magnetic Float Polishing
  - Magnetorheological Finishing
  - Hybrid and Allied Approaches
    - Magnetic Abrasive Deburring
    - Ultrasonic Assisted Magnetic Abrasive Finishing
    - Electrolytic Magnetic Abrasive Finishing
    - Magnetic Abrasive Jet Finishing
    - Magnetorheological ball end finishing

- Magnetic Field Assisted Finishing with flexible flow of abrasive
  - Magnetic Abrasive Flow Machining
  - Magnetorheological Abrasive Flow Finishing
  - Rotational Magnetorheological Abrasive Flow Finishing

The common procedure of grinding followed by lapping or conventional mechanical polishing may not be a practically feasible and an optimum solution in many of the stringent requirements in micro/nano finishing (Jain, 2013). The major limitations are in the cost involved, order of finish achievable, processing time, accessibility to complex shaped components and intricate profiles, limitations posed by advanced engineering materials and difficult-to cut materials like hardened steel, ceramics, glasses, titanium and nickel based super alloys, etc. Moreover, 'nano finish' refers to a delicate and fine refinement of surface profile without altering its form and without creating sub surface damage. Conventional procedures of loading hard abrasives into the work surfaces, especially diamond, may produce deeper penetration of abrasive grains leading to surface and sub surface damages. Furthermore, production cost also becomes high in the case of super abrasives (Jain, 2013). To address the aforementioned demands in ultra fine finishing, a set of advanced abrasive techniques based on mechanical, electrochemical and chemical principles are developed in recent past. Table 1.1 shows a list of fine finishing techniques in this category and some of the hybrid approaches reported in the literature (Jain, 2013; Jain, 2010).

In Abrasive Flow Finishing (AFF), a polymer-based viscoelastic abrasive medium is extruded through the passage formed by workpiece and tooling. According to Jain et al. (2009), the medium used in abrasive flow finishing can be idealized as a viscoplastic medium when the elastic strains are negligible. Silly putty, low molecular weight soft styrene butadiene polymer (SBP) or polyborosilixane mixed with processing oil are reported as typical examples of abrasive medium (Jain and Adsul, 2000; Jain et.al., 2009; Sankar et al., 2009a). Special abrasive gel prepared by mixing fine abrasives with silicone rubber with additives is also used for abrasive flow finishing (Wang and Weng, 2007). The basic AFF system consists of a hydraulic unit forcing the polymer-abrasive medium through the tooling at selected pressure and flow rate. The major function of tooling is to direct the flow of medium and control the abrasion area (Jain, 2013; Rhoades, 1991; Loveless et al., 1994). AFF is found to be an effective method for deburring and polishing of mechanical components (Jain, 2013; Kim and Kim, 2004), including the removal of recast layers produced by electric discharge machining, fine finishing of internal passages and micro/nano finishing of automotive, aerospace and biomedical components. As a representative example, an improvement of surface finish from an initial average roughness of 2 μm to 0.2 μm is reported on a die surface after abrasive flow finishing (Sankar et al., 2013).

The media of applying abrasives in AFF is comprised of a base carrier polymer, rheological additives such as plasticizers and softeners. The selection and proportion of additives are important criteria which decide the viscosity of abrasive-polymer medium. Viscosity of the medium, extrusion pressure, abrasive grit size, flow rate of the medium, number of cycles and the temperature are reported as major process variables in AFF (Jain, 2010). The material removal in AFF is only by mechanical abrasion. The radial forces during the extrusion will make the abrasive grains in the media to penetrate into the work surface, whereas the axial force pushes the indented abrasive grains to remove material in the form of microchip (Rhoades, 1991; Jain, 2013).

According to various studies, the abrasive action is highly influenced by the change in rheological behaviour of the medium when it is extruded through a restricted passage (Rhoades, 1988; Rhoades, 1991). Because of this, extrusion pressure is a very critical parameter to be controlled properly. Typical range of extrusion pressure reported is 1 to 20 MPa with maximum flow rate of the medium about 15-20 L/min (Jain, 2010; Sankar et al., 2009a; Jain et al., 2009; Jain, 2013). The ratio of radial force to the axial force acting on an abrasive grain in the media is a function of extrusion pressure. The depth of abrasive grain penetration will be higher at higher extrusion pressure, sometimes making the axial force insufficient to remove the material. In this case, particle may rotate inside the medium to adjust the height or it may lock inside the work material leading to its fracture or non cutting condition (Jain, 2013; Jain, 2009). A typical experimental study by Sankar et al. (2009a) showed that the extrusion pressure in the range 6 to 6.5 MPa is optimum for abrasive flow finishing of aluminium based metal matrix composite.

Various experimental studies reported in abrasive flow finishing were clearly indicating the importance of controlling the composition and viscosity of polymer-abrasive media (Rhoades, 1988; Rhoades, 1991; Williams and Melton, 1998; Jain, 2009; Jain, 2010). Based on the experimental study by Sankar et al. (2009a), the percentage weight of additives plays an important role in the rheological properties of the medium. Abrasive concentration, medium temperature and abrasive grain size are also found to have significant effect on the medium viscosity (Jain, 2009). When an abrasive medium prepared using abrasives, polymer and hydrocarbon processing oil was used for abrasive flow finishing, 10% by weight of processing oil (plasticizer) is found optimum surface finish. Small quantity of plasticizer makes the medium too stiff with inferior rheological behaviour, whereas an increase in percentage weight of processing oil will reduce the abrasive holding capacity of the medium (Sankar et al., 2009a; Jain, 2013). The loose abrasive bonding in a low viscosity medium facilitates easy flow, but the abrasives may not get sufficient bonding backup from the medium to create cutting effect. Because of this, the abrasives may simply rotate inside the medium or simply slide over the surface without cutting (Jain, 2013; Sankar et al., 2009a, Jayswal et al., 2005a; Sankar et al., 2009c).

Initial surface roughness, material and geometrical configuration of work material, difference between cross-sectional area of media cylinder and extrusion passage, and cycle time are the major other process variables to be controlled and selected properly to get a better finishing performance in AFF (Jain, 2010; Loveless et al.,1994). The material removal characterises of abrasive flow finishing is analysed by many researchers using various theoretical and experimental approaches. Experimental investigations into the cutting forces and active grain density during abrasive flow finishing by Gorana et al. (2004), Force prediction in abrasive flow finishing by Gorana et al. (2006), Modelling of material removal and surface roughness in abrasive flow finishing using finite element method by Jain et al. (1999a) and Jain et al. (2009), neural network analysis by Jain and Jain (2000) and Jain et al. (1999b), stochastic simulation of active grain density in abrasive flow finishing by Jain and Jain (2004) are typical examples.

Extending the basic concepts of abrasive flow finishing, different methodologies and hybrid approaches are also proposed as listed in Table 1.2

A set of fine finishing methodologies which can be manipulated using magnetic fields are referred to as magnetic field assisted abrasive finishing techniques. In Magnetic Abrasive Finishing (MAF), abrasive grains are used in the form of a flexible magnetic brush that neither need compensation nor dressing (Shinmura et al., 1990; Komanduri et al., 1997; Jain, 2009; Jain, 2013). The abrasive grains like silicon carbide, aluminium oxide, diamond, etc. can be mixed with ferromagnetic particles in a small quantity of mineral oil, kerosene or SAE30 motor oil to form Unbounded Magnetic Abrasive (UMA) medium (Singh et al., 2005a; Jain, 2013; Fox et al., 1994). As the magnetic field is introduced, the ferromagnetic particles get aligned along the magnetic lines of force with abrasives grains entwined in the chain to form the magnetic abrasive brush. The abrasive particles can also be applied in the form of a Bonded Magnetic Abrasive (BMA) medium, where abrasive grains are held in ferromagnetic matrix by sintering, chemical processing or by other means (Shinmura et al., 1990; Fox et al., 1994). It is also reported that the material removal using UMA is higher than BMA because of the availability of free abrasives, producing deeper scratches than bonded abrasives. Because of this, it is recommended to apply magnetic abrasive finishing using UMA followed by BMA to get a nano finished surface from poor initial surface finish (Jain, 2013).

