POLISHING OF 3/4 INCH SILICON NITRIDE BALLS USING THE LARGE BATCH MAGNETIC FLOAT POLISHING APPARATUS

By

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SUMMARY

The large batch magnetic float polishing (MFP) apparatus has been used to finish two batches of 3/4" diameter Si_3N_4 balls - 46 balls in each batch. Nine runs of the first batch were used to determine the highest material removal rate (MRR) with the application of Taguchi's method of statistical analysis. A 4 by 9 matrix, known as a $L_9(3^4)$ orthogonal array, was developed where the parameters - load, speed, and abrasive concentration, were varied to obtain the combination providing the highest MRR. The results were applied to the remaining runs when high MRR was desired.

The parameters involved include abrasive (type, size, and concentration), load, speed, and duration. The abrasives used include B_4C, SiC, and CeO_2, with grit sizes ranging from 500 to 10000, and concentrations ranging from 5 to 20% by volume. The loads used were 0.5, 0.75, 1.0, and 1.5 N/ball. The ball circle diameter of the apparatus was 11.625 in. Speed variations were 350, 400, and 550 rpm, where 400 rpm was found to be optimum and was kept constant for the most part. The durations of polishing varied from 20 to 180 minutes.

Different combinations of abrasives, concentration, load, speed, and duration were used to perform different tasks throughout the polishing stages. During initial stages, high MRRs are desired and therefore aggressive conditions,

such as B_4C, 500 grit, at 20% abrasive concentration, with 1.5 N/ball loading, were used. This provided the high MRR but improvements in sphericity (roundness) and surface finish obtainable were limited. At intermediate stages, less aggressive conditions were used and concentration shifted to roundness and surface finish. Here, parameters such as SiC, 600 to 1200 grit, at abrasive concentrations of 5 to 10%, and loads of 0.75 to 1.0 N/ball were adequate. For the final stage, where surface finish is the primary concern (since the required size and sphericity had already been reached), abrasives such a SiC, 10000 grit, and CeO_2, 5 µm size particles, were found to be most successful. Low loads of 0.5 N/ball and low abrasive concentration of 5% were used in the final run.

Best results obtained were 0.62 µm roundness (average of the batch), with a standard deviation of 0.15 µm. The best single ball measured had a roundness of 0.35 µm. For surface finish, the best Ra obtained was 11 nm for the batch.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Advanced ceramics, such as silicon nitride (Si_3N_4) have become the material of choice for demanding bearing applications where high speeds, high temperatures, and corrosive environments are involved. This is due to their superior properties including high hardness, high modulus (stiffness), low thermal expansion, high compressive strength, and high chemical stability compared to conventional bearing steel material. Typical uses include high-speed precision spindles, aircraft turbines, and other applications where performance and reliability are paramount. Advanced ceramics are incorporated into bearings as a hybrid design, where the rolling elements are made of Si_3N_4, and the inner and outer races are made of conventional steel.

The manufacture of Si_3N_4 bearing balls involves powder metallurgy techniques, where ceramic powder and additives are pressed into blanks, followed by sintering and/or hot isostatically pressing (HIP'ing) the blanks close to theoretical densification (near zero porosity), and then polishing to final dimensions. Significant factors determining the performance of the bearing are the final surface quality and geometrical accuracy of the balls. Extremely smooth surfaces with near perfect sphericities (roundness) are required for optimum performance. The improvement of these through the final polishing stages is the main interest of this research.

Conventional method of polishing is the V-grooved lapping process, as shown in Figure 1.1 (Yuan *et al*, 2002). Balls are loaded between two plates (discs) where at least one of the plates has a V-shaped groove formed in it. The balls are positioned within the groove(s) and the plates are made to move relative to one another. The balls and plates make a 3- or 4-point contact and material is removed at these points. For initial machining, the plates can be

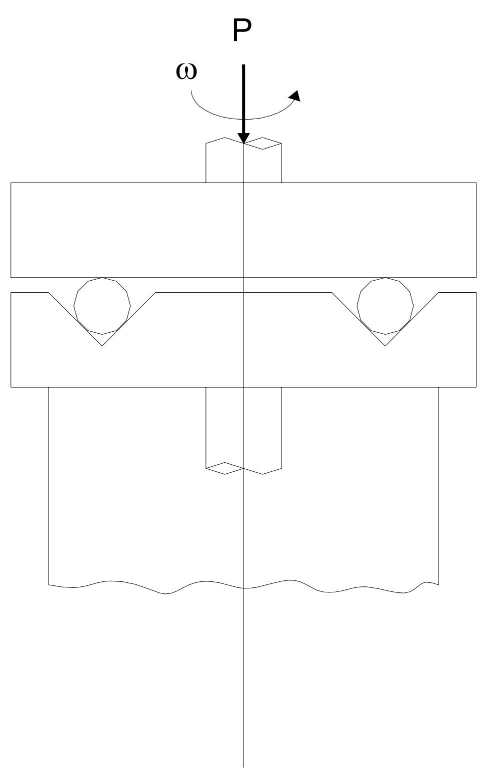


Figure 1.1 - Conventional V-grooved Lapping Apparatus for Polishing Balls

made with abrasive particles bound to them; a grinding process. For final polishing, smooth plates can be used with fine abrasives supplied through a liquid medium.

Process parameters for conventional lapping include low rotational speeds of the plates, high loading of the balls, and hard abrasives - usually diamond (the hardest known material). While this process produces high quality balls, in terms of surface finish and sphericity, there are some inherent problems associated with it. First, the amount of time required to finish a batch of balls is approximately two to three weeks; where a batch consists of several hundred balls. Second, the combination of hard diamond abrasives and relatively high loads gives rise to surface and subsurface micro-defects, which can severely degrade the life expectancy of the bearing. The low fracture toughness of ceramics (relative to steel), means that extremely small cracks, called the initiation sites, have a tendency to propagate easily throughout the material when loaded (much more so than in steel). The high loads and diamond abrasive used during V-groove lapping are the cause of these initiation sites. Therefore any surface defect is a potential source of ball failure. Likewise, since the hertzian stress for loaded spherical elements is maximum at a distance below the surface of the ball, subsurface defects are equally important. With that said, the limitations associated with conventional lapping are apparent, and it is for these reasons that new methods of polishing ceramic balls are pursued.

Many improvements and variations to the original V-groove lapping design have been made with corresponding improvements in results and performance; but due to inherent limitations of the process - high loads, hard abrasives and low speeds - there is a limit to the obtainable results. To avoid these problems, magnetic float polishing (MFP) has been developed and is a new approach to

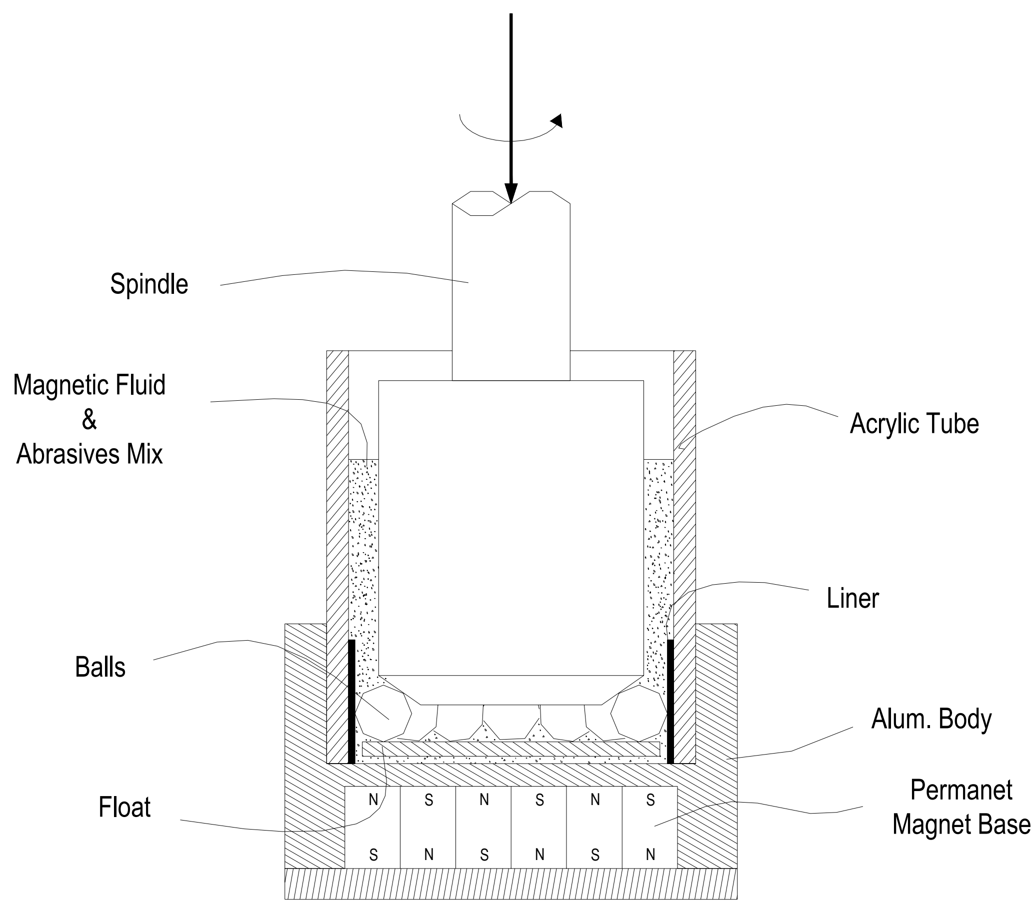


Figure 1.2 - Magnetic Float Polishing Apparatus for Polishing Balls
(Small Batch Polishing)

polishing balls. The underlying features are low loads, softer abrasives (relative to diamond), and high speeds. Figure 1.2 is a schematic of the system used for small batch polishing (Jaing and Komanduri, 1998). A bank of permanent magnets in place at the bottom base of the polishing chamber produces the required magnetic field, which levitates the float and the balls with the use of a magnetic fluid. The magnetic fluid repels all non-magnetic materials, and so the float and balls are pushed upward into contact with a spindle. The balls, placed around the perimeter of the chamber, make a 3-point contact with the spindle, chamber wall, and float. Abrasive particles mixed within the magnetic fluid form the polishing agent. As the spindle is rotated, material is removed at these contact points. The benefits of this process are that the lower loads on the balls and softer abrasives used significantly reduce the amount of surface and subsurface damage, and the higher rotational speeds increases the material removal rate (MRR) which therefore decreases the polishing time. A batch of balls can be finished in approximately 24 hours, compared to some three weeks with lapping. A comparison of the process parameters for lapping and MFP are given in the Table 1.1 (Childs *et al*, 1995; Komanduri *et al*, 1996).

	Lapping	MFP
Abrasives	Diamond	B_4C, SiC, CeO_2
Load	50 - 100 N/ball	0.5 - 1.5 N/ball
Speed	~50 rpm	~400 rpm
Number of balls*	1000 - 5000	10 - 100

*1/2” diameter balls

Table 1.1 - Comparison of V-Groove Lapping and MFP Process Parameters (Childs *et al*, 1995), (Komanduri *et al*, 1996)

The remainder of this chapter will describe the silicon nitride work material, the polishing abrasives used in this investigation, and details of the magnetic fluid. Chapter 2 gives a review of the literature on the magnetic field assisted polishing. Chapter 3 gives the problem statement and objectives of this research. Chapter 4 gives details of the MFP apparatus showing the system components as well as the variables involved. The methodology used for polishing 3/4-inch Si_3N_4 balls is given in chapter 5. Chapter 6 presents the results of two batches polished followed by a discussion of these results with regards to sphericity, surface finish, material removal rate, diameter, and set-up considerations. Chapter 7 gives the concluding remarks.

1.2 SILICON NITRIDE WORK MATERIAL

Silicon nitride, boron carbide, aluminum oxide, and many other ceramics are given the name "advanced ceramics" since their unique properties - mechanical, thermal, electrical, chemical, physical, etc. - allow their use as advanced engineering materials. This sets them apart from the traditional ceramics such as those used for pottery and clay products. For extremely harsh environments, where metals and polymers will quickly degrade or even fail instantly and catastrophically, these advanced ceramics can operate safely and efficiently for extended periods of time with little or no signs of wear. The properties of some advanced ceramics along with bearing grade steel are given in Table 1.2 (Jaing, 1998). Their high-temperature capabilities, high abrasion resistance, high stiffness, chemical inertness, high compressive strength, and low density are among their most useful properties. For high-speed bearing applications, Si_3N_4 is the material of choice among the advanced ceramics because of its high fracture toughness and low density. Some mechanical and thermal properties of Si_3N_4 balls (product number NBD-200), manufactured by Saint-Gobain Industries (parent company of Norton Advanced Ceramics) are given in Table 1.3 (Hah *et al*, 1995) along with their chemical composition in table 1.4 (Hah *et al*, 1995).