In a plane magnetic abrasive finishing process, the magnetically energized ferromagnetic particles are acting as a binder that holds free abrasives within the working gap. The normal force components, both magnetic as well as mechanical, are responsible for the penetration of abrasive grain in to the work surface, whereas the tangential force due to the rotation of ferromagnetic abrasive brush along with tangential component of magnetic forces are responsible for the cutting action (Singh, 2005; Singh et.al. 2006; Mori et al., 2003; Jain, 2013; Jain, 2009). A detailed clarification on the mechanism of material removal by magnetic abrasive brush is reported by Mori et al. (2003), whereas Jayswal et al. (2005a ; 2005b) discussed the parametric and modelling studies on magnetic abrasive finishing. In addition to flat surface, this methodology has been applied by many researchers to finish internal and external cylindrical surfaces of both magnetic as well as non-magnetic materials. The method is also applicable to perform operations such as polishing, deburring and removal of oxide films. Study on cylindrical magnetic abrasive finishing by Chang et.al (2002), studies on magnetic abrasive polishing of free-form surfaces by Kim and Choi (1997), investigations on inner surface finishing of aluminium, brass and stainless steel tubes using magnetic abrasives by Wang and Hu (2005), internal polishing of thin and long austenitic stainless steel tubes studied by Wang et al, (2004), studies on magnetic field assisted internal finishing of alumina ceramic components by Yamaguchi and Shinmura (2004), assessment of surface modification by internal magnetic abrasive processes (Yamaguchi and Shinmura, 1999), development and assessment of an internal magnetic abrasive finishing method using magnetic pole rotation (Yamaguchi and Shinmura, 2000; Yamaguchi et al.,1996), investigations into magnetic abrasive micro deburring (Madarkar and Jain, 2007; Ko et al., 2007), studies on surface and edge finishing by magneto abrasive particles (Khairy, 2001) are some of the examples. Experimental results of magnetic abrasive finishing are published by many other researchers and many of them compared this approach with other methodologies (Kurobe and Imanaka, 1984; Komanduri, 1996; Komanduri et al., 1997; Kim and Choi, 1995). An experimental investigation on magnetic abrasive finishing using UMA mixed with silicone gel is an interesting example in this group (Wang and Lee, 2009). This method has been applied effectively on a cylindrical steel rod, reducing its average roughness from 0.677 µm to the order of 40-50 nm in 30 minutes. Recycling efficiency of the magnetic-abrasive media is another important aspect examined in this work.

Table 1.2: Different methodologies of abrasive flow finishing

(Jain, 2013; Jain, 2010; Brar et al., 2010)

Methodology	Important characteristic features
One way AFF	➢ Extrude the medium unidirectional using an appropriate hydraulic system (Rhodes et al.,1994)
Two way AFF	➢ Extrudes the medium in to and fro direction (Rhodes and Kohut, 1991; Walch, 2005)
Orbital AFF	➢ Combination of form grinding and two way AFF ➢ Medium reciprocates in two ways and an orbital motion is given to the form tool (Rhoades,1990)
Micro-AFF	➢ Medium with very low viscosity and very fine abrasive grains area used (Walch et al., 2002, Greenslet and Rhoades, 2005)
Electrochemically assisted AFF	➢ Combination of electro chemical action and abrasion ➢ Polymeric electrolytes like polypropylene glycol and water gels are used as carrier medium ➢ Polymeric electrode forced through narrow passage takes the form of semi liquid paste. (Debrowski et al., 2006)
Ultrasonic Flow Polishing	➢ Combination of Ultrasonic machining and AFF ➢ Medium pumped centrally through an ultrasonic tool (Yan et al., 2007, Wei-Chan et al., 2010)
Centrifugal Force assisted AFF	➢ Centrifugal force is generated in the finishing zone using a rectangle, spline, triangular or square rod. ➢ Turbulent flow of abrasive media improves the surface finish (Walia et al., 2006a; 2006b)
Drill bit guided AFF	➢ Freely rotatable drill bit is placed in the finishing zone with the help of special fixtures. ➢ Combination of reciprocation and scooping flow across drill bit flute imparts dynamic motion to abrasive grains. (Sankar et al., 2009b)
Rotational AFF	➢ Workpiece fixture is rotated externally using a variable frequency drive (Sankar et al., 2009a; 2010a; 2010b)

Voltage, working gap, rotational speed of magnetic brush, abrasive grain size, work material properties, volume fraction of loose abrasives and processing time are the influencing process parameters in magnetic abrasive finishing (Singh et al.,2004; Jain and Jain, 2001). Performance of flexible magnetic abrasive brush and the surface texture generated by these brushes are also analysed in detail by Singh et al, (2005, 2005a). Magnetic abrasive finishing using electromagnets energized by normal as well as pulsed DC power supply are some of the interesting discussions found in the literature (Jain et al., 2008). The major technical issues associated with normal DC power supply and Static-Flexible Magnetic Abrasive Brush (S-FMAB), are overheating of electromagnetic coils and lack of stirring /refreshing effects of loose abrasives. Kurobe and Imanaka (1984) attempted an approach of using an on-off DC supply, periodically turning on and off, during magnetic abrasive finishing. Resolving the difficulty of on-off control, Yamaguchi et al. (2003) developed a precision internal finishing system using alternating magnetic field and studied the finishing characteristics. In a pulsed DC supply, in the case of Pulsating Flexible Magnetic Abrasive Brush (P-FMAB), magnetization and demagnetization is happening periodically that facilities a stirring effect to bring fresh abrasive grains into action (Singh et al., 2013). Finite element analysis of magnetic abrasive finishing process and the usage of electromagnet with and without slots are also reported by many researchers (Jain, 2013; Jain, 2009; Jayswal, 2005; Jayswal et al., 2004; Jayswal et al., 2005a; Jayswal et al., 2007). Some other studies indicated that the introduction of axial vibratory motion of magnetic pole or work piece can improve the performance of magnetic abrasive finishing (Shaohui and Shinmura, 2004 a; 2004 b).

A different variant of magnetic field assisted abrasive finishing technique developed for spherical surfaces such as ceramic balls is referred as Magnetic Float Polishing (MFP). In this method, a magnetic fluid containing fine abrasive grains and extremely fine ferromagnetic particles in water or hydrocarbons like kerosene with appropriate surfactants is used for finishing (Komanduri et al., 1997). During the application of magnetic field, the magnetic-abrasive fluid is attracted towards the area of higher magnetic field and an upward buoyancy force is exerted on a non metallic float supporting the ceramic balls. The hydrodynamic behaviour of the abrasive media and the corresponding buoyancy force is facilitating the interaction of abrasive grains with the work surface. A rotating drive shaft is used to maintain the required force level in this process and it is reported that the technique is capable of generating damage free surfaces on hard and brittle spheres because of the low buoyancy force (Umehara et al., 2005; Tani and Kawata, 1984). Typical application includes the finishing of Si_3N_4 balls for high speed bearings.

Another highly promising methodology working with the support of magnetic field is Magneto Rheological Finishing (MRF) where the abrasives are applied for finishing in the form of a controllable smart fluid referred as magnetorheological fluid (MR fluid). A typical magnetorheological fluid is composed of micron sized magnetic Carbonyl Ion Particles (CIP), loose abrasive grains in a carrier fluid (oil or water based) with stabilizers such as glycerol, grease, oleic acid etc. to reduce the sedimentation. The presence of magnetic field can transform the MR fluid to a semi-solid state from its liquid like state, through the formation of CIP chains along the magnetic field lines (Kordonski and Jacobs, 1996; Kordonski and Golini, 1999; Sidpara et al., 2009). In the absence of magnetic field, an ideal MR fluid acts like a Newtonian fluid, whereas external magnetic fields make them non-Newtonian (Jain, 2009; Jain, 2013). Rheological properties of magnetorheological fluids are easily controllable through magnetic field and are capable of carrying heat and debris from polishing zone. Composition of MR fluid and the concentration of magnetic particle in it are to be controlled properly to avoid the difficulties associated with their rheological behaviour. For example, higher concentration of magnetic particles in MR fluid may create issues like low fluidity. At the same time, a very high percentage of abrasive concentration and low percentage of magnetic particles may reduce the stiffness of MR fluid (Jain, 2013; Sidpara et al., 2009). With appropriate control of process parameters, MRF is found suitable for the nano finishing of flat, concave or convex shaped surfaces in glass, ceramics, hard and brittle materials and non-magnetic metals (Jain, 2009; Jain, 2010).

The various other methodologies and hybrid approaches in magnetic field -assisted abrasive finishing are listed in Table 1.3.

Table 1.3: Different methodologies of magnetic field assisted abrasive finishing

Methodology	**Important characteristic features**
Ultrasonic assisted MAF	➢ MAF coupled with ultrasonic vibration ➢ typical finish value of 20-50 nm is observed on hardened steel with Silicon carbide grits (Mulik and Pandey, 2011)
Electrolytic MAF	➢ Electro chemical machining + MAF ➢ Gap between tool electrode and workpiece is filled with electrolytes and a soft film coating is produced on work surface by electrochemical action (Yan et al., 2003)
Ultrasonic-magneto-electrochemical micro machining	➢ Ultrasonic machining + Magnetic Abrasive Finishing + Electrochemical Machining (Pa., 2009)
Magnetic abrasive Flow finishing	➢ Magnetically controlled Abrasive Flow finishing ➢ Medium composed of silicon polymer, hydrocarbon gel, ferromagnetic powder and abrasive grains (Singh and Shan, 2002; Singh et al.,2002)
Magnetic abrasive jet finishing	➢ Carrier fluid with magnetic abrasives is supplied as jet ➢ Suitable for internal surfaces of hollow cylinders (Kim et al.,1997)

Table 1.3 Continues...