	Si_3N_4	B_4C	SiC	Al_2O_3	ZrO_2	Bearing Steel
Density g/cm^3	3.24	2.52	3.06	3.78	5.9	7.85
Young's Modulus GPa	314	448	410	360	200	200
Hardness (Hv10kg) GPa	16	28	24	22	12.5	7
Flexural Strength MPa	700	300	450	240	500	2500
Fracture Toughness MNm$^{-3/2}$	7	3	4.5	4.9	8	20
Therm. Exp. Coef. 10^{-6}/ºC	3.2	5.8	4.6	8	9.8	11.6
Therm. Conductivity W/mºK	32	26	85	25	38	40
Maximum Work Temp. ºC	1100	1750	1700	1200	950	200
Corrosion Resistance	High	High	High	High	High	Moderate
Failure Mode	Spalling	Fracture	Fracture	Fracture	Spalling	Spalling

Table 1.2 - Properties of Some Advanced Ceramics and Bearing Steel
(Jaing, 1998)

The higher modulus (stiffness) and hardness of Si_3N_4 allow the balls to be polished to greater accuracies, in terms of both surface finish and sphericity. Material at the small asperities or "high spots" on the ball will be cut (or fractured and removed) during polishing rather than simply deformed, elastically and plastically, as with steel or other softer, more ductile materials. Some significant benefits of greater finishes include less vibrations of the bearing, greater fatigue life of the balls since the loading will be more constant, and less heat generated. These alone will greatly reduce the wear of the balls and result in longer bearing life. Additionally, since the Si_3N_4 balls and steel races are metallurgically incompatible, there is no chance of adhesion, or micro welding, between the two which further reduces the wear and heat generation.

As shown in Table 1.2, the working temperature of Si_3N_4 is over 1000ºC, verses 200ºC for steel. This is one of the major advantages of this material, allowing its use in high temperature aircraft turbines and ultra high-speed machine tools - to name a few. An added benefit is that less, or even no lubrication is required for cooling; allowing an even greater role for hybrid bearings, such as for vacuum and space applications. Temperatures generated during use are also significantly less for Si_3N_4 due to its high stiffness, since less elastic deformation occurs during each cycle of the ball. One drawback to this high stiffness is that higher contact pressures exist due to smaller areas of contact. This could initiate spalling of the race if its curvature is not designed properly. The lower density of Si_3N_4 is another factor that allows for higher rotational speeds since centrifugal forces are much less.

Corrosion resistance is another property that gives Si_3N_4 hybrid bearings an edge over conventional steel bearings. In moist environments, dental drills for

PROPERTY	VALUE
Flexural Strength, Mpa	800
Weibull Modulus	9.7
Tensile Strength, Mpa	400
Compressive Strength, Gpa	3
Hertz Compressive Strength, Gpa	28
Hardness, Hv (10kg), Gpa	16.6
Fracture Toughness, K_{1c}, $MNm^{-3/2}$	4.1
Density, g/cm^3	3.16
Elastic Modulus, Gpa	320
Poisson's Ratio	0.26
Thermal Expansion Coefficient at 20-1000ºC, /ºC	2.9×10^{-6}
Thermal Conductivity at 100ºC, W/mºK	29
Thermal Conductivity at 500ºC, W/mºK	21.3
Thermal Conductivity at 1000ºC, W/mºK	15.5

Table 1.3 - Mechanical and Thermal Properties of NBD-200 Si_3N_4 Balls
(Hah *et al*, 1995)

Mg	Al	Ca	Fe	C	O	Si_3N_4
0.6 - 1.0	$\le$ 0.5	$\le$ 0.04	$\le$ 0.17	$\le$ 0.88	2.3 - 3.3	94.1 - 97.1

Table 1.4 - Chemical Composition of NBD-200 Si_3N_4 Balls
(Hah *et al*, 1995)

example, there's no chance for rusting or pitting of the balls. A summary list of some of the important features, benefits, and applications of Si_3N_4 hybrid bearings is given in Table 1.5 (Jiang, 1998).

1.3 POLISHING ABRASIVES

Abrasives used in this investigation for polishing Si_3N_4 include boron carbide (B_4C), silicon carbide (SiC), and cerium oxide (CeO_2). The properties of these are given in Table 1.6 (Jiang and Komanduri, 1998), along with other candidate abrasives for MFP in Table 1.7. The selection of these is based mainly on the hardness relative to Si_3N_4. As a comparison, in turning operations on a lathe, cutting tools need to be at least 20% harder than the workmaterial.

Similarly, for polishing, the abrasive particles should be harder than the Si_3N_4 for efficient cutting (or polishing). For the abrasives used, B_4C and SiC are slightly harder than Si_3N_4 while CeO_2 is softer. The choice of using only "slightly" harder abrasives instead of diamond or others significantly harder follows the idea presented earlier, where more "gentle" conditions than those of V-groove lapping will give a better finish with less surface and subsurface damage.

For the final polishing stage, CeO_2, although softer, is found to be an excellent abrasive because of its chemo-mechanical action with Si_3N_4. CeO_2 reacts chemically with Si_3N_4 - an oxidization-reduction reaction - to form a layer of SiO_2 on the ball. This layer, which has a hardness of 6.5 on the Mohs scale, is only slightly harder than the CeO_2 particles, which are a Mohs 6. Therefore, the CeO_2 can hardly scratch the Si_3N_4, of Mohs 8.5, but the SiO_2 layer formed on the Si_3N_4 can be removed by subsequent mechanical action of the CeO_2 (Jiang, 1998). This type of abrasive finishing is termed "chemical-mechanical polishing," or "chemo-mechanical polishing," (CMP); and is useful for the final stage because of its extremely low material removal rates and the very fine surface finish achievable.

Features:	**Applications:**
60% lighter than steel balls ▪ Lower centrifugal forces ▪ Less heat build up ▪ Lower vibrations ▪ Lower ball skidding ▪ Increased fatigue life 50% higher modulus of elasticity ▪ Higher spindle rigidity ▪ Fatigue resistance Tribochemically inert ▪ Low adhesive wear ▪ Improved lubricant life ▪ Superior corrosion resistance **Benefits:** ▪ Bearing service life is two to five times longer ▪ Running speeds over 50% higher ▪ Overall accuracy and quality improves. (better work piece finish characteristics) ▪ Lower operating costs ▪ Productivity boost ▪ High temperature capability ▪ Cutting tool life increased	Machine tools ▪ Grinding ▪ Milling ▪ Boring ▪ Drilling Aircraft accessories/aerospace ▪ Generators ▪ Gyros ▪ Gearboxes ▪ APU's ▪ Turbine engines ▪ Radar ▪ Weapon systems ▪ Satellites Industrial machinery ▪ Turbomolecular pumps ▪ Diesel fuel injection pumps ▪ Textile machines ▪ Woodworking machinery ▪ Food processing equipment ▪ Drilling equipment Medical equipment ▪ Dental drills ▪ Centrifuges ▪ X-ray tubes

Table 1.5 - Some Features, Benefits, and Applications of Hybrid Ceramic Bearings (Jiang, 1998)

The polishing mechanism for the B_4C and SiC abrasives is a mechanical action. The particles, mixed with the magnetic fluid, come between the balls and the spindle. This results in either a 2-body or 3-body cutting action, as shown in

Abrasive	Density (g/cm^3)	Knoop Hardness (kg/mm^2)	Elastic Modulus (GPa)	Melting Point (ºC)
B_4C	2.52	2800	450	2450
SiC	3.2	2500	420	2400
CeO_2	7.16	625	165	2500

Table 1.6 - Properties of Abrasives Used (Jiang and Komanduri, 1998)

Abrasive	Hardness	
	Mohs	Knoop (kg/mm^2)
Diamond	10	7000
Aluminum Oxide (Al_2O_3)	9	2150
Chromium Oxide (Cr_2O_3)	8.5	1800
Silicon Nitride (Si_3N_4)	8.5	1600
Zirconium Oxide (ZrO_2)	8	1200
Silicon Oxide (SiO_2)	7	820
Iron Oxide (FeO_3)	6	-
Yttrium Oxide (Y_2O_3)	5.5	700
Copper Oxide (CuO)	3.5	225
Molybdenum Oxide (Mo_2O_3)	1.5	-

Table 1.7 - Properties of Other Candidate Abrasives for MFP
(Jiang and Komanduri, 1998)

Figure 1.3 where the top body is the spindle, the abrasive particle is the center object, and the ball is the bottom body. For 2-body abrasion the particle is embedded into the spindle and cuts by a shearing action, as in a single point cutting tool. In 3-body abrasion, the particle is not embedded, but is loosely held between the spindle and ball and removes material by micro fracture of the ball surface as the particle "rolls" between the two. The parameters chosen during polishing - load, speed, and abrasive type - determine which abrasion mechanism is dominant.

In addition to abrasive type, the size of the particles and the concentrations levels - expressed as a volume percentage of the amount of magnetic fluid used - have an important role in the quality of the results and the material removal rates. The determination of the abrasive type, size, and concentration level, along with applied load and speed, which will give optimum results in terms of material removal rates, surface finish, and sphericity, is the ultimate goal of this research.

1.4 MAGNETIC FLUID

Magnetic fluid is a colloidal suspension of sub-domain magnetic particles in a liquid carrier. These particles have an average size of about 100 angstroms and are coated with a stabilizing dispersing agent, which prevents particle agglomeration. When brought under a magnetic field, the magnetic particles in the magnetic fluid are attracted downward to the area of higher magnetic field and an upward buoyant force is exerted on all non-magnetic materials

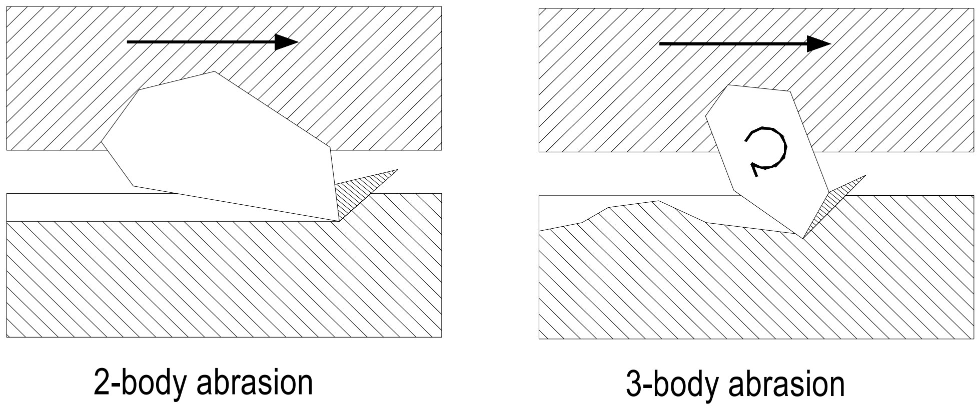


Figure 1.3 - Schematic of 2-body and 3-body Abrasion Modes

inside the fluid to push them to the area of lower magnetic filed [Jaing, 1998]. The type of magnetic fluid used for this study is Ferricolloid W-40 (also known as ferrofluid). The carrier fluid for W-40 is water, which is the reason for its use here. The water combines with the CeO_2 abrasive to produce the chemo-mechanical reaction needed for fine polishing. For magnetic float polishing, the magnetic fluid is used to levitate the float, which in turn serves as a "forgivable" base for the balls to ride on. Figure 1.4 shows a diagram of the magnetic base, with north and south poles, the magnetic fluid being repelled, and the float and balls being levitated.

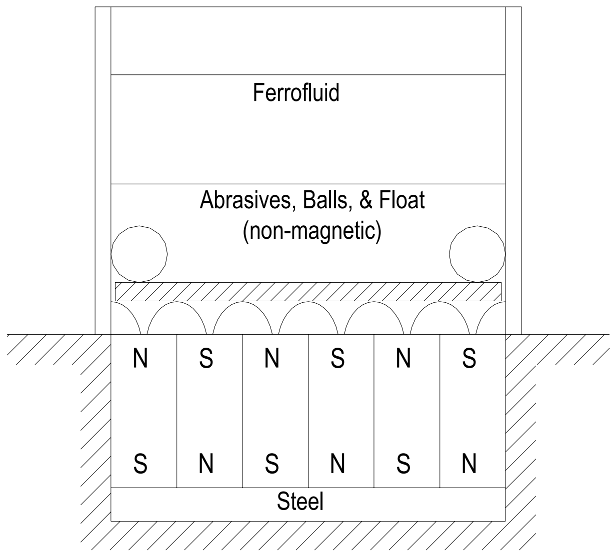


Figure 1.4 - Schematic of the float Chamber with Magnetic Field and Magnetic Fluid

CHAPTER 2

REVIEW OF THE LITERATURE

Magnetic float polishing has evolved from the field of abrasive finishing, and more specifically, magnetic field assisted polishing (MFAP). Abrasive finishing uses relatively small particles to remove stock material from a work piece. The particles can be loose or supplied through a liquid or gas media. This technology has been around for quite some time and includes such processes as abrasive jet machining, ultrasonic machining, abrasive flow finishing, abrasive water jet machining, as well as the conventional lapping process, to name a few.

The category of abrasive finishing covers several processes, as the name is general in scope. Magnetic field assisted polishing, also known more generally as magnetic abrasive finishing (MAF), is derived from abrasive finishing since the fundamental idea is using abrasive particles to remove material. The principle behind this process is the use of a magnetic field to control the position and/or force of the abrasives as they make contact with the work material. MFP is a result of the evolution of MAF technology with the goals of better results, in terms of form and material removal rates, and increased efficiency. This chapter presents the major contributors in the development of MFP.

One of the first accounts of MAF was by H. P. Coats (1940). Coats developed and patented an apparatus and method for cleaning and polishing the inside surfaces of cylinders. The main focus was to clean the weld seam of two cylinders which were welded together, since the inner surface had a scale as a result of the welding process. The cleaning was required due to the cylinders being used for food storage applications.