Magnetorheological abrasive jet finishing	➢ Use a jet of magnetorheological (MR) fluid (Kordonski and Shorey et al., 2007; Kordonski et al., 2006)
Magneto Rheological Abrasive Flow Finishing (MRAFF)	➢ Combination of magnetorheological finishing and abrasive flow finishing ➢ Suitable for finishing internal surfaces to nano scale (Jha and Jain, 2004; 2008; Jha et al., 2006; Das et al, 2008)
Rotating Magnetorheological abrasive flow finishing	➢ MRAFF with rotating magnets ➢ Circular motion to MR fluid in addition to axial motion (Das et al., 2010)
Magnetorheological ball end finishing	➢ Hemispherical ball end finishing spot of MR fluid at the tool tip is used, with CNC motion controller ➢ Capable of finishing 3D surfaces with intricate shaped surfaces (Singh et al., 2011) ➢ Movement similar to ball end cutter in CNC machine (Singh et al., 2012 a; 2012 b)

According to the classification reported by Jain (2009), abrasive flow finishing is a nano-finishing technique without an external control of forces. In this case, the forces acting on work surface are not controllable externally. Chemo- mechanical method and elastic emission method discussed above used for silicon wafers also can be categorized into this group. But the magnetic field assisted techniques listed above are with external control of forces. The forces acting on work surface can be controlled by varying electric current through electromagnet or by adjusting the working gap in the case of permanent magnet.

Slightly different approaches found in literature were again directed towards the development of energy efficient fixed abrasive techniques using polishing tools capable of self dressing/replenishing during the polishing process.

One of such attempts is the use of a frozen abrasive tool that can continuously expose fresh abrasive particle by melting the frozen layer during polishing. The frozen mixture of water and abrasive used by Belyshkin (1966) and the frozen colloidal silica used by Zang et al. (2001) are typical examples of this approach. Nano scale surface finish is reported in glass specimens polished by these frozen mixture under controlled process conditions. Ice Bonded Abrasive Polishing (IBAP) is another approach in this category, which utilizes a cryogenic polishing tool to generate fine finished surfaces. Mohan and Ramesh Babu (2010) demonstrated the feasibility of IBAP for ultra fine finishing of copper specimens with an abrasive tool prepared by freezing the slurry of water and abrasives. One of the critical prerequisites of this method is the preparation and characterization of a perfect Ice Bonded Polishing tool, followed by a precise control of temperature by suitable supply of liquid nitrogen. By studying the kinematics of belt polishing, lapping and chemo- mechanical polishing, Mohan and Ramesh Babu (2011) made an attempt to design, develop and characterize the ice bonded abrasive tools for better results. From these literatures, it can be summarized that this methodology is suitable for polishing flat surfaces, whereas the development of ice bonded tool and the accessibility limitations are the major challenges in intricate/free form surfaces.

Instead of abrasion, surface erosion using impact of free abrasives is another promising option to finish the complex work pieces which pose accessibility issues. This mechanism has already found applications in processes such as Abrasive Jet Machining (AJM) and Abrasive Water Jet Machining (AWJM). In these processes, a jet of abrasives suspended in air or water impinges on the target surface at relatively higher velocity, typically of the order 150-350 m/s. Since the loose abrasives can be directed easily to difficult-to-access regions, such erosion based techniques can be used effectively for intricate shapes and freeform surfaces. But due to high impingement velocity, the material erosion is severe in the aforementioned techniques and they are ideally suited for macro scale material removal leading to “cutting” or deburring (Jain and Jain, 2001). Methodologies like micro abrasive blasting, abrasive jet micro machining and shot peening (Ko, 2010; Achtsnick et al., 2005; Karpuschewski et al., 2004;

Cláudio et al., 2011) also use free abrasive jets at relatively higher velocities to produce various surface modifications. On the other hand, when the discussion is about ultrafine surface finishing with an average roughness (Ra) value, down to the order of 10 to 100 nm, the surface profile needs to be refined delicately without altering its form. Usage of very fine abrasive grains and low velocity impingement are typical strategies to achieve this critical requirement.

Fluidized abrasive polishing is a promising finishing approach utilizing low velocity impingement erosion. The basic idea is to suspend the abrasive particles in a fluid media and direct the target work piece against the suspended abrasives so as to erode the target material at a low impact velocity of the order of 1 to 5 m/s or lower. Preliminary experimental study on fluidized abrasive finishing with relatively lower impingement velocity, of the order 0.75 m/s is reported by Jaganathan and Radhakrishnan (1997). In this work, silicon carbide grits of size range 250-590 µm, falling in the category of Geldart group B (Geldart, 2005) are used to demonstrate the concept. Abrasive grits of medium size range are selected here to ensure sufficient kinetic energy transfer during impact, to get sufficient erosion and material removal action (Jaganathan, 1997; Jaganathan and Radhakrishnan, 1997). They have also concluded that the usage of very fine abrasive grits in its loose form will amplify the cost of environmental safe guards to be adopted, and leads to practical and operational complexities.

Turbo abrasive machining (TAM) is another methodology reported with a similar fluidization concept, which is developed for deburring and edge finishing of gears, impellers, sprockets, rotors, etc. According to Massarsky and Davidson (1995; 1997; 2007), the basic idea in TAM is to rotate the components at high speed in a low speed abrasive air stream to allow high intensity of abrasive impacts per unit time, typically of the order 200-500 per mm^2/s. Improvement in average roughness (Ra) from an initial value 2 µm to 0.2 µm is reported by this method after few minutes of cycle time, by Massarsky et.al. (1997). Here again, deburring and mass finishing are the major objectives addressed with reasonably high material removal compared to other loose abrasive techniques.

A slightly different methodology is attempted by Barletta et al. (2007a, 2007b) to develop Fluidized Bed Assisted Abrasive Jet Machining (FB-AJM) for precision internal polishing of aluminium and inconel 718 tubes. The experimental system in FB-AJM includes a compressor, two fluidized beds, venture pipes, three-way valves and a nozzle to allow the impingement of abrasive grits at moderate velocity, of the order 10-15 m/s. Experimental studies performed by Barletta et al. (2007a, 2007b), with a jet velocity 10m/s showed an improvement in the average roughness (Ra) from 3 to 5 µm to 0.6 to 0.7 µm on aluminium tubes, where as a change from 1.3 µm to 0.11 µm is recorded in inconel tubes at a jet pressure of 4 bar and velocity of 13 m/s. Another fluidized bed machining system developed by Barletta (2006, 2009) is reported to be applied for the surface finishing of aluminium alloys. An improvement in Ra from 1.53 µm to 0.57 µm has been observed in this case.

Even though the above fluidization methodologies have been projected as promising options in fine finishing, one of the major technical challenges is the limitation posed by the size of the abrasive particles. Abrasive grits having the size range below 40 to 35 µm are very difficult to fluidize because of their cohesiveness and agglomeration tendency. According to Geldart (2005), these particles are categorized as Geldart Group C particles.

Abrasive jet finishing using magnetic abrasives and magneto rheological (MR) fluid are also attempted by various researchers (Kim, 1997; Kordonski and Shorey, 2007). In these processes, working fluid mixed with magnetic abrasives/ MR jet is impinged on the work surface to get the required finishing action. Arrangement of magnetic poles, controlling of jet and the preparation of jet media are critical technical concerns in this regard.

1.3 Motivation and Research Objectives

One of the major technical issues associated with bonded abrasive finishing techniques is the accessibility limitations imparted by the geometry of wheel/stick, making them ideal only for well defined surfaces. This is a serious technical challenge while addressing meso/micro scale components with intricate profiles and stringent finish requirements. Development of dedicated abrasive tool and the order of finish achievable are the major concerns in this regard. Moreover, specific cutting energy required for these techniques are very high (Marinescu et al., 2007a; Malkin and Guo, 2008; Shaw, 1996; Komanduri et al.,1997). The surface topography of grinding wheel also gets affected by the flattening of abrasive particles or loading of pores with debris, which in turn may affect the surface form. Even in flat surfaces, to get good finish, proper control of grinding forces, monitoring of process parameters, proper selection and dressing of wheels and adequate supply of coolant are very essential. The damage of the sub surface layer and probability of form error are some of the other issues in conventional grinding procedure. The grinding forces can be reduced by an electrolysis action in the case of ELID grinding. But the geometry of work surface that can be finished, selection of an appropriate abrasive bonding and proper supply of electrically conducting fluid at the contact interface are significant technical challenges (Komnaduri et al., 1997; Marinescu et al., 2004). Accessibility of complex profiled surfaces is yet another limiting factor. Diamond turning is another ultra precision method of using abrasive in its bonded form, proven effective for the generation of semi conductor and optical surfaces. But the surface roughness and shape accuracy depends greatly on the rigidity of machine tool (Jain, 2010). The movement of cutting tool needs to be controlled very precisely to achieve reasonably good finish. In ultra precision micro machining operations, highly negative effective rake angle of cutting edge, the size effect and the pronounced ploughing action may cause significant subsurface damage (Liu et al., 2004). Micro grinding is also capable of ultra precision finishing, but high precision spindle requirement in machine tool and the production of miniaturized grinding wheel are the challenging requirements (Jain, 2013). Another interesting example of fixed abrasive technique discussed is abrasion assisted wire EDM. Here again, the geometrical shape of work surface that can be finished and the cost of diamond coated wire are the serious limitations (Menzies and Koshy, 2008).