In this method, abrasives were placed inside the container at the welded seam. An electromagnet was placed near the outside, adjacent to the weld. As the cylinder was made to rotate, the abrasives were drawn to the magnetic field and repeatedly moved over the welded seam, cutting or polishing the surface. This method of MAF, or machining, was a precursor for developments in internal polishing techniques. Coats' apparatus is shown in Figure 2.1.

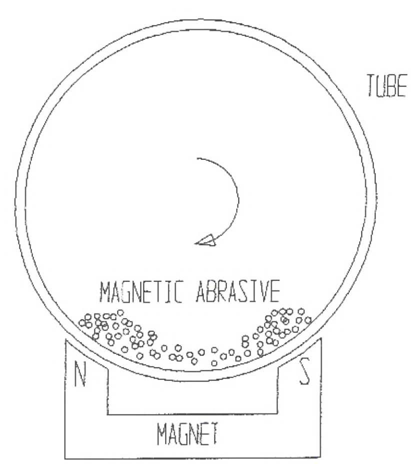


Figure 2.1 - Coats' Apparatus for Polishing Cylinders (Coats, 1940)

Imanka (1981) was an early researcher studying polishing methods using magnetic fluid. In his apparatus, shown in Figure 2.2, surfaces to be polished are placed into the chamber and lowered against a pad, which is supported by a magnetic fluid, enclosed in a membrane. The chamber is placed over an electromagnetic base and an abrasive slurry mixture is placed in the chamber. The magnetic field repels the fluid, creating the compressive force necessary for polishing. Some of the materials polished were copper, glass, and silicon.

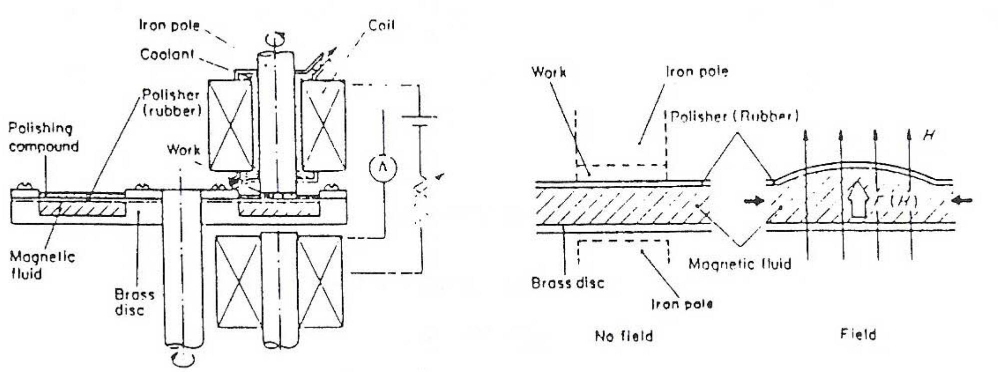


Figure 2.2 - Polishing Setup Used by Imanka (1981)

Taking this a step further, Tani and Kawata (1984) were some of the first to use the magnetic fluid as the polishing media. Here, silicon carbide abrasives mixed in the magnetic fluid were used to polish acrylic resin. The process was limited to soft work material due to the low forces that could be generated and had little effects when used on harder materials such as steels, glass, or advanced ceramics.

Kato and Umehara (1990) improved on this method by the addition of a float to the system - hence the name magnetic float polishing. The float allowed much higher polishing forces, which increased the material removal rates. With this method harder materials including sintered silicon nitride could be polished. The significance of their work can be seen below in figure 2.3 (a-d), with the effects of polishing with and without a float compared.

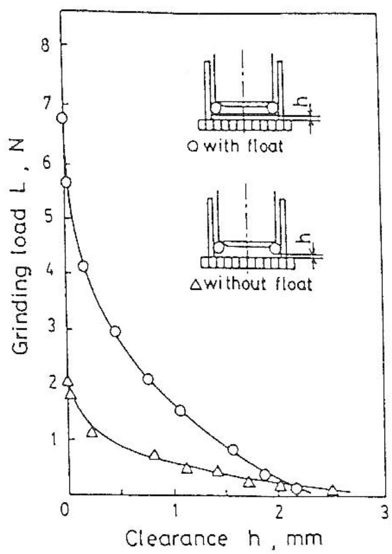


Figure 2.3 (a) - Effect of Float on Buoyancy Force (Umehara and Kato, 1990)

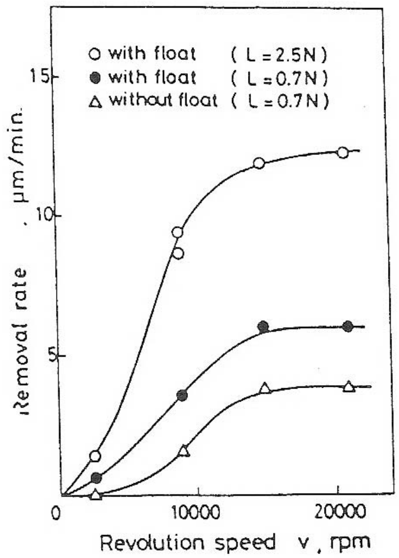


Figure 2.3 (b) - Effect of Float on MRR at Various Speeds
(Umehara and Kato, 1990)

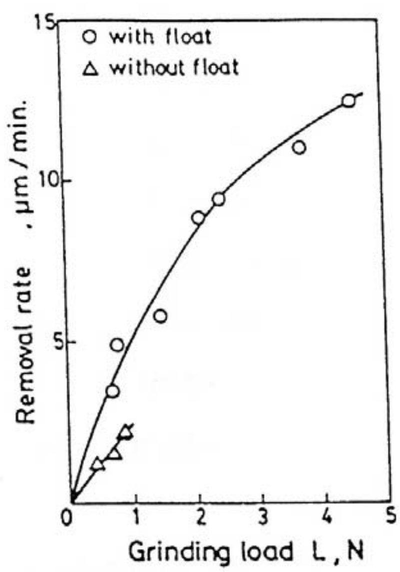


Figure 2.3 (c) - Effect of Grinding Load on MRR (Umehara and Kato, 1990)

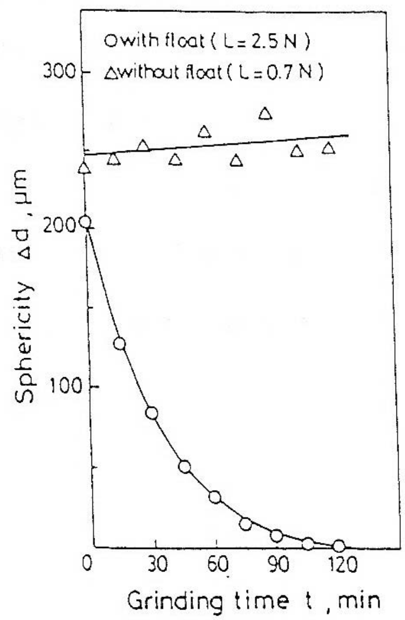


Figure 2.3 (d) - Effect of Float on Sphericity (Umehara and Kato, 1990)

One of the most obvious accomplishments with the addition of the float is the increase in MRR, making the process valid for hard, difficult to machine materials. The improvements in sphericity with the float, Figure 2.3 (d), are also very significant since quality is absolutely necessary for bearing grade balls.

Kato and Umehara also studied the effects of abrasive on MRR. Their results indicated that an increase in abrasive size and concentration give an increase in MRR, up to a critical point. Figures 2.4 and 2.5 show the effects of abrasive concentration and size on MRR, respectively.

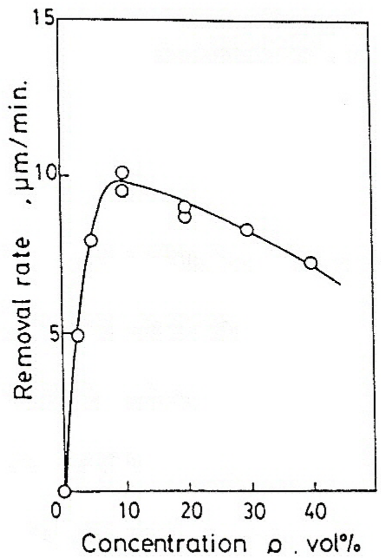


Figure 2.4 - Effect of Abrasive concentration on MRR
(Umehara and Kato, 1990)

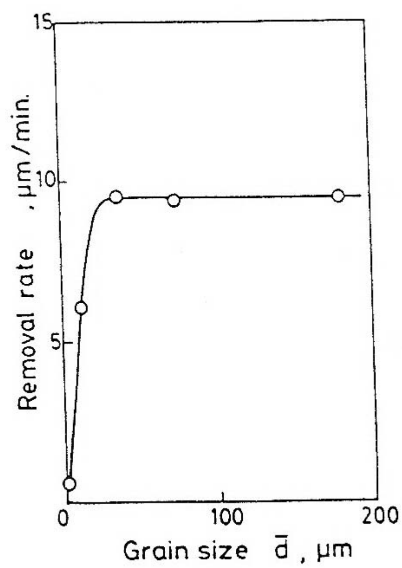


Figure 2.5 - Effect of Abrasive Particle Size on MRR
(Umehara and Kato, 1990)

While MFP can be applied to flat, cylindrical, and spherical surfaces, much of the effort is directed towards round balls for high-grade bearings and other advanced technology applications. Up to this point (early 1990s), the research has contributed to the design of the MFP system and the general methodology for polishing spherical balls. This includes the general design of the polishing spindle, chamber, materials for chamber wall and float, and ranges for spindle rotational speed, abrasive types and concentrations, and polishing durations. Most of the research from this point on includes studies on optimizing the system design, process parameters, and ball kinematics.

Childs *et al*, (1994) analyzed the motion of the ball (as it circulates around the chamber) in order to understand the polishing process more thoroughly. As mentioned briefly in chapter one, removing material from the ball involves either 2-body abrasion (scratching), or 3-body abrasion (brittle micro-fracturing). The type of cutting mechanism determines the surface quality of the ball - as 2-body abrasion gives a superior finish (Jaing, 1998). The motion of the ball is complex since, as it circulates, it both spins and slides relative to the spindle, float, and chamber wall. Childs et al derived relationships for the sliding speeds between the ball and shaft, ball and chamber wall, and ball and float, as given below. The motion vectors and forces acting on the balls are shown in Figure 2.6 (a and b).

$$V_c = R_f \Omega_b - R_b \omega_b \sin\beta$$

$$V_s = R_s \Omega_s - R_f \Omega_b - R_b \omega_b \cos(\beta-\theta)$$

$$V_f = R_f \Omega_b - R_b \omega_b \cos\beta - R_f \Omega_f$$

If there's no sliding at the three points, the relationship between ball circulation speed and float speed is:

$$\alpha = \Omega b/\Omega f = [(Rs + Rf\ (\Omega f / \Omega s) \cos\theta) / (Rf\ (1 + \cos\theta + \sin\theta))]$$

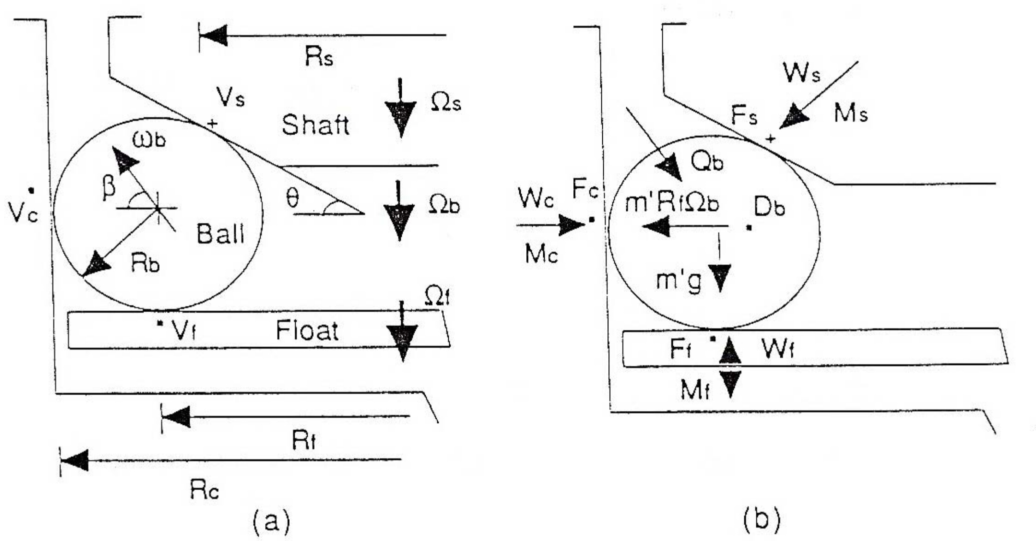


Figure 2.6 - (a) Motion Vectors of Various Elements in MFP
(b) Forces Acting on the Ball (Childs et al, 1994)

where R_c = inner radius of guide ring

R_b = radius of the ball

$R_f = R_c - R_b$ = radius at which the ball contacts the float

$R_s = R_f - R_b \sin\theta$ = radius at which ball contacts the shaft

θ = chamfer angle of the shaft

β = angle between the horizontal and the spin axis of the ball

ω_b = angular speed of the ball

Ω_b = ball circulation speed around the guide ring

Ω_f = angular speed of the float

Ω_s = shaft rotation speed

V_c = sliding speed at contact point between ball/guide ring

V_s = sliding speed at contact point between ball/shaft

V_f = sliding speed at contact point between ball/float

Recent studies in MFP have included variations in the apparatus design. Dock (1994) investigated the use of electromagnets for the magnetic field source, replacing the permanent magnets originally used. His goals were to generate higher polishing forces on the balls and therefore increase the material removal rate, and to control the amount of force more precisely, which would give better results in terms of sphericity. The results of his study were an increase in polishing force by five newtons per ball; from seven n/ball (as with permanent magnets) to twelve n/ball (with electromagnets). The sphericity also showed improvements from run to run of the polishing sequence. Starting from an initial sphericity of over 123 μm, his final result was 2.9 μm.