Finishing methodologies like lapping and polishing are showing the effective utilization of abrasive grains in its loose form. The hardness of lapping plate and polishing pad is found to be an important factor deciding the surface finish. Very hard wheels/pads may push the abrasive grains deeply into the surface, sometimes fading the surface quality (Marinescu et al., 2007b). In conventional polishing with soft pads, it is also found that the flatness may deteriorate as stock removal increase. On the other hand, mechanochemical polishing can be used to maintain the flatness, but the chemical reaction by the slurry medium is a serious concern in mechanochemical and chemo-mechanical polishing (Marinescu et al., 2007b). In many situations, lapping and polishing are found to be incapable of producing required surface characteristics, particularly in micro/nano finishing of complex shaped components. The major bottleneck lies in the control of abrading forces and the accessibility of intricate features. For example, optical quality surface generation in free-form shapes are really difficult to achieve using conventional polishing procedures (Jain, 2013). Proper control of finishing forces to get delicate refinement of surface profile without damaging the sub-surface and without altering the surface form is a critical requirement in all these micro/nano finishing (Komanduri et al., 1997; Jain, 2013). Even though polishing operations can be fine tuned to achieve some of the above requirements, they require expensive equipment and long processing time, making them economically incompetent (Jain, 2013). The continuous usage of liquid carrier medium/slurry is another critical environmental issue.

The term ‘micro/nano finishing’ refers to delicate refinement of surface profile with limited quantity of material removal, without altering the surface form, yielding an average roughness of the order of few nanometres. Conventional grinding, lapping and polishing procedures, micro grinding, mechanical micro machining, laser beam machining and other similar methodologies may produce unwanted side effects such as micro/nano cracks, recast metal, micro/nano burrs, metallurgical phase changes, sub surface damage, form error, etc., making them often incapable of meeting the stringent fine finishing requirements (Jain, 2013). As discussed earlier, accessibility issues with free form surfaces and complex geometrical profiles such as internal grooves, intricate pockets, and high aspect ratio bores etc. are also challenging.

Advanced free abrasive finishing techniques like AFF, MAF, MRF, CMP and EEM showed the usage of finer grade abrasives in various forms, which enabled the removal of smaller quantity of material through flexible flow of abrasives. Preparation and selection of abrasive carrier media, arrangement of energy sources, precise feeding of abrasive carrier media, requirement of special tooling, and development of fixtures are some of the bottlenecks in these unconventional methodologies. For example, the preparation of magnetorheological fluid in its proper proportion, development of special nylon fixture to hold the workpiece in centrifugal force assisted abrasive flow, supply of colloidal silica slurry and the periodic reconditioning of pad in chemo-mechanical polishing, etc. are exigent tasks (Brar et al., 2010; Jain, 2010). From the detailed literature survey, it can be summarised that the major drawbacks observed in many of these methodologies are the pitting effect, weakening of grain boundaries due to reaction of strong chemicals with surfaces and the form/ flatness error due to irregular nature of material removal (Mohan and Ramesh Babu, 2010). Another important issue in technical as well as commercial perspective is the change in rheological behaviour required according to the variation in the approach. More specifically, an abrasive carrier medium prepared for normal abrasive flow finishing may not be suitable even for its hybrid approaches. For example, a low viscosity medium allowing the migration of ferromagnetic particles towards the magnet is ideally suited for magnetic abrasive flow finishing. But for spiral polishing, the results were excellent in the case of high-viscosity medium. Low viscosity medium cannot be scooped up and down as a lump (Jain, 2013). On the other hand, low viscosity media is preferred for centrifugal force assisted abrasive flow finishing for facilitating easy flow of the media (Jain, 2013).

As described earlier, micron-sized abrasives are preferred for fine finishing operations because of low finishing force, small cutting edges, reduced depth of penetration, nano- scale material removal and the possibility of more number of active grains per contact area. Since the material is removed in the form of micro/nano chips, these abrasives can be employed to achieve better surface finish and dimensional tolerance, even in harder and difficult-to-cut materials (Komanduri et al., 1997; Inasaki et al., 1993; Jain, 2013). But handling of micron and sub-micron sized fine abrasives is really inconvenient and filling them in their loose state in the working zone, unbounded magnetic abrasive finishing for example, is also very difficult. During magnetic abrasive finishing, it is also found that the abrasive grains in their loose form may easily flow away from the working zone and the abrasives cannot be recycled after the finishing operation. These observations motivated researchers like Wang and Lee (2009) to think about a flexible bonding of abrasives through silicone gel in magnetic abrasive polishing. But it is still interesting and demanding to have a promising methodology which can replace the usage of these gels or slurry medium. Further to it, as discussed previously, fine abrasive powders in Geldart group C category having size range below 35 μm cannot be applied directly for methodologies like fluidized abrasive finishing where cohesiveness and agglomeration of fine powders impart the restriction (Jagannathan and Radhakrishnan, 1997).

The recent research work reported by Mohan and Ramesh Babu (2010, 2011, 2012) proposed an alternative way of utilizing abrasive grains in their bonded form in an ice matrix, which can expose fresh grains periodically without any dressing. Though it is demonstrated to have certain special features and capable of fine finishing ductile as well as brittle materials, the preparation of ice bonded tool, its handling and the maintenance of cryogenic condition are the major complexities.

Considering the aforementioned issues, it is worthwhile looking at the possibility of developing a fine finishing approach, which is neither in the category of rigid bonded abrasives nor in the group of fully loose ones that use a slurry/liquid carrier medium. Any new approach should be capable of bridging the gap between loose abrasive finishing and rigid bonded abrasive finishing, combining the practical advantages of both.

In the case of erosion, usage of finer grade abrasives, impinging at lower velocity, can yield fine refinement of surface profile. But, handling of fine particles in its loose form is technically, economically and environmentally challenging. Fluidization based techniques found in literature are also facing the same practical difficulty. The possibility of using fine abrasive grains in fluidized finishing is an exigent task, because of the size limitation in fluidization, making it impossible to fluidize Geldart group C particles in normal working conditions (Jaganathan and Radhakrishnan, 1997). Some of the recent literatures in chemical engineering, related to fluidization of powders, have indicated the possibility of improving the fluidization behaviour of Group C particle with the aid of mechanical vibration (Xu and Zhu, 2006). Based on this, Sooraj and Radhakrishan (2012) made an attempt to develop a *vibration assisted fluidized finishing setup,* in which the fluidized bed was provided with an acoustic vibration unit. The role of vibration was to enhance the fluidization and to avoid the chance of cohesion and agglomeration. The development of the setup, positioning of the vibratory units without affecting fluidization process and achieving good finish were tough propositions though the results obtained were reasonably good. In approaches like MR and magnetic abrasive jet finishing, the relative movement of 3D work surface and the arrangement of magnetic poles are major aspects of concern (Singh, 2012b).

It was also noted that feasibility studies on many of the existing finishing techniques are published dedicatedly for a specific class of surface geometries, in many cases only for flat surfaces, cylindrical shapes or internal profiles (Komanduri et al., 1997; Jain, 2013). In this regard, development of a new methodology that can be applied to various surface geometries using a single abrasive media, without the complexities of preparing dedicated abrasive media in each case, applicable to both internal and external surfaces, is of great practical interest. Another important point is that the abrasive media used in abrasion based processes such as AFF or MAF are not at all suitable for erosion based approaches such as fluidized abrasive finishing. Preparation of separate abrasive media or the usage of abrasives in diverse forms, for different kinds of processes described above is technically demanding from its general-purpose implementation point of view. In this regard, a unique mode of applying abrasives that allow them to use in the same form, for both erosion as well as a variety of abrasion techniques will be of great research and industrial relevance.

Based on all the above points, it can be summarised that an approach that can be used for multi-mode applications, capable of finishing a variety of normal and intricate surface forms is an interesting research problem still to be addressed. Some of the existing methodologies may be improvised through hybrid approaches and special attachments to meet some of the special requirements. But here again, the economical incompetency and practical adaptability are matters of concern. Considering these challenges, significant technical issues to be addressed further in micro/nano finishing can be summarized as follows;

- Development of a multiple application oriented flexible approach, which can be customized according to the processing requirements.
- Development of a simple and convenient finishing media which is cost effective and environmental friendly and reusable.
- A workable concept capable of fine finishing internal, external, flat, cylindrical, curved, grooved and any other complex profiled surfaces of micro/meso components, without altering the surface form and without damaging sub-surface.
- Exploring the possibilities of using erosion based approaches that facilitate easy accessibility of intricate surfaces.
- Introducing an effective methodology to apply very fine abrasives (Geldart group C particles) in fluidized abrasive finishing methodology.
- Developing a promising mode of fine abrasive application that can be used in erosion as well as abrasion based systems, depending on the user requirements.