Perry (1997) varied the MFP technique by using an eccentric shaft. He also experimented with the use of ultrasonics, incorporated in the original MFP design. For the eccentric shaft, the spindle, which in this case is flat on the bottom side, is offset from the centerline of the balls perimeter. The expectation was higher material removal rates and better sphericity. His results indicated somewhat success in terms of MRR but with degrading sphericity.

The ultrasonic design used a transducer in the magnetic fluid to generated high frequency vibrations. The idea followed that of ultrasonic machining, where abrasives particles are placed on a workpiece and impacted at a high frequency and low amplitude, resulting in material removed from the workpiece. The idea for this method was that increased material removal rates could be seen as well as better sphericities by inducing these small vibrations. As material is removed by small micro scratches, by reducing the length of these scratches and increasing the number of them, the sphericity would improve. Though this idea seems logical, there were problems with the hardware of the apparatus and no results were reported.

Extensive studies have been carried out on the parameters used in MFP (using the small batch apparatus, Figure 1.2) with the objective of obtaining the best possible surface finish. These parameters include the abrasive (type, size, and concentration), polishing force, spindle speed, and polishing duration. The abrasive types were studied as to their significance to polishing in terms of both mechanical and chemo-mechanical actions.

Jaing (1998) studied the effects of force, abrasive concentration, and speed on the surface finish during mechanical polishing using 1500 grit, boron carbide (B_4C) abrasive (abrasive grain size of 1-2 μm). He used Taguchi's statistical analysis method to determine the optimum values for these parameters. The parameters evaluated by Jaing are shown in Table 2.1. The results indicated: 1) an increase in load resulted in a decrease in Ra (better

Level	A: Load	B: Conc.	C: Speed*
	N/ball	*Vol. %*	*rpm*
1	0.4	5	2000
2	0.8	10	4000
3	1.4	20	7000

*Based on a ~2.5" Spindle

Table 2.1 - Parameters Used and Their Levels (Jaing, 1998)

finish); 2) an increase in abrasive concentration resulted in an increase in Ra; and 3) an increase in spindle speed resulted in a decrease in Ra. Taguchi's method was also used to determine the analysis of variance (ANOVA) for Ra – showing the relative significance of each parameter. Jaing reported that polishing force was most significant for Ra (40%), followed by speed (35%) and abrasive concentration (20%); with 5% contributed to unknowns. The surface finish obtained with this abrasive ranged from 23 to 39 Ra.

Jaing explained that at lighter loads, the cutting mechanism is mainly by 3-body abrasion, resulting in deep brittle fracture indentations on the surface of the balls. At higher loads, the abrasive particles become embedded into the shaft, resulted in a 2-body type abrasion; where shallow scratches are dominant – giving a better surface finish.

In terms of spindle speed, Jaing reported that an increase in speed causes an increase in relative sliding speed between the ball and shaft. This ultimately results in a change from 3-body to 2-body abrasion, from lower to higher speeds. For abrasive concentration, where lower concentrations give better finishes, Jaing explained that at these lower concentrations, the larger of the polishing particles coming between the contact areas have more freedom to be forced away. As the concentration is increased, these larger particles are forced between the contact points and therefore are more likely to damage the ball by brittle fracture. Therefore, to obtain the best surface finish during mechanical abrasion (verses chemo-mechanical action), the results from Jaing indicate that high loads (1.4 n/ball), low abrasive concentration (5% by volume), and high speeds (7000 rpm) should be used.

For the final polishing stage, where significant improvements in surface finish is desired, chemo-mechanical polishing (CMP) has proven to be an effective method. Komanduri *et al* (1998) described the mechanisms involved in CMP along with the effectiveness of various abrasives. The principle of CMP is the chemical reaction between the abrasive, workpiece, and environment, resulting in a soft layer of SiO_2, relative to the abrasive, formed on the surface of the ball. With the abrasive being softer than the Si_3N_4 ball, but harder than the SiO_2 layer, subsequent mechanical action of the abrasive removes the SiO_2 layer but does not scratch the Si_3N_4 surface, resulting in a fine finish.

The most effective abrasives used in CMP were found to be cerium oxide (CeO_2) and zirconium oxide (ZrO_2), followed by iron oxide (Fe_2O_3) and chromium oxide (Cr_2O_3). This is due to CeO_2 and ZrO_2 being much softer than Si_3N_4, and therefore no possibility of mechanical damage and scratching. The Cr_2O_3 is slightly harder than the Si_3N_4 and so, although there is CMP taking place, there is the possibility of scratching and brittle fracture (Komanduri *et al*, 1998). The surface finish results obtained by Komanduri are given in Table 2.2.

Abrasive type	Abrasive size (um)	Test time (min)	Surface finish		Effectiveness
			Ra (nm)	Rt (nm)	
SiC 8000	1	60	15	0.15	Excellent
ZrO_2	5	120	4	0.04	
SicC 8000	1	60	15	0.15	Excellent
CeO_2	5	120	4	0.03	

Table 2.2 – Surface finish after CMP (Komanduri et al, 1998)

Komanduri also studied the effects of the magnetic fluid type on the CMP process. It was found that a water-based fluid is necessary for the process to take place, and little, if any, CMP action occurs with oil-based magnetic fluids (Komanduri *et al*, 1998).

The methodology reached to date for the MFP process includes initial mechanical polishing by abrasive particles which are relatively harder than the work material followed by a CMP process to obtain the best surface finish possible. During the mechanical stage, also known as the initial roughing and intermediate stages, the abrasive type, size and concentration is varied to achieve the desired results in terms of MRR, sphericity, and surface finish.

CHAPTER 3

PROBLEM STATEMENT

The industry practice for finishing ceramic bearing balls is by the conventional lapping process. With process parameters of high loads, low speeds, and expensive diamond abrasives, the limitations are long polishing times, high cost, and micro surface and subsurface defects on the balls. Magnetic float polishing is a process developed to overcome these limitations using low loads, high speeds, and softer abrasives, thus providing 'gentle' polishing conditions.

While the technology of MFP has been ongoing for some time, research on a large batch system with relatively large balls has yet to be studied. Therefore the current investigation is directed at polishing 3/4" silicon nitride ceramic balls using the large batch MFP apparatus (LBMFP). Objectives of this study include:

- To polish 3/4" Si_3N_4 balls to the best possible sphericity and surface finish - to a nominal size of 0.75"
- Develop a process (sequence) to be used for the entire polishing process to complete a batch

- Perform a detailed study of the LBMFP apparatus and make appropriate changes as necessary which will improve upon the sphericity and surface finish results
- Develop a list of variables inherent to the MFP polishing process which are considered most important to the polishing process

Currently, the best ball quality specified according to AFBMA standards is grade 3. A single Si_3N_4 ball meeting this specification would cost several hundred dollars. So, the most common ones are in the range of 5 to 16. The table below shows surface conditions allowed for each grade of ball.

	Allowable Ball Diameter Variation	Allowable Deviation from Spherical Form	Maximum Surface Roughness R_a	Allowable Lot Diameter Variation	Nominal Ball Diameter Tolerance (+/-)	Container Marking Increments
	For Individual Balls			For Lots of Balls		
Grade	Micrometers					
3	0.08	0.08	0.012	0.13	a	0.25
5	0.13	0.13	0.02	0.25	a	0.25
10	0.25	0.25	0.025	0.5	a	0.25
16	0.4	0.4	0.025	0.8	a	0.25
24	0.6	0.6	0.5	1.2	a	0.25
48	1.2	1.2	0.8	2.4	a	1.25
100	2.5	2.5	0.125	5	12.5	a
200	5	5	0.2	10	25	a
500	13	13	A	25	50	a
1000	25	25	A	50	125	a

[a] Not applicable

Table 3.1 - AFBMA Standard Balls
Tolerances for Individual Balls and for Lots of Balls

CHAPTER 4

LARGE BATCH MAGNETIC FLOAT POLISHING APPARATUS

The large batch MFP system is basically the same as the small batch as shown in Figure 1.2, with the main difference being the size of the chamber. The small batch has a three-inch chamber while the large batch is 12.375 inches. As a reference, the ball capacity for the small and large batch chambers, for 1/2-inch size balls, is 15 and 69, respectively. One other difference between the two is the way in which the loading is applied. For the small batch system, the chamber is moved upward - into contact with the spindle - by moving the milling machine table. A dynamometer, placed between the chamber and mill table, is used to measure the exact loading. For the large batch, the chamber sets on top of a platform, which, mounted with four linear bearings, can move vertically only. This platform is attached to a counter-weight system that causes it to be lifted upward into contact with the spindle. The amount of counterweights used determines the loading. Schematics of this large batch system are shown in Figures 4.1, 4.2, and 4.3, along with photographs in Figures 4.4 through 4.7. A photograph of the small batch system is shown in Figure 4.8 for comparison.