The methodology highlighted in this thesis is the usage of fine abrasives embedded with an elastomeric medium in the form of meso/micro scale balls, *referred to as elastic abrasives*, with all the special features summarised above. Specific scope of study includes the development of elastic abrasives, and investigations into its multi-mode application capabilities. Major research objectives covered in the thesis are;

- Design, development and characterization of proposed elastic abrasives.
- Theoretical and experimental investigations on the applications of elastic abrasives for fine finishing of internal as well as external surfaces, including complex profiled internal surfaces like internal circumferential groove, based on both abrasion and erosion approaches.
- Studies on the applications of elastic abrasives for fine finishing of surfaces, with the aid of magnetic field.

1.4 Thesis Outline

The thesis has been organized as follows;

The importance of micro/nano finished surfaces and the significance of abrasive based fine finishing methodologies are introduced in ***Chapter 1***, with a special emphasis on the relevance of present research work. A detailed literature review of the existing finishing techniques and mode of applying abrasives in these state-of-the-art techniques are discussed in detail. Following this, the major challenges faced in many of these prior techniques and motivation for a 'new thinking' is described. The major research objectives, its scope and applications are listed in brief.

The proposition, working principle, composition and the relative advantages elastic abrasives are exclusively described in ***Chapter 2.*** The selection of ingredients and the preparation of elastic abrasives are documented, with a detailed discussion on its special and flexible features, which can be modified easily according to the application requirements. Design and development of a mechanical setup for the preparation of elastic abrasive spheres is illustrated. A detailed characterization of elastic abrasives is also reported in this chapter.

Chapter 3, 4, 5 and 6 are focused on the application of these elastic abrasives. These chapters are organized in such a way that the multi-mode application capabilities of proposed elastic abrasives are well illustrated with a detailed analysis on the mechanism of material removal.

Chapter 3 includes the details of experimental and theoretical investigations on the application of elastic abrasives for fine finishing of internal surfaces. A simple experimental setup designed for finishing internal surfaces such as tubes, sleeves, etc. are introduced with a description of its working methodology. A mathematical model is presented in this chapter to predict the quantity of material removal during the finishing cycle, supplemented with a systematic experimental investigation on the effect of process variables using response surface methodology.

Chapter 4 addresses the application of the same elastic abrasives for fine finishing of internal circumferential groove, which is identified as a relatively complex task. Here again, the experimental setup, methodology and mechanism of material removal are explained, highlighting the advantages of elastomeric medium. A detailed experimental study to assess the influence of major process variables is also documented

In addition to the abrasion based methodologies above, the feasibility of using the same elastic abrasives both for erosion based fine finishing method is discussed in ***Chapter 5***. A unique idea of low velocity impingement erosion through a *carrier type fluidization approach using elastic abrasives* is explained in this chapter. A simplified mathematical model is presented to explain the effect of elastomeric medium and the quantity of material removal. Experimental investigation using response surface methodology is also included in this chapter to assess the influence of major process variables

Another interesting mode of using elastic abrasives for magnetic field assisted fine finishing documented in ***Chapter 6***. A magnetic abrasive finishing system using elastic abrasives (*referred to as elasto-magnetic abrasive finishing*) and the associated experimental results are shown in this chapter.

Chapter 7 summarizes the most important conclusions from all the chapters. Scope and technical perspective of the future work are provided toward the end with a brief description of already initiated works.

CHAPTER 7

CONCLUSIONS AND SCOPE OF FUTURE WORK

The work reported in this thesis aims at developing a simple, easy to handle and cost effective approach for fine finishing of engineering surfaces using elastically bonded abrasives in the form of small spherical balls. It covers various applications of this concept to suit different geometries of surfaces including free from surfaces, different work materials and different material removal mechanisms.

The thesis presents in detail the working concept of elastic abrasives and their advantage in controlling the material removal, leading to ultra fine finishing of surfaces. Detailed theoretical studies on the action of elastic abrasives in achieving fine finish are presented in this work together with preliminary experimental results supporting these studies. They cover both abrasion and erosion mechanisms involved in fine finishing using elastic abrasives.

The formulation and preparation of elastic abrasives in good quantities has been achieved using simple laboratory set-ups. A slightly modified procedure is developed to make the elastic abrasive, magnetic, leading to the development of elasto-magnetic abrasives. Characterization of elastic abrasives including its wear under various loading conditions has been done. These results could be of benefit in selecting the right elastomeric medium for specific applications other than the one used in these investigations.

Major conclusions based on theoretical studies and detailed experimental investigations on the application of elastic as well as magneto elastic abrasives in practical situations are given below.

7.1 Development of a New Abrasive Medium, Referred as '*Elastic Abrasives*'

The proposition of elastic abrasives and the methods adopted for its preparation are the primary contributions of this research work. Through the direct chemical procedure reported, it is very simple and convenient to produce sufficient quantity of magnetic as well as non-magnetic elastic abrasives. The general behaviour of elastic abrasives and possible extent of wear under various loading conditions are well demonstrated in the characterization studies reported in this thesis. The results can be utilized further to select an alternative elastomeric medium, or to re-configure the elastic abrasives, or to envisage the anticipated wear rate under different finishing conditions.

7.2 New Approaches of Fine Finishing Using Elastic Abrasives

Elastic abrasives were applied in various modes to achieve micro/nano scale surface finish on various forms of surfaces, and in various categories of materials. It covered a wide spectrum, including flat surfaces, tubular internal surfaces, oval shaped internal surfaces, internal circumferential grooves, etc. The work materials were also chosen from both magnetic as well as non magnetic group, typically include stainless steel (SS 304), hardened steel (440C-58 HRC), tungsten carbide, mild steel, etc.

Through the experimental studies reported, it is clearly illustrated that the proposed elastic abrasives can be utilized for both abrasion as well as erosion based finishing methods. 'Elastic abrasive-internal finishing' and 'fluidized elastic abrasive finishing' are the representative examples in abrasion and erosion category, respectively. **Fluidized-elastic abrasive finishing** is a unique approach introduced through this research work, which is a carrier type fluidization methodology adopted for using very fine abrasive grains that can yield nano scale surface finish. Although a preliminary study on fluidized abrasive polishing is reported in literature, about 16 years ago by Jaganathan and Radhakrishnan (1997), it was not getting a wide acceptance because of the difficulty in fluidizing fine grade abrasives. Fluidized elastic abrasive finishing, using the principles of low velocity impingement erosion, is proved as a viable solution to this technical issue. It also facilitates the finishing of free form/difficult-to access surfaces by the free impingement of elastic abrasives.

Development of '*elasto-magnetic abrasive ball*' is another milestone achieved in this research work. Its capability is well demonstrated for a magnetic abrasive finishing system, in which the flexible abrasive bush formed by these balls is conveniently used for fine finishing of surfaces. It significantly reduced the complexities of handling very fine abrasive powders in its loose form, or the necessity of sintering abrasives to the magnetic media as practiced in some of the existing magnetic finishing approaches.

Elastomeric action is the key advantage of elastic abrasives compared to standard abrasive grit of same size. The elastomeric polymer is not only acting as a soft flexible medium, but also reduces the equivalent elastic modulus at the contact interface. During impact of elastic abrasive balls, the resilient medium allows the balls to absorb energy and release it during rebounding. Because of this, the coefficient of restitution increases and the net energy transferred to the work surface reduces. In effect, the depth of penetration and volume of material removed get reduced during abrasion and erosion, in comparison with the action of conventional abrasive grits. Due to the deformation of elastomeric beads, simultaneous involvement of a number of active grains in the contact zone for penetration/micro cutting is another important feature of elastic abrasive action.

An additional characteristic of finishing methodologies discussed in this thesis is that the fine finish is achieved without the usage of any slurry/liquid medium. So the environmental/health issues associated with the flood of liquid medium are not at all present in the new proposal. It has been proved during the characterization that the presence of conventional coolant/liquid/oil medium will not produce any chemical/property changes in the elastic abrasives. So if necessary, it also allows the usage of minimum quantity coolants during the operations, for example during the squeezing of elastic abrasive balls in the proposed internal finishing setup.

Even though the abrasive grains are in bonded form, the elastic abrasive balls of size 3mm presented in this work can act like loose abrasive particles with the freedom to move within the bulk. This is really useful in many situations, for example making it convenient to fill inside tubular work specimens, or making it convenient to fluidize, or to form magnetic-abrasive brush. So it neither falls in loose abrasive methodology nor in rigid bonded abrasive technique. The balls can freely flow/rotate within the work specimen, and deform in conformity to work surface during its loading. Due to this, the fine finishing of surfaces in all the methods discussed is achieved without altering the basic form of the surface. This is a significant advantage of the proposed approach. Another positive aspect of elastic abrasives is the ease in handling and cleaning.