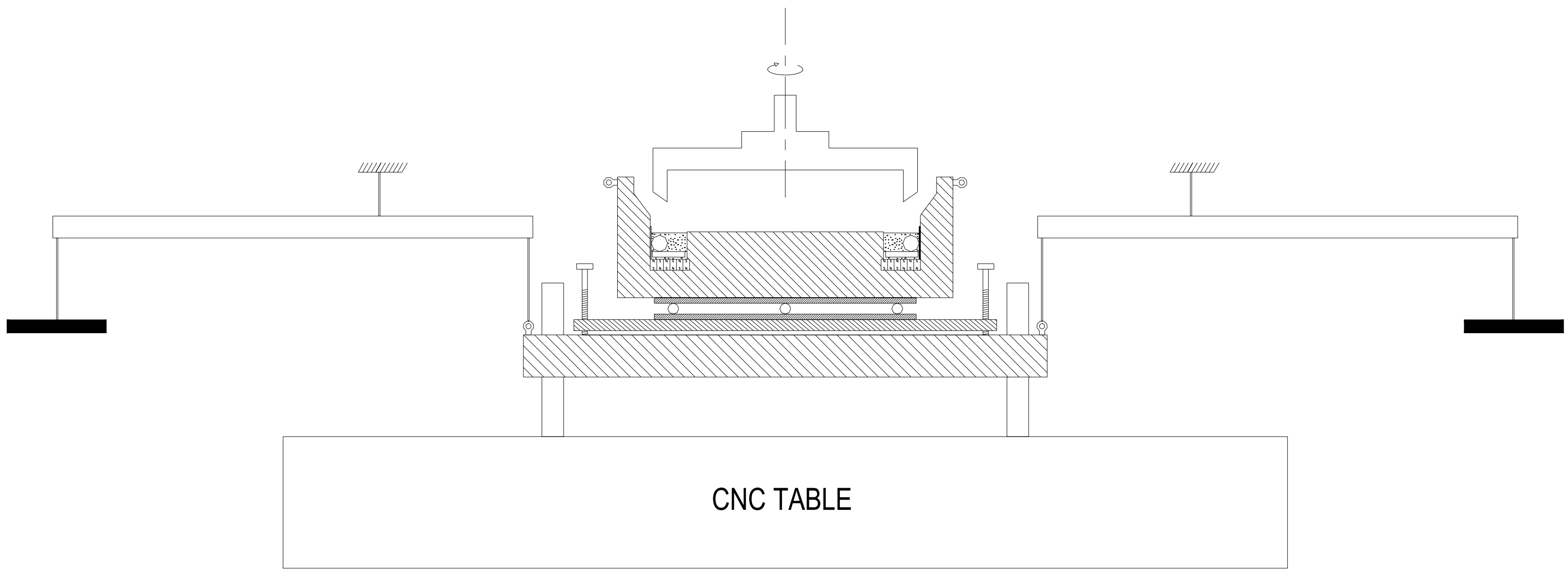


Figure 4.1 - Schematic of the Large Batch MFP
Apparatus

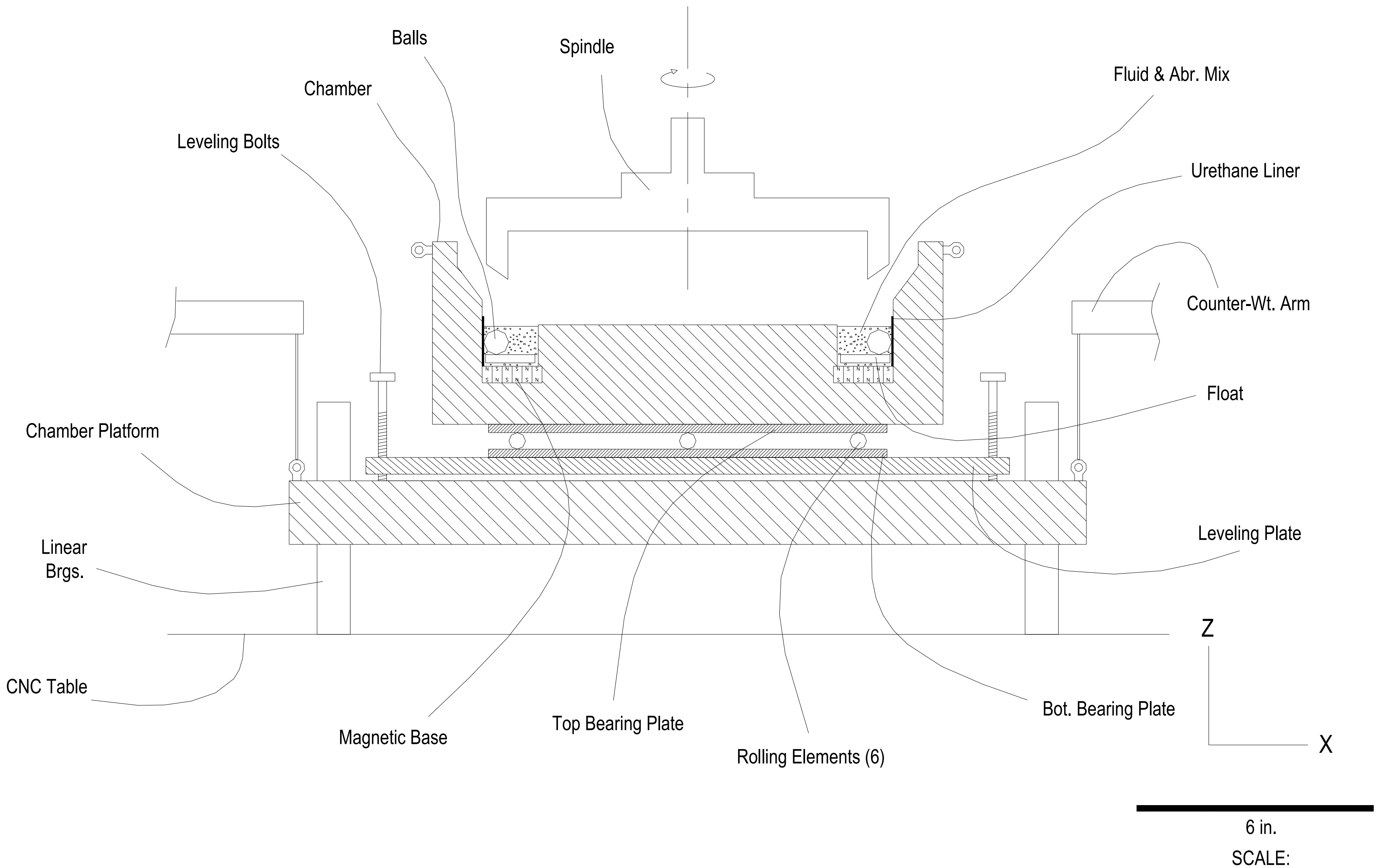


Figure 4.2 - Schematic of the Large Batch MFP Apparatus (side view)

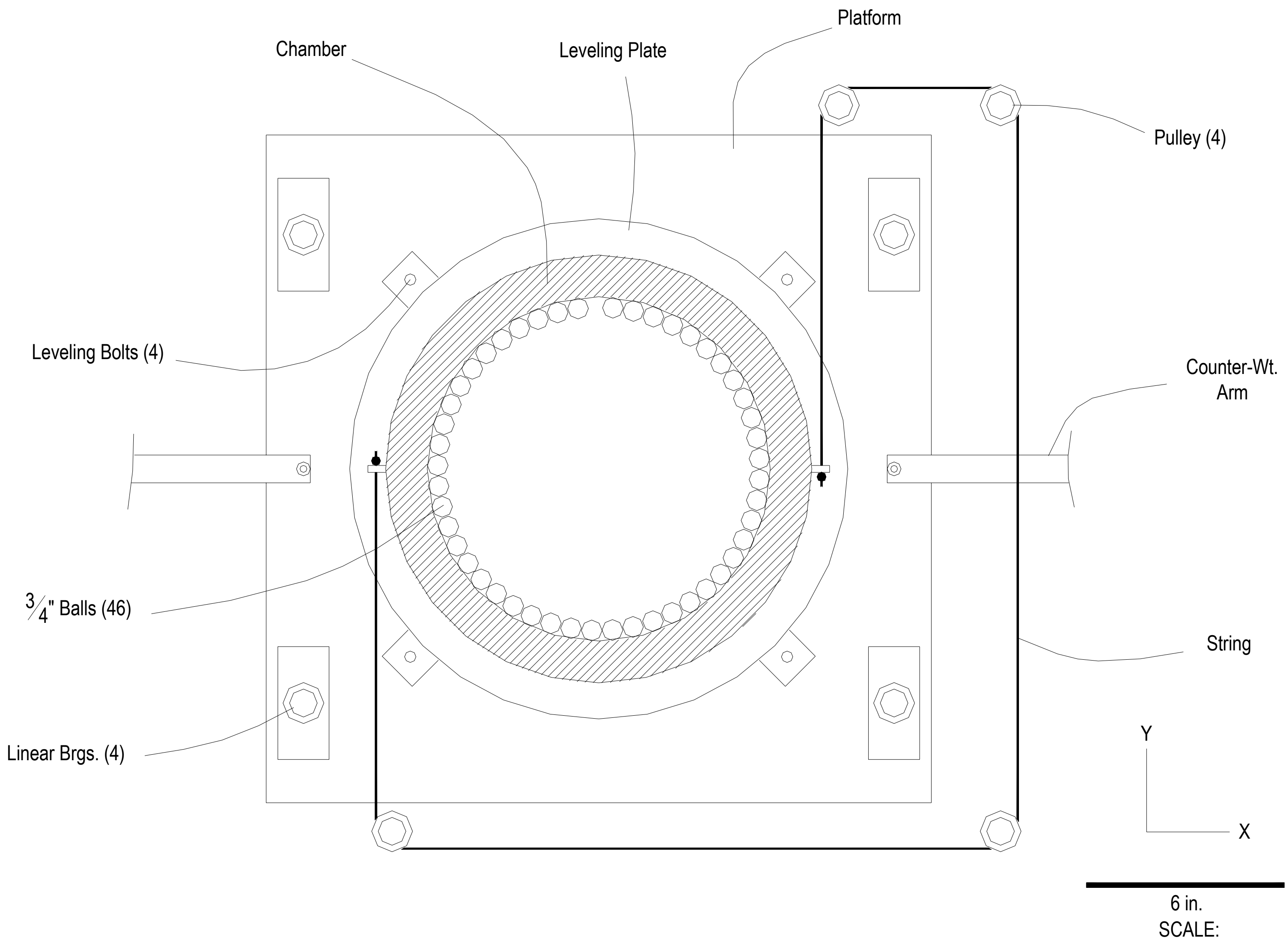


Figure 4.3 - Schematic of the Large Batch MFP Apparatus (top view)

Figure 4.4 - Photograph of the Large Batch MFP

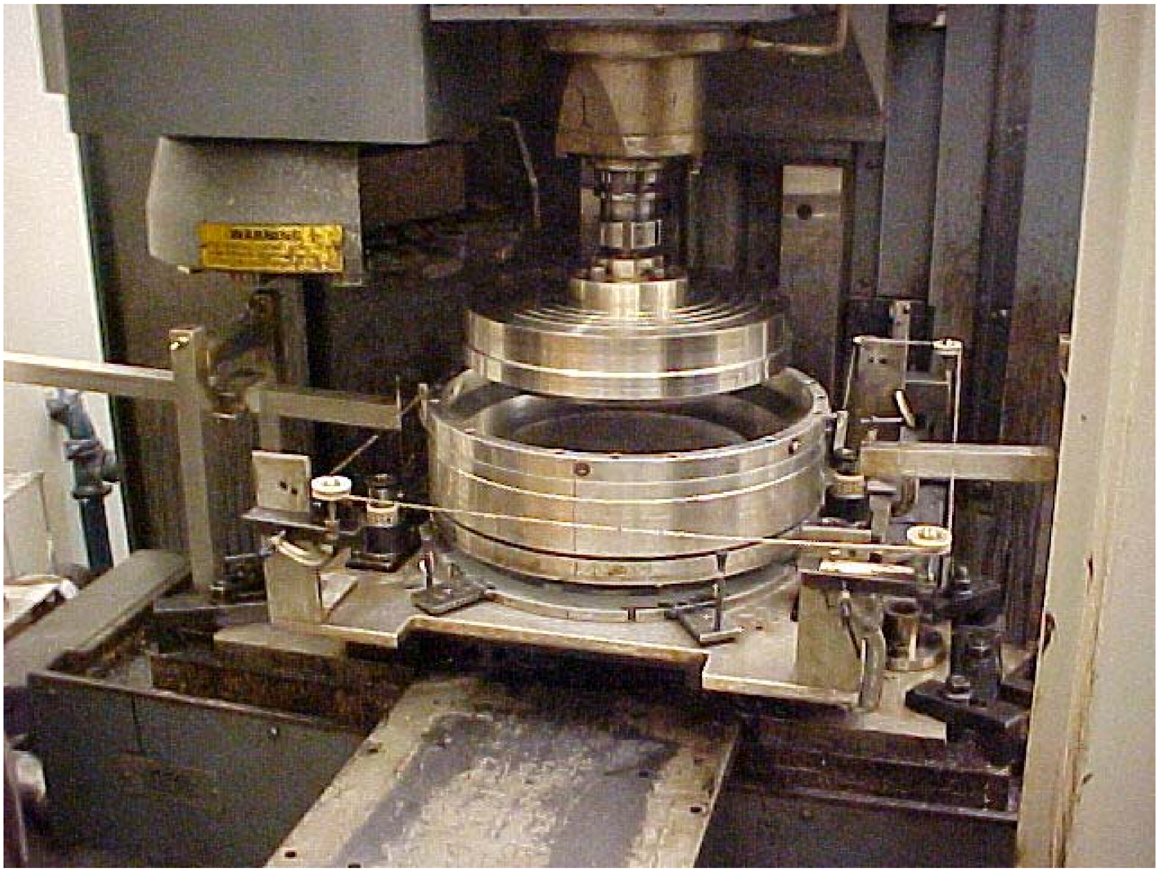


Figure 4.5 - Detailed Photograph of the Large Batch MFP

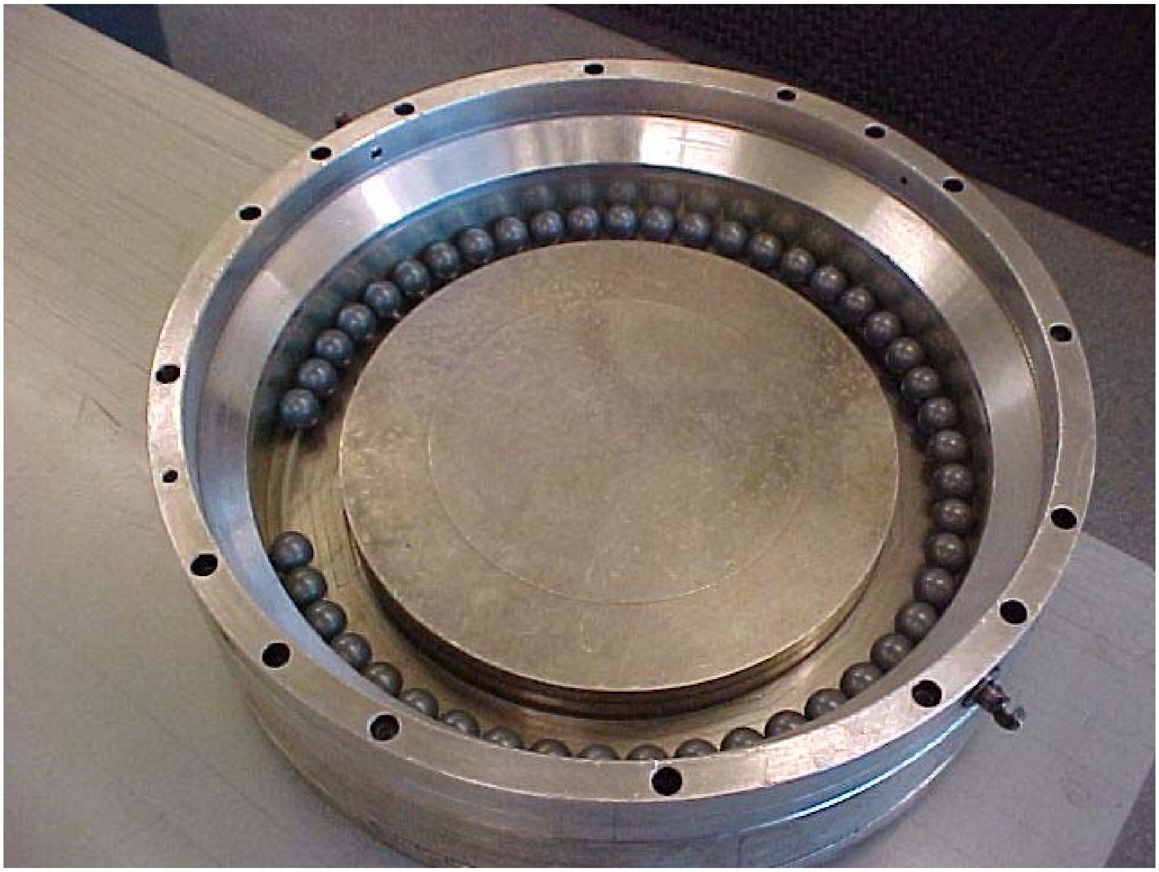


Figure 4.6 - Photograph of the Chamber with PMMA Float (under balls), Liner (along chamber perimeter), and Balls in Place

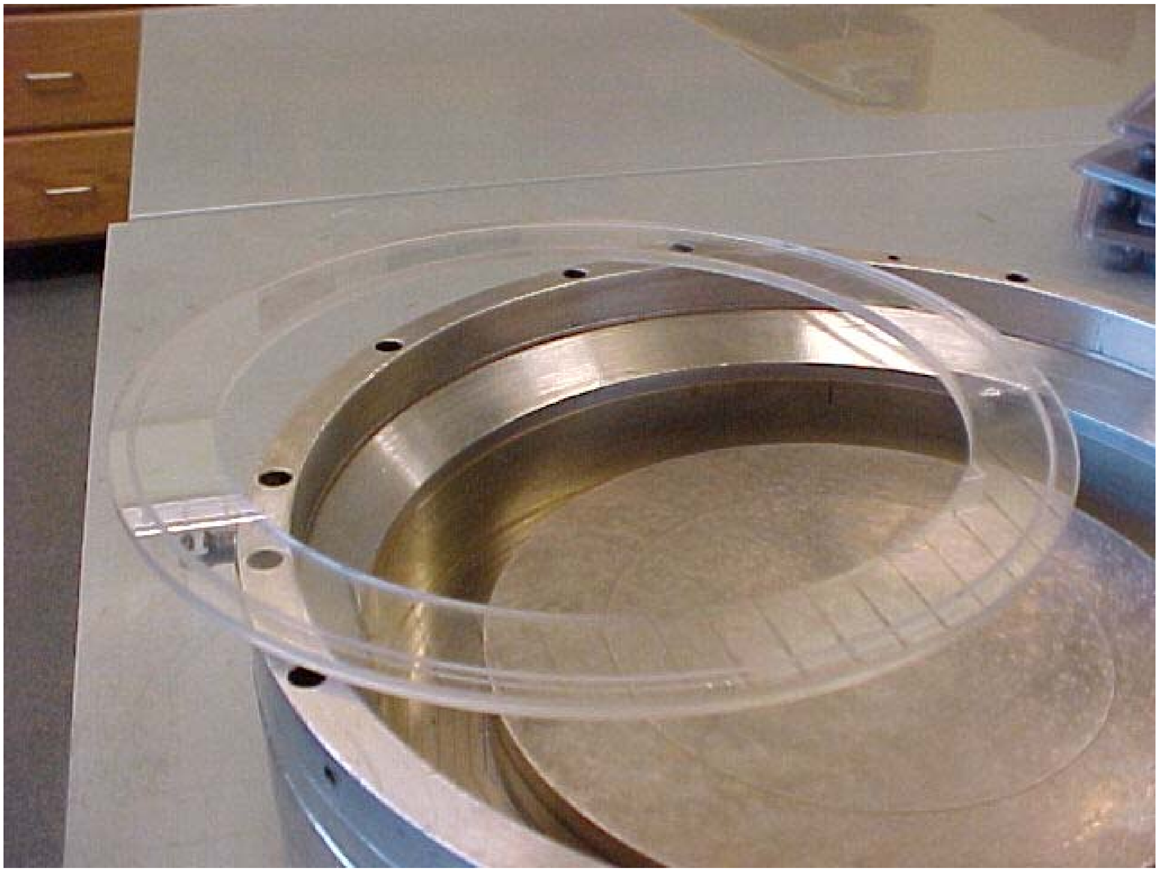


Figure 4.7 - Photograph of the PMMA Float showing Wear Pattern

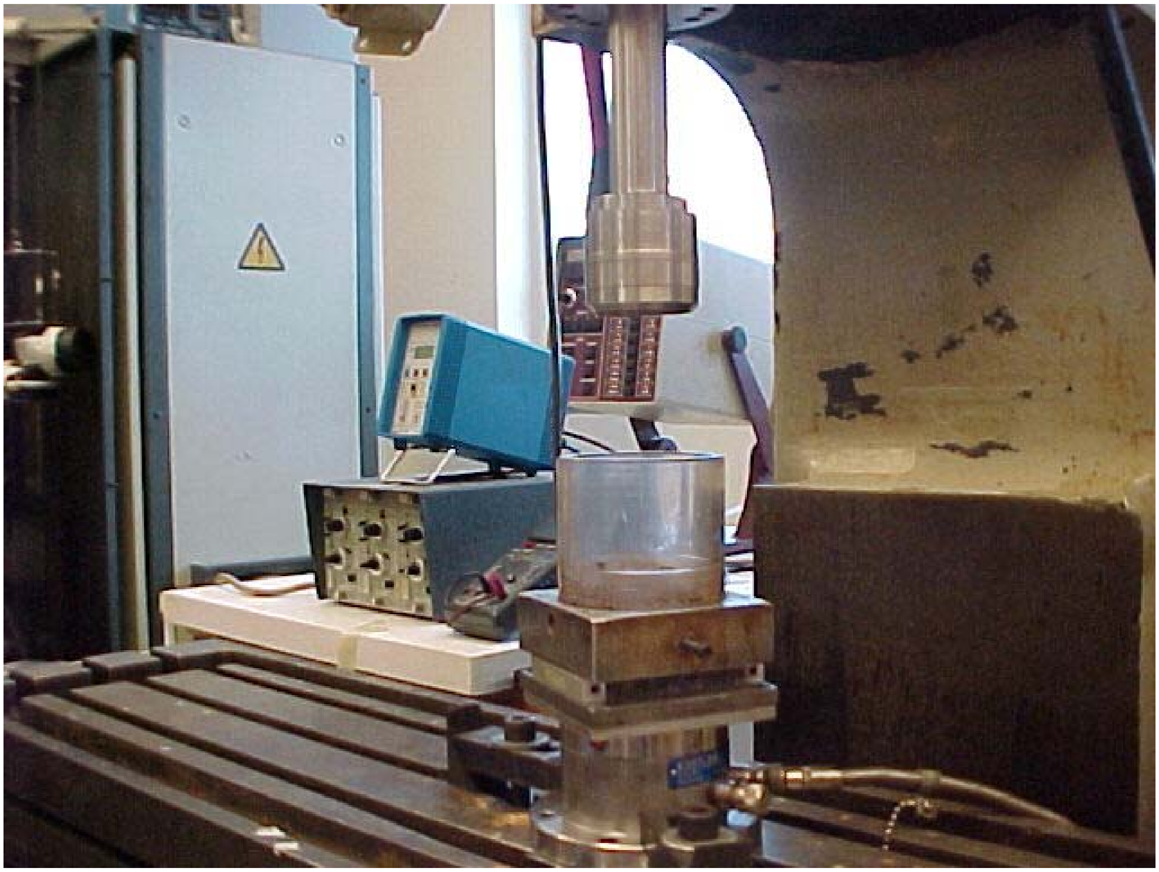


Figure 4.8 - Photograph of the Small Batch MFP

4.1 OVERVIEW

The basic idea behind MFP is the 3-point contact, where one of the points - the spindle - is made to move relative to the other two. This causes the balls to rotate in such a way that their entire surfaces are machined, or polished, uniformly. The abrasives cause the cutting action by coming between the contact points and fracturing or shearing the ball - on a micro scale. The parameters - abrasive, speed, and load - directly affect the surface quality of the balls as well as the material removal rate.

The loading of the balls is accomplished in two ways. First, the magnetic fluid causes the PMMA (plexiglas) float and balls to levitate inside the chamber. Secondly, the chamber, supported by the platform, is elevated by the counter-weight system. Initially the entire system - platform, chamber, fluid, balls, etc. - is balanced by counter-weights, so that the chamber is suspended (balanced vertically). At this point, when the spindle is moved and makes initial contact with the balls, there is zero load on the balls (the spindle just touches the balls). Next, the exact loading of the balls is accomplished by adding the appropriate amount of counter-weights, which will, in turn, force the chamber upward, into the spindle.

In order to obtain best results, in terms of sphericity, the chamber must be aligned exactly co-axial with the spindle. This is one of the most significant factors affecting the results, and has proved to be the most challenging aspect of the entire process. If the two are not aligned properly, unequal loading will result which will cause higher material removal rates at areas of higher loading;

meaning that, as a ball circulates around the chamber, some areas of the ball's surface will be machined more than others, severely degrading the sphericity. Also, this unequal loading is a source of vibrations, which again has the same affect.

The approach taken to ensure that the spindle and chamber maintain co-axiallity is to allow the chamber to move freely in the horizontal direction. The idea is to allow the chamber and balls to "conform to the spindle." This is accomplished by placing smooth balls between the chamber and platform, allowing the chamber to roll horizontally in any direction. The forces acting on the balls, from the spindle, cause the chamber to "self-align" so that a state of equilibrium is reached between the forces around the chamber.

This proved to be an excellent method of aligning the spindle, but presented a new problem. With the spindle completely free, a means of preventing its rotation must be made. Also, the smooth balls and bearing plates make the entire system extremely sensitive to vibrations. As shown in Figures 4.3 and 4.5, a single nylon string, running through the four pulleys, is connected at ends to the sides of the chamber, preventing rotation. The use of a single string verses two individual ones assures equal tension throughout and therefore exerts equal and opposite force to each side of the chamber in the direction of pulling. Care must also be taken to make sure the strings are parallel to one another on each side of the chamber or else the forces will not pull exactly opposite to one another. This is done by adjusting the position of the pulleys.

4.2 LARGE BATCH MFP COMPONENTS

The major components of this system are listed below. These are described along with the modifications made to the original design during this investigation.

I. Spindle

- Type 304, stainless steel spindle, non-magnetic
- Spindle re-machining post
- Bridgeport CNC milling machine - Interact 417 model

II. Chamber

- Aluminum chamber with a magnetic base
- Support platform with linear bearings for vertical movement
- Leveling plate
- Chamber liner for wear prevention
- Bearing plates with rolling elements for self-alignment
- Float
- String and chamber locking mechanism

III. Counter-weight system

Spindle

The spindle is made of a non-magnetic, type 304, stainless steel tube with a top plate and one-inch rod welded on for attachment to the milling machine head. The outer diameter is 12.125 inches with a 0.65-inch wall thickness. The bottom edge is beveled at 35° (from the plane parallel to the bottom of the spindle). The weld reinforcements, inner and outer, of the full penetration weld from the tube to the plate, are machined flush for a smooth finish.

The most important concern regarding the spindle is that it be perfectly balanced and aligned with the mill axis. With running speeds of 400 rpm, any unbalance will cause vibrations and quickly degrade the results. Also, when attaching the spindle to the mill, it is equally important that the two be co-axial. With the spindle even slightly slanted, with respect to the axis of the mill, extreme vibrations can occur. This becomes important when removing and reattaching the spindle to the mill. Since the abrasives used are harder than steel, the spindle will also be worn during polishing, along the circulation path of the balls. During roughing stages, where large, hard abrasives are used with high loads, a typical wear groove can be as much as 1/4-inch wide and 1/8-inch deep, on the beveled edge. This requires the spindle to be re-machined after each polishing run. Initially this was done by removing the spindle from the mill, re-machining it on a lathe, and then attaching it back to the mill. The problem with this is that it's impossible to install the spindle to be exactly co-axial to the mill. Therefore it was decided that the best approach to this problem is for the spindle to be re-machined in place.