7.3 Design and Development of Experimental Setups

In this work, the concept and design of the following experimental setups are brought out and the hardware were realized.

- ✓ Mechanical setup for the development of elastic abrasive spheres
- ✓ Elastic abrasive-Internal finishing setup with an additional option of workpiece rotation
- ✓ Attachments for the above internal finishing system, facilitating the finishing of oval bores
- ✓ A simple setup to finish internal circumferential grooves, using a general purpose lathe

- ✓ Fluidized-elastic abrasive finishing system with an option of a vibrating platform
- ✓ Magneto-elastic abrasive system that can be attached to a CNC milling machine

The above setups are basically application-oriented, developed for defined purposes. These designs are easily reconfigurable according to the variations in the shape and size of work specimens. Often only minor modifications are required in workpiece clamping and guiding attachments. Even though a commercial comparison is not performed as a part of this research work, it is clear from the basic configurations that the costs associated with all these setups are relatively low.

7.4 Experimental and Theoretical Contributions

The major experimental studies reported as a part of this thesis are;

- ✓ Experimental investigations on elastic-abrasive internal finishing, with and without workpiece rotation, on hardened steel (440C-58HRC) and stainless steel (SS 304) specimens using response surface methodology.
- ✓ Internal surface finishing of oval bores and tungsten carbide bushes.
- ✓ Feasibility study on the nano finishing of internal circumferential grooves on stainless steel specimens using elastic abrasives.
- ✓ Fluidized elastic abrasive finishing of hardened steel (440C-58HRC) and stainless steel (SS 304) specimens using response surface methodology.
- ✓ Elasto-magnetic abrasive finishing of ferrous and non ferrous materials such as mild steel, stainless steel and bearing steel (440C)

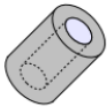
All the significant process variables that may influence the surface finish are addressed in the experimental studies, and the effect of individual parameters and their interactions are reported thoroughly for further references. To theoretically substantiate these findings and to understand the mechanism of material removal, mathematical models are also developed for internal finishing and fluidized finishing systems. Though both these models are derived based on certain assumptions and considerations, they are very useful to gain a fundamental idea on these proposed methodologies. Similar trends obtained between experimental and theoretical results indicated that the assumptions are reasonable and the physics of the processes can be interpreted from these models.

7.5 Multi-Purpose Utility and the Order of Finish Achieved

It should be noted that the same elastic abrasive balls can be used for both erosion as well as abrasion based finishing approaches, for finishing a wide range of surfaces as indicated in Table 7.1. The scope of using elastic abrasives for multiple applications is a significant advantage, as many of the existing procedures demand for radical changes in the abrasive media for different applications.

The finish achieved in terms of average roughness (**Ra**) is of the order of 13.6 to 39 nm in various cases, from an initial value of 0.18 to 0.5 µm and measured at a cut-off value 0.25. The parameters like **Rt**, **Rp** and **Rpk** were also showing significant improvement. It can be enhanced further by the usage of sub micron sized abrasive grains, and improved hardware and control systems. But according to the interactions with some of the industries during the International Machine Tool Exhibition (IMTEX), the order of finish achieved and the shape of work specimens considered for the study are of great industrial value. Hence to a great extent, the approaches and outcomes reported in this thesis are of academic and industrial relevance.

Table 7.1: Various applications of elastic abrasives covered in the present thesis

Sl. No.	Type of surface	Material	Initial Ra (µm)	Final Ra (µm)	Principle	Time
1	Internal-Tubular 	Hardened steel 440C-58 HRC	0.158	0.016 to 0.02	Abrasion	Processing time is of the order of 40 to 60 minutes
3	Internal-Oval 	Hardened steel (58 HRC)	0.2	0.02		
4	Internal- Bush 	Tungsten carbide	0.05	0.0286		
5	Internal Circumferential groove 	Stainless steel (SS 304)	0.5	0.0136		
6	Cylindrical flat (disc shaped) 	Hardened steel (440C-58 HRC)	0.18	0.027	Erosion	
7	Cylindrical flat (disc shaped) 	Mild Steel & Stainless steel	0.18	0.04	Magnetic assisted abrasion	

7.6 Future Work

As the work reported in this thesis covers the basic concepts of elastic abrasives, their mechanism of finishing, wide application possibilities and excellent finish achieved, future works should look at improving these aspects further. Some of the possibilities include the following;

- Applications of micro-elastic abrasives for the fine finishing of meso/micro components.
- Exploring wider industrial applications of elastic abrasives.
- Investigations on selective polishing of surfaces using elastic abrasive erosion.
- Design and development of a multi mode-sophisticated elastic abrasive finishing machine for fine finishing of internal/ external surfaces, grooves, shafts etc. of specific size range.
- Investigations on the application of elasto-abrasive wires for fine finishing of small diameter-high aspect ratio bores (l/d >20).
- Different strategies to optimize the preparation of elastic abrasives and elasto magnetic abrasive spheres in an industrial environment.
- Possibilities of preparing magnetic polymer beads to which the abrasives can be embedded without the use of additional magnetic powders.
- Progressive finishing (in stages) using different elastic abrasives having coarse to fine abrasive particles (100 µm to submicron sizes) in them.
- Detailed analysis on the elasto-plastic behaviour of abrasive embedded polymer ball at the contact interface.

7.6.1 Some of the initiatives

The idea of elastic abrasive ball is further expanded to make elasto-abrasive wire composed of a core wire (typically high tension Kevlar wire), coated with an elastomeric polymer medium over which fine abrasives are embedded as shown in Figure 7.1. Proposed wire can be used effectively for fine finishing of small diameter high aspect ratio bores, which are relatively difficult to finish by existing finishing techniques. Internal finishing setup (without work piece rotation) described in Chapter 3 can be used for this purpose as indicated in Figure 7.2.

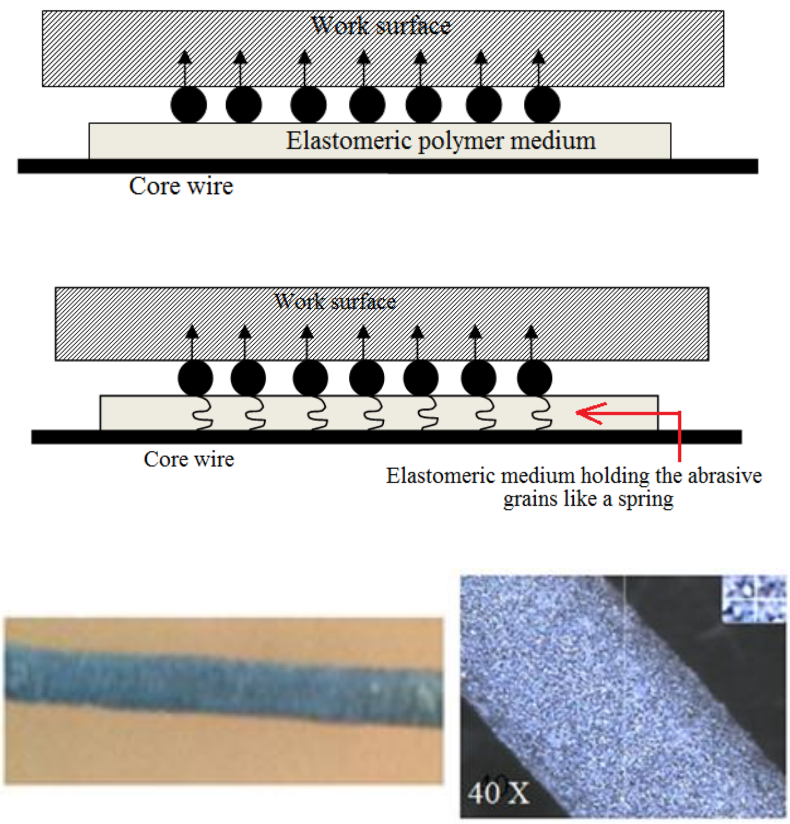


Figure 7.1: Concept of elasto-abrasive wire

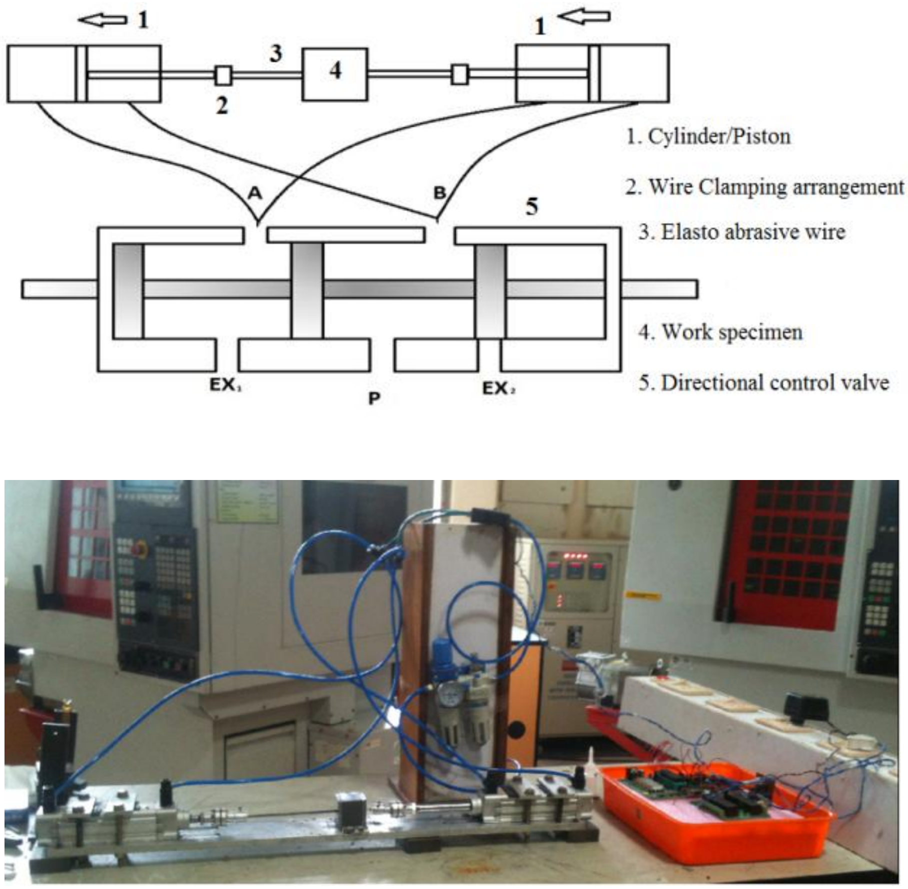


Figure 7.2: Finishing of internal surfaces using elasto-abrasive wires

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Appendix 1

Linked to Chapter 2

Development of Elastic Abrasives: Experimental Trials

Sl. No	Polymer	Organic solvent	Abrasives	Remarks
1	Aromatic thermoplastic polyurethane elastomer- Tecophilic grade	Dichloromethane	SiC / Al_2O_3	Found successful (Can be used)
2	Thermoplastic polyurethane –Tecoflex-80 A	Dichloromethane	SiC / Al_2O_3	Found successful (Can be used)
3	Thermoplastic polyurethane –Tecoflex B40 grade (with 40% Barium sulphate)	Dichloromethane	SiC / Al_2O_3	Relatively hard balls Procedure found successful (Can be used)
4	Thermoplastic polyurethane –Tecoflex-B20 grade (with 20% Barium sulphate)	Dichloromethane	SiC / Al_2O_3	Slightly hard balls Found successful (Can be used)
5	NBR rubber beads	Toluene	SiC / Al_2O_3	Partially successful. Need more experiments to optimize the procedure

Appendix 2

Linked to chapter 3

Specification of Stylus type Roughness Measuring Instrument

Machine	Form Talysurf
Make	Taylor Hobson
Traverse length	0.1 mm to 50 mm
Traverse/Measuring Speeds	10 mm/s (max)- 1 mm/s
Stylus arm length, tip size, force	60 mm arm, 2 µm radius diamond stylus, 1 mN force
Cut-off used	0.25

Appendix 3A

Linked to chapter 3

Internal finishing experiments

Two level two factorial experiments: Observed values of average roughness (**Ra**)

Grain size d_g **(µm)**	**Axial pressure Pa (x 10^5 Pa)**	**Longitudinal Velocity** V_c **(m/min)**	**Average roughness (Ra-µm)**	
			Replication 1	**Replication 2**
10	1	4	0.058	0.056
250	1	4	0.063	0.063
10	5	4	0.047	0.047
250	5	4	0.057	0.055
10	1	12	0.03	0.03
250	1	12	0.044	0.046
10	5	12	0.028	0.029
250	5	12	0.052	0.052

Appendix 3B

Linked to chapter 3

Internal finishing experiments

Two level two factorial experiments: Observed values of average roughness (**Rt**)

Grain size d_g **(µm)**	**Axial pressure** P_a **(x 10^5 Pa)**	**Longitudinal Velocity** V_c **(m/min)**	**Peak to Valley Roughness (Rt-µm)**	
			Replication 1	**Replication 2**
10	1	4	0.720	0.698
250	1	4	0.892	0.882
10	5	4	0.735	0.724
250	5	4	0.973	0.976
10	1	12	0.613	0.625
250	1	12	0.542	0.540
10	5	12	0.555	0.551
250	5	12	0.560	0.552

Appendix 4A

Linked to chapter 3

Internal finishing experiments: Centre levels used

Average roughness at centre level

Grain size d_g **(µm)**	**Axial pressure** P_a **(x 10^5 Pa)**	**Longitudinal Velocity** V_c **(m/min)**	**Average roughness (Ra-µm)**	
			Replication 1	**Replication 2**
130	3	8	0.032	0.033

Peak to valley roughness at centre level

Grain size d_g **(µm)**	**Axial pressure** P_a **(x 10^5 Pa)**	**Longitudinal Velocity** V_c **(m/min)**	**Peak to Valley Roughness (Rt-µm)**	
			Replication 1	**Replication 2**
130	3	8	0.50	0.53

Appendix 4B

Linked to chapter 3

Internal finishing experiments -Two level two factorial experiment **ANOVA TABLE (Curvature testing)**

Source	Sum of Squares	Mean Square	F Value	p-value Prob > F	
d_g	*7.16E-04*	*7.16E-04*	*503.25*	*< 0.0001*	
P_a	*3.31E-05*	*3.31E-05*	*23.25*	*0.0004*	
V_c	*1.14E-03*	*1.14E-03*	*801.1*	*< 0.0001*	
$d_g. P_a$	*3.31E-05*	*3.31E-05*	*23.25*	*0.0004*	
$d_g. V_c$	*1.38E-04*	*1.38E-04*	*97.1*	*< 0.0001*	
$P_a .V_c$	*1.27E-04*	*1.27E-04*	*89.01*	*< 0.0001*	
Curvature	6.11E-04	6.11E-04	429.37	< 0.0001	**Significant ****
Lack of Fit	*7.56E-06*	*7.56E-06*	*8.76*	*0.013*	***Significant *****

***** Because of this significant curvature effect, it was decided to proceed with FCC analysis***

Appendix 5

Linked to chapter 3

Internal finishing experiments –**FCC design-** Statistical results

Analysis of Variance					
Source	***Sum of Squares***	***Mean Square***	***F Value***	***p-value Prob > F***	
Model	2.02E-03	2.25E-04	25.85	< 0.0001	Significant
Lack of Fit	*3.35E-05*	*6.70E-06*	*0.56*	*0.7349*	Not significant

Signal to noise ratio		
S/N ratio	*1.63E+01*	Adequate signal

Sequential Model Sum of Squares					
Source	***Sum of Squares***	***Mean Square***	***F Value***	***p-value Prob > F***	
Linear	1.32E-03	4.39E-04	7.94	0.0025	
Quadratic	5.62E-04	1.87E-04	21.57	0.0003	Suggested

Appendix 5 (cont..)

Linked to chapter 3

Internal finishing experiments –FCC design- **Statistical results (Cont..)**

Lack of Fit Tests

Source	*Sum of Squares*	*Mean Square*	*F Value*	*p-value Prob > F*	
Linear	7.38E-04	6.71E-05	5.59	0.0915	
Quadratic	3.35E-05	6.70E-06	0.56	0.7349	Suggested

Model Summary Statistics

Source	*Std. Dev.*	*R-Squared*	*Adjusted R-Squared*	*Predicted R-Squared*	
Linear	7.44E-03	0.6298	0.5504	0.2837	
Quadratic	2.95E-03	0.9668	0.9294	0.8021	Suggested

Appendix 6

Linked to chapter 4

Finishing of internal circumferential groove

Observed values of **Ra** and **Rt** at various levels of processing time

Processing time	**Ra (µm)** (Mean value of two replications)	**Rt (µm)** (Mean value of two replications)
0	0.5616	4.9681
10	0.1105	1.1276
20	0.0870	0.7684
30	0.0599	0.7299
40	0.0272	0.1722
50	0.0198	0.1318
60	0.0136	0.1055

@ Processing Condition;

Workpiece Rotational Speed: 300 rpm

Grain size of embedded abrasives: 10 µm

Appendix 7

Linked to chapter 5

Specification of non-contact 3D profiler

Machine	Talysurf CCI Lite- Non contact 3D profiler
Make	Taylor Hobson
Measurement Technique	Coherence Correlation Interferometry
Maximum measurement area	6.6 mm (> 75 mm with X, Y stitching)
Vertical Resolution	0.01 nm