To do this, a tool post was made and mounted to the X-Y table of the CNC. A small, manual type X-Y table was attached to this post and a single point cutting tool fit to it. A photograph of this setup is shown in Figure 4.9. This device was also used to balance the spindle after it was initially attached to the

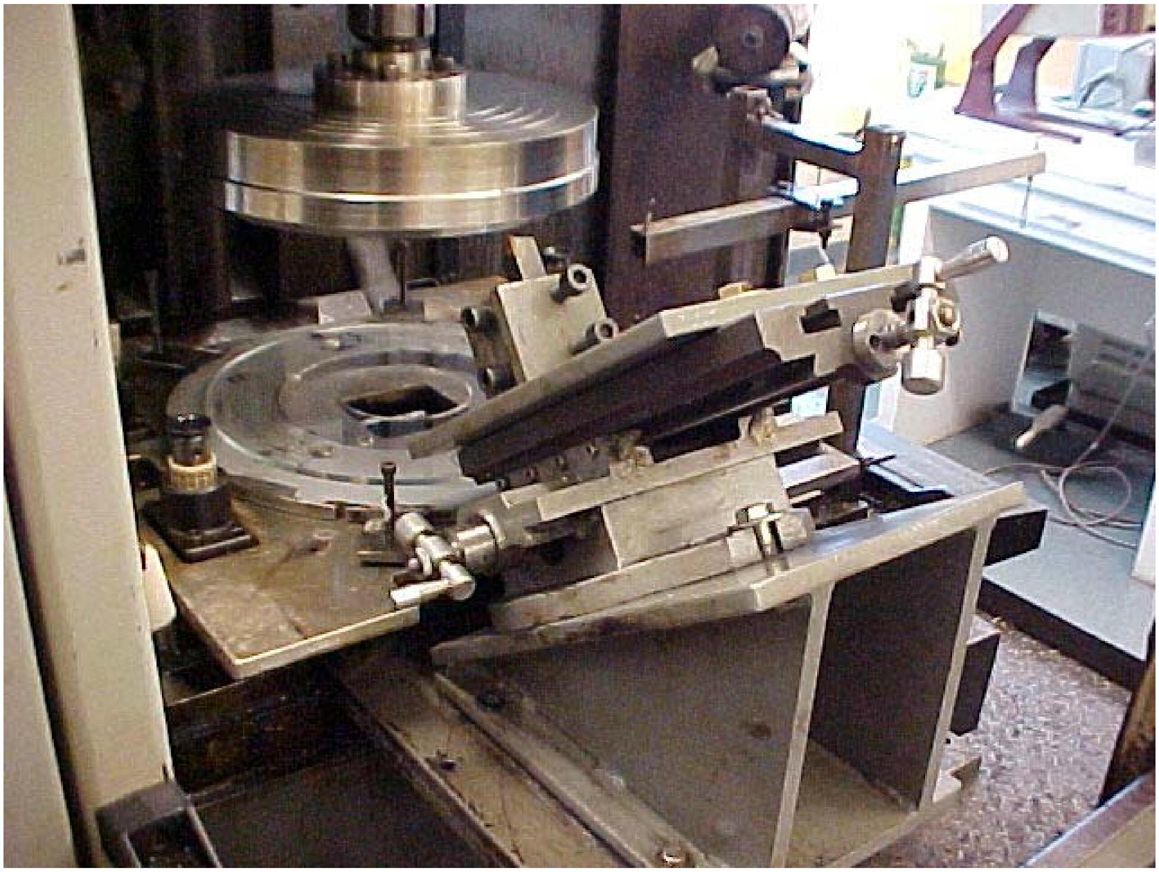


Figure 4.9 - Photograph of Spindle Re-machining Post

mill. Here, all sides of the spindle - outer top, outer side, inner side, and inner top surface - were machined in place. Small depths of cut were made to these surfaces until there was no longer an intermittent cut. This ensured true balance, and the spindle was not removed from the mill after this. To measure the accuracy of the spindle after this was performed, a dial indicator, with a 0.0001" resolution, was set perpendicular to the beveled edge. When the spindle was rotated by hand, there was no deflection of the dial's needle; and so at least under static conditions, there's confidence that the spindle was balanced and co-axial to the mill. As a comparison, when this test was performed on the spindle prior to machining it in place, the dial indicator showed a deflection of nearly 0.007".

<u>Chamber</u>

The chamber is made of aluminum with a 12.375-inch inside diameter. It is composed of a base and chamber wall. The base has permanent magnets, Nb-Fe-B type, made into it, flush with the top surface. Figure 4.10 shows the layout of the magnets, with intensities and polarity. Figure 4.11 shows a photograph of the arrangement of the magnets on the chamber's base. The wall is a two-inch high aluminum ring with a 1.5-inch thickness. The height is determined by the size of the balls; where larger balls require more magnetic fluid and thus more height in order to prevent the extra fluid from spilling out.

One of the most significant features of the chamber is the roundness of

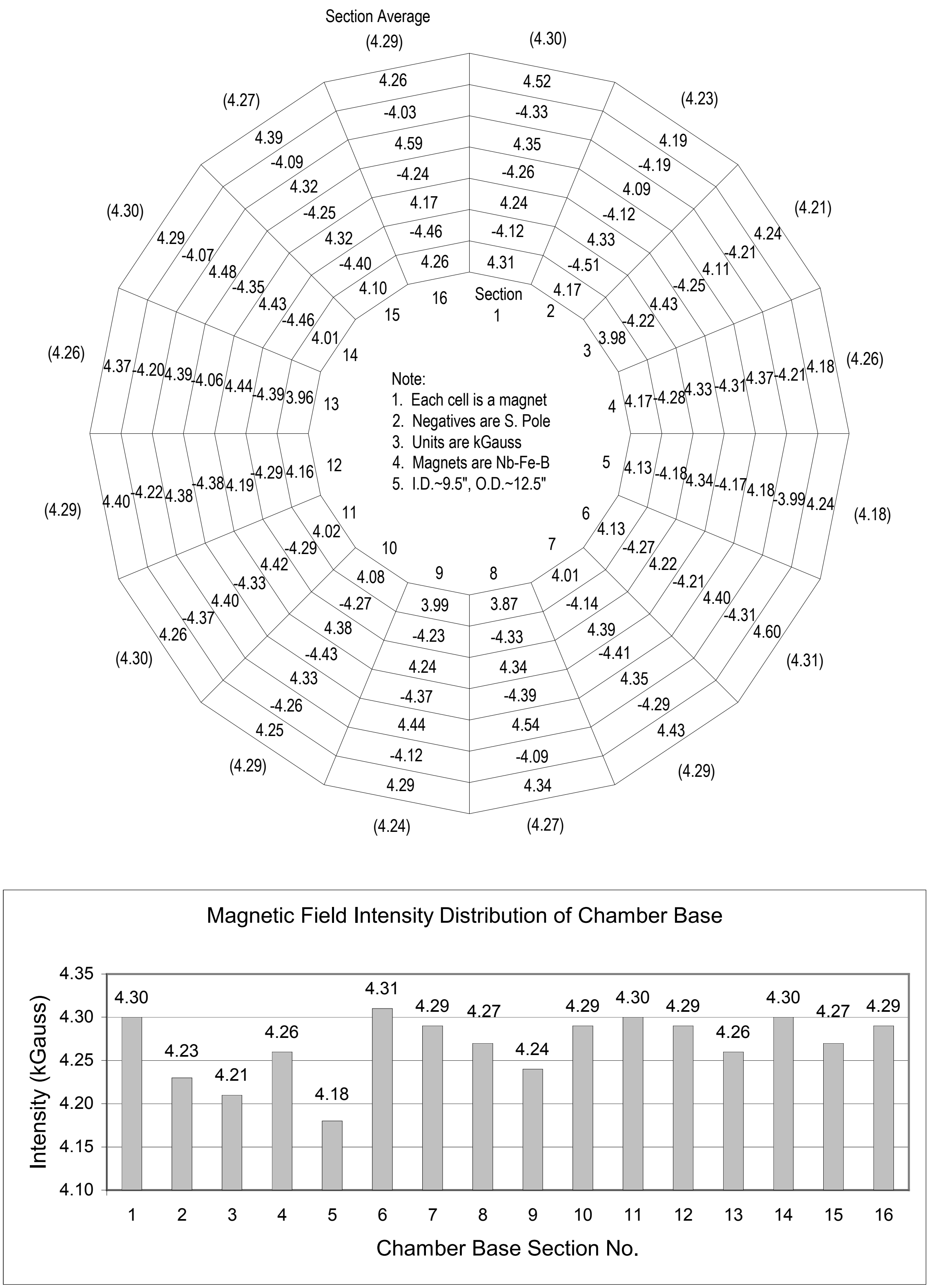


Figure 4.10 - Magnetic Base Layout Showing Magnetic Field Intensities and Distribution

Figure 4.11 - Photograph of Chamber Base Showing Arrangement of the Magnets

the wall. If it is not perfectly round, the balls will rotate in some type of elliptical pattern, resulting in unequal loading. The initial design of the chamber used an aluminum ring with its inner wall having a 1/8-inch thick polyurethane layer bonded to it (90 shore A hardness). The purpose of this layer is to prevent the abrasives from wearing the soft aluminum wall. The problem is that after three or four polishing runs, at one hour each, the wall becomes elliptical by about 0.003 inches. This requires the polyurethane liner to be removed and a new one cast in place - using a mold. Due to the high costs and uncertainties associated with this, it was decided that a new chamber wall, made of aluminum, was a better solution. The one-piece chamber wall was machined on a lathe, which guaranteed true roundness. To prevent wear from taking place, a similar type of polyurethane sheeting (also 90 shore A hardness) was placed around the inner perimeter of the chamber wall. The difference in this case being that the liner was not permanently attached to the wall, which enabled it to be changed out after each run. This was quite a bit cheaper, as well as much faster; since the chamber wall does not need to be sent out for re-coating.

Another factor regarding the chamber that significantly affects the results is the angle it makes with respect to the spindle. The base of the chamber must be exactly parallel to the bottom plane of the spindle (or perpendicular to the spindle's axis), or again, the balls will circulate in an elliptical pattern. A tilt of only 0.18 degrees can cause a one-millimeter difference in ball heights - on opposing sides of the chamber (with ~12" diameter ball perimeter). This is noticed by a difference in gap at these opposite locations between the spindle's outer edge and the chamber's inner wall. For this 0.18-degree tilt, the difference is 0.056"; 0.237" gap on one side and 0.293" on the other. This is also a misalignment problem but is different than in the case of spindle-chamber misalignment. Misalignment caused by unbalanced forces acting on the chamber causes variations in the forces acting on the balls as they circulate. This disturbs the ball circulation and ultimately causes different MRRs on different areas of each ball - damaging sphericity. In the case of chamber tilt, it is not apparent if the forces on the balls are unequal since the chamber and spindle are still self-aligning and have reached an equilibrium state; but this does cause the balls to circulate in an elliptical pattern. The extent to which sphericity is affected is still not understood, but efforts have been made to alleviate this; namely, the use of the leveling plate under the chamber; shown in Figure 4.12. By using a dial gage, or any other type of feeler gage, between the spindle bottom and chamber bottom, the leveling plate can be adjusted to maintain parallelism between the two.

Counter-weight system

As previously mentioned, the counter-weight arms (one on each side of the chamber) are connected to the platform supporting the chamber. The original design of this system utilized a series of pulleys, which a steel cable would ride over. The friction associated with the pulleys and the cable prevented the chamber from maintaining a constant and controllable load on the balls. Therefore, this arrangement was replaced with the system shown in the Figure 4.1 (other views in Figures 4.5, 4.9, and 4.12). The counter-weight arms are

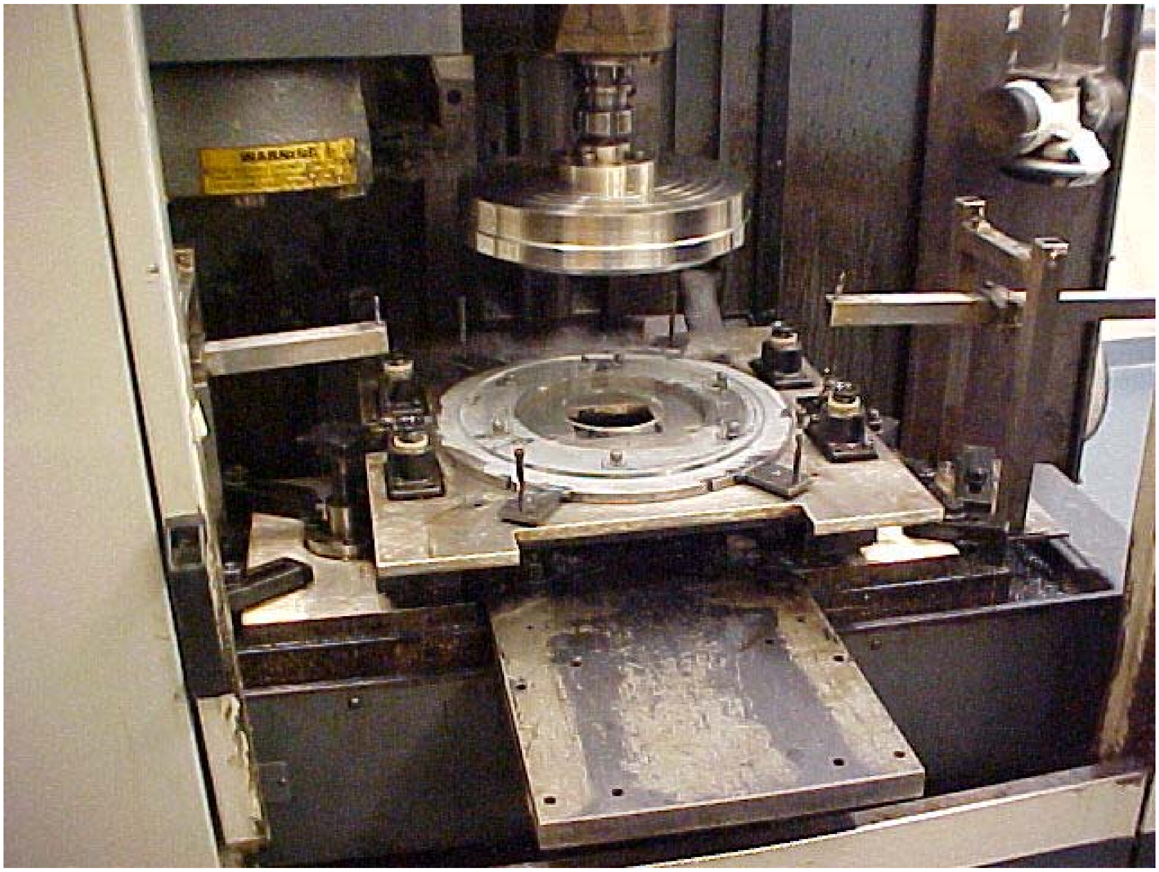


Figure 4.12 - Photograph of the Leveling Plate with Bottom Bearing Plate and Balls

supported with a cable at approximately 1/3 the length of the arm. This virtually eliminates any friction and the loading is highly controllable and repeatable.