Appendix 8

Linked to chapter 5

Fluidized elastic abrasive finishing experiments

Two level two factorial experiments with four centre point runs

Sl. No.	Ratio of fluidized bed height to static bed height F	Rotational speed of workpiece *N* (rpm)	Average roughness Ra (μm)	
			Replication 1	Replication 2
1	1.67	100	0.087	0.086
2	2.67	100	0.077	0.075
3	1.67	600	0.055	0.055
4	2.67	600	0.0755	0.076
5	2.17	350	0.032	0.0325
6	2.17	350	0.034	0.034
7	2.17	350	0.032	0.034
8	2.17	350	0.031	0.032

Note: *Since the curvature effect is found significant, it is decided to proceed with FCC analysis*

Appendix 9

Linked to chapter 5

Fluidized elastic abrasive finishing experiments - **Material: Hardened steel**

FCC design- **Statistical results**

Analysis of Variance

Source	***Sum of Squares***	***Mean Square***	***F Value***	***p-value Prob > F***	
Model	4.585E-3	9.171E-4	649.72	< 0.0001	Significant
Lack of Fit	3.469E-6	1.156E-6	*0.69*	*0.6145*	Not significant

Signal to noise ratio

S/N ratio	64.379	Adequate signal

Sequential Model Sum of Squares

Source	***Sum of Squares***	***Mean Square***	***F Value***	***p-value Prob > F***	
Linear	3.954E-4	1.977E-4	0.42	0.6669	
Quadratic	942 E-3	1.97 E-3	1396.35	<0.0001	Suggested

Appendix 9 (Cont..)

Linked chapter 5

Fluidized elastic abrasive finishing experiments – **Material: Hardened steel**

FCC design- **Statistical results (Cont.)**

Lack of Fit Tests

Source	*Sum of Squares*	*Mean Square*	*F Value*	*p-value Prob > F*	
Linear	4.19 E-3	6.99 E-4	419.33	0.0002	
Quadratic	3.47 E-6	1.16 E-06	0.69	0.6145	Suggested

Model Summary Statistics

Source	*Std. Dev.*	*R-Squared*	*Adjusted R-Squared*	*Predicted R-Squared*	
Quadratic	1.19 E-3	0.9982	0.9966	0.9918	Suggested

Appendix 10

Linked chapter 5

Fluidized elastic abrasive finishing experiments - **Material: Stainless steel**

FCC design- **Statistical results**

Analysis of Variance					
Source	***Sum of Squares***	***Mean Square***	***F Value***	***p-value Prob > F***	
Model	3.68 E-3	7.36 E-4	70.04	< 0.0001	Significant
Lack of Fit	4.23E-5	1.41 E-5	*2.04*	*0.2865*	Not significant

Signal to noise ratio		
S/N ratio	20.172	Adequate signal

Sequential Model Sum of Squares					
Source	***Sum of Squares***	***Mean Square***	***F Value***	***p-value Prob > F***	
Linear	3.75 E-4	1.87 E-4	0.5	0.6221	
Quadratic	2.80 E-3	1.4 E-3	133.19	<0.0001	Suggested

Appendix 10 (Cont..)

Lined to chapter 5

Fluidized elastic abrasive finishing experiments – **Material: Stainless steel**

FCC design- **Statistical results (Cont.)**

Lack of Fit Tests					
Source	***Sum of Squares***	***Mean Square***	***F Value***	***p-value Prob > F***	
Quadratic	4.23 E-5	1.41 E-5	2.04	0.2865	Suggested

Model Summary Statistics					
Source	***Std. Dev.***	***R-Squared***	***Adjusted R-Squared***	***Predicted R-Squared***	
Quadratic	3.24 E-3	0.9832	0.9691	0.9011	Suggested

Appendix 11

Linked to chapter 6

Elasto-magnetic abrasive finishing experiments – **Material: Mild steel**

Two level Two factorial experiments **-Statistical results**

Analysis of Variance					
Source	***Sum of Squares***	***Mean Square***	***F Value***	***p-value Prob > F***	
Model	4.32 E-4	2.16 E-4	6527.5	< 0.0001	Significant
Lack of Fit	2.25E-8	2.25 E-8	*0.61*	*0.4906*	Not significant
Curvature	1.25 E-9	1.25 E-9	*0.038*	*0.8554*	Not significant

Signal to noise ratio		
S/N ratio	282.559	Adequate signal

Model Summary Statistics					
Source	***Std. Dev.***	***R-Squared***	***Adjusted R-Squared***	***Predicted R-Squared***	
Linear	1.6 E-4	0.9997	0.9996	0.9993	Recommended

LIST OF PUBLICATIONS/PATENTS BASED ON THIS WORK

➢ PATENT FILED

"*Multipurpose resilient elasto-magnetic-abrasive spheres for fine finishing of surfaces*", applied for Indian patent, filed on 26th July 2013.

➢ INTERNATIONAL JOURNALS

PUBLISHED/ACCEPTED

1. V.S. Sooraj, V. Radhakrishnan, Fine finishing of internal surfaces using elastic abrasives -International Journal of Machine Tools and Manufacture (Elsevier)-Accepted for publication-Jan 2014. http://dx.doi.org/10.1016/j.ijmachtools.2014.01.001

2. V.S. Sooraj, V. Radhakrishnan, Elastic impact of abrasives for controlled erosion in fine finishing of surfaces- Manufacturing Science and Engineering (ASME) : 135(5), 051019 (2013) - DOI :10.1115/1.4025338

3. V.S. Sooraj, V. Radhakrishnan, Feasibility study on fine finishing of internal grooves using elastic abrasives- Materials and Manufacturing Processes (Taylor and Francis): 28: 1110–1116, 2013 DOI: 10.1080/10426914.2013.792418

4. V.S. Sooraj, V. Radhakrishnan, Prospective methodologies to use impact wear for micro/nano finishing of surfaces- International Journal of Manufacturing Technology and Management (Inderscience)- Accepted for publication- Jan 2014.

UNDER REVIEW

1. V.S. Sooraj, V. Radhakrishnan, A study on fine finishing of hard workpiece surfaces using fluidized elastic abrasives, Submitted to International Journal of Advanced Manufacturing Technology (Springer)

➢ Conference Publications/Presentations

1. Sooraj V. S., Radhakrishnan, V. (2012). Impact wear as a surface finishing technique: approaches and assessments", In *4^{th} International and 25^{th} All India Manufacturing Technology Design and Research (AIMTDR) Conference*, India, December 14-16, 2012, pp.815-821.

2. Sooraj V. S., Radhakrishnan, V. (2012). On the Concept of Finishing Internal Grooves using Elastic Abrasives, In *National conference on Micro/nano fabrication (M^nF)*, CMTI Bangalore, January 21-23, 2013, pp. 305-309.

3. Sooraj V. S., Radhakrishnan, V. (2013). Surface finishing using elastomeric magnetic abrasive balls, In *International Conference on Precision Meso Micro Nano Engineering (COPEN)*, India, December 2013.

4. Sooraj V. S., Alisha, S., Manohar, P., Radhakrishnan, V. (2013). Finishing of small diameter high aspect ratio holes using elastic abrasive wires- In *International Conference on Precision Meso Micro Nano Engineering (COPEN)*, India, December 2013.

➢ Symposium

1. Sooraj V. S., Radhakrishnan, V. (2013). Application of elastic abrasives for micro/nano finishing, Academic pavilion of IMTEX 2013, India, January 24-30, 2013.

2. Sooraj V. S., Radhakrishnan, V. (2013). Multi-Application studies of elastomeric abrasive balls in fine finishing, In *Research scholar's day*, IIST, December 16-17, 2013.

3. Sooraj V. S., Radhakrishnan, V. (2012). Application of elastic abrasives for micro-nano finishing of surfaces, In *Research scholar's day*, IIST, December 17-19, 2012.

4. Sooraj V. S., Radhakrishnan, V. (2011). Investigations on vibration assisted fluidized finishing of surfaces, In *Research scholars day*, IIST, December 16-17, 2011.

➢ Awards and Achievements

I. First prize for the innovative research work, presented in the academic pavilion of International Machine Tool exhibition-IMTEX 2013

II. Best paper award for the following papers

1. V.S. Sooraj and Prof. V. Radhakrishnan, "*Impact wear as a surface finishing technique: approaches and assessments"*, Presented and published in the proceedings of AIMTDR 2012.
2. V.S. Sooraj and Prof. V. Radhakrishnan, "Application of elastic abrasives for micro nano finishing of surfaces", Presented and published in the proceedings of Research scholars day, 2012 : IIST

3. V.S. Sooraj and Prof. V. Radhakrishnan, "Multi-Application Studies of Elastomeric Abrasive Balls in Fine Finishing", Presented and published in the proceedings of Research scholars day, 2013 : IIST