4.3 MFP VARIABLES AND APPARATUS DESIGN CONSIDERATIONS

The list below shows the variables involved in large batch MFP. They are divided into four area: a) direct run variables that vary each run (parameters), b) set-up considerations which should be kept constant every run, c) initial fabrication considerations, d) variables that are inherent to the system and are hard to change or not changeable at all.

a) Direct run variables/parameters

- Abrasive: type, size, concentration
- Run duration
- Speed
- Amount of Magnetic Fluid
- Load

b) Set-up considerations (to be kept constant every run)

- Eccentricity between spindle and chamber
- Chamber tilt
- Surface finish of the spindle bevel
- Float dimensions
- Dampening of chamber during run
- Fluid evaporation prevention

c) Initial Fabrication Considerations

- Spindle balance and roundness
- Chamber roundness
- Quality of bearing plates and rolling elements under chamber (for true self-aligning)
- Mass of the chamber
- Angle of spindle bevel

d) Variables inherent to the system and hard or not controllable

- Rigidity of CNC milling machine spindle
- Consistency of magnet intensities
- Size and strength of the magnets
- Float quality (waviness in dimensions, concave/convex)
- Liner junction(s) (different thicknesses at junction may cause a step)
- Liner quality (waviness in dimensions)
- Fluid getting behind liner during run
- Fluid viscosity
- Friction in sleeve bearings (preventing consistent loading during run)
- Gap between the balls (varies as ball diameters decrease - run-to-run)
- Properties of spindle
- Abrasive contamination

CHAPTER 5

METHODOLOGY

5.1 APPROACH

Polishing Si_3N_4 balls involves machining the surface by mechanical and/or chemo-mechanical means to obtain the desired surface finish, sphericity, and diameter. For the large batch magnetic float polishing process, forty-six 3/4" balls, considered a single batch, are machined from the as-received diameter of 0.783 inches to the final diameter of 0.750 inches by a series of polishing runs.

Each run has a particular set of parameters (speed, load, duration, and abrasive) specifically chosen to obtain the results desired for that run. Approximately twenty runs are needed to completely polish a batch, with each run lasting between 60 and 180 minutes.

The approach taken to polish a batch of balls is the use of somewhat aggressive conditions during the initial stages, for high material removal rates (MRR) and moderate improvements in surface finish and sphericity, to more gentle conditions for the later stages, for optimum sphericity and surface finish with very little MRR. These are divided into five stages as shown below.

- Stage 1a: Emphasis on high MRR
- Stage 1b: Emphasis on MRR with Sphericity as 2nd priority
- Stage 2a: Emphasis on Sphericity with MRR as 2nd priority
- Stage 2b: Emphasis on Sphericity with Surface Finish as 2nd priority
- Stage 3: Emphasis on Surface Finish

Table 5.1 lists the parameters used for polishing. These served as a starting point and were based on the results of previous research on MFP. It was shown from these past results that boron carbide (B_4C) (the hardest of the abrasives used) was an adequate abrasive for high MRRs, while the softer abrasives were better for improving sphericity and surface finish. Therefore B_4C, with a grit size of 500, was selected as the abrasive for stage 1 above.

Abrasives & Grit Sizes	B_4C - 500, 1000, 1500 grits SiC - 600, 1200, 8000, 10000 grits CeO_2 - < 5um particle size
Abrasive Concentrations	5, 10, 20 % (by volume)
Loads	0.5, 0.75, 1.0, 1.5 Newtons/Ball
Speeds	300, 350, 400, 450, 550 rpm
Durations	20 - 180 minutes

Table 5.1 - Parameters Used in Polishing

In order to determine the remaining parameters of abrasive concentration, load, and speed (with run duration held constant at 60 minutes), Taguchi's method of statistical analysis was used. This method uses statistics to minimize the number of test runs needed to extract information. With this method, only nine test runs were needed; verses twenty-seven that would have been required using the single factor method - where every possible combination of the three would need to be tested. Table 5.2 shows the orthogonal array setup for the Taguchi method.

Trial No.	Factors Investigated				Results
	A	**B**	**C**	**D**	
1	1	1	1	1	
2	1	2	2	2	
3	1	3	3	3	
4	2	1	2	3	
5	2	2	3	1	
6	2	3	1	2	
7	3	1	3	2	
8	3	2	1	3	
9	3	3	2	1	

Table 5.2 - Taguchi's Method - $L_9(3^4)$ Orthogonal Array Set-up (Jaing, 1998)

The variations of the load, abrasive concentration, and speed for Taguchi's method are given in Table 5.3. Table 5.4 shows the orthogonal array incorporating these variables - with results. These data are investigated to give the optimum conditions for highest MRR. The effects of the parameters are shown below in Table 5.5 and graphical representations of these are shown in Figure 5.1.

Level	A: Load	B: Conc.	C: Speed
	N/ball	*Vol. %*	*rpm*
1	0.5	5	300
2	1	10	400
3	1.5	20	550

Table 5.3 - Parameters Used for Taguchi's Method to Determine the Highest MRR

Trial No.	Factors Investigated				Results MRR (mg/min)	*Batch A run no.*
	Load (N/ball)	**Abr. (%)**	**Speed (rpm)**	*not used*		
1	0.5	5	300	-	28.45	*15*
2	0.5	10	400	-	70.65	*7*
3	0.5	20	550	-	49.95	*8*
4	1	5	400	-	57.92	*9*
5	1	10	550	-	89.90	*10*
6	1	20	300	-	93.36	*11*
7	1.5	5	550	-	88.85	*12*
8	1.5	10	300	-	54.13	*13*
9	1.5	20	400	-	133.75	*14*

Table 5.4 - Taguchi's Method - $L_9(3^4)$ Orthogonal Array Used - with Results Obtained

As shown in Table 5.5 the highest MRR is given for the combination of 1.5 newtons per ball, 20% abrasive concentration (as a volume percent of the magnetic fluid added to the chamber), and at a spindle speed of 400 rpm. From Figure 5.1, it is shown that increasing both the load and abrasive concentration, will give a corresponding increase in MRR. On the other hand, Figure 5.1c shows that the optimum speed is 400 rpm; where above or below this will

Table 5.5 - Average effect of each on MRR
(a) Load Level, (b) Abrasive Concentration, (c) Speed

(a)

Load (N/ball)	Analysis		Average Response
	Test No.	MRR (mg/min)	MRR (mg/min)
0.5	1 2 3	28.45 70.65 49.95	49.68
1	4 5 6	57.92 89.90 93.36	80.47
1.5	7 8 9	88.85 54.13 133.75	92.24

(b)

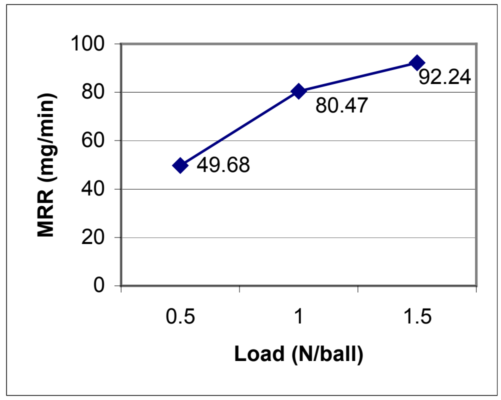
Abr. Conc. (%)	Analysis		Average Response
	Test No.	MRR (mg/min)	MRR (mg/min)
5	1 4 7	28.45 57.92 88.85	58.41
10	2 5 8	70.65 89.90 54.13	71.56
20	3 6 9	49.95 93.36 133.75	92.35

(c)

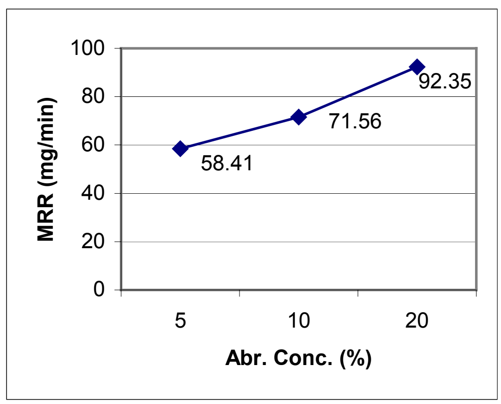
Speed (rpm)	Analysis		Average Response
	Test No.	MRR (mg/min)	MRR (mg/min)
300	1 6 8	28.45 93.36 54.13	58.65
400	2 4 9	70.65 57.92 133.75	87.44
550	3 5 7	49.95 89.90 88.85	76.23

Figure 5.1 - Response of each on MRR
(a) Load Level, (b) Abrasive Concentration, (c) Speed

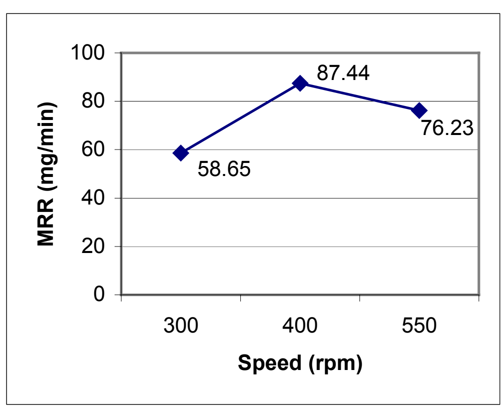
(a)



(b)



(c)



only decrease the MRR. Therefore these conditions are used for stage 1a.

For stage 2, where the main thrust is obtaining the best sphericity, a systematic approach - Taguchi's method or the like - was not performed. This is due to inconsistencies involved in the setup of the apparatus for each run. These inconsistencies are listed in section 4.3 above and include variables such as chamber-spindle misalignment, chamber tilt, etc. Therefore, no real conclusions could be based on the results of a certain set of run parameters since unknown setup variations are just as significant as the parameters themselves. This can easily be seen from a pair of runs performed under the same set of conditions but with large differences in results - in terms of sphericity, surface finish, and to a lesser extent, MRR. In response to these issues, the approach taken for stage 2 is to study and reduce these setup variations and to establish a standard procedure for making runs which will give repeatable results for a given set of run parameters. Most of the effort during this research has been devoted to this, and it is without a doubt the most limiting factor to the MFP process at this point. Concerning the parameters involved during stage 2 runs, the parameters chosen are based on both trial and error data as well as results from previous researchers.

5.2 PROCEDURE FOR POLISHING

The following is a detailed procedure for polishing balls with the large batch MFP apparatus:

a) The leveling plate is placed on the platform with bottom bearing plate and rolling elements on top
b) Polyurethane liner is fitted inside the chamber; top bearing plate is placed under the chamber (taped in place)
c) Chamber is set on the rolling elements and locked in place (the chamber is set exactly in the center of the platform); the single string is attached at ends, with its sides (on opposite sides of the chamber) made parallel to one another by adjusting the position of the pulleys
d) Chamber is leveled (base made parallel to the spindle's bottom edge) using the leveling plate with feeler gages
e) The float, magnetic fluid, abrasives, and balls are placed inside the chamber
f) Chamber is centered to the spindle using the CNC axes to within 0.5 mm
g) Counter-weights are set to the desired load (this causes the chamber and platform to rise approximately one inch - until it reaches a stop-plate)
h) Spindle is lowered with the CNC Z-axis until the chamber moves vertically downward (by approximately 1/2-inch)
i) Spindle is made to rotate ~50 rpm; the chamber is unlocked so that it's free to move in the X-Y direction. This allows the chamber to self-align to the spindle
j) Spindle speed is increased to 400 rpm (or desired speed); during roughing stages, the chamber is slightly locked to dampen vibrations; for final stages there is no need for locking since there are no noticeable vibrations

5.3 CHARACTERIZATION EQUIPMENT

The following equipment is used to characterize the balls:

- Talyrond for sphericity measurements
- Talysurf for surface finish measurements
- Precision scale for weight measurements of the balls
- Micrometer for diameter measurements (0.0001 in. accuracy)

<u>Talyrond</u>

To measure the sphericity (roundness) of the ball, a stylus type of instrument was used – Talyrond model 250 made by Rank Taylor Hobson Inc. The specification of this equipment is given in Table 5.6.

The roundness of several balls within the batch was measured for each run. The roundness is determined by measuring 3 perpendicular planes; with the final value being the largest of the three measurements. This is measured for each of the selected balls. This value is calculated by the least squares method.

Roundness error	0.05 μm
Radial resolution	0.06 μm
Angular resolution	0.72 degrees (500 points per revolution)
Filter type	2CR
Cut-off	50 upr
Gauge range	$\pm$ 1 mm
Circle computation method	Least squares

Table 5.6 - Roundness Measurement Specification for Talyrond

Talysurf

The surface finish was measured using a stylus type surface finish measuring instrument – Form Talysurf model 120 L made by Rank Taylor Hobson Inc. The specification of this equipment is given in Table 5.7. The testing procedure is the same as that for the roundness measurements – three measurements are taken from each ball on three perpendicular planes with the greatest value (worst surface finish) being the recorded surface finish of the ball.

Brinkmann Precision Balance

To determine the amount of material removed and thus the material removal rate (MRR) for a test run, the batch of balls were weighed using a precision balance – Model 1712 MP8 from Brinkmann Instruments Company. The resolution is 0.1 mg and the range is 160 g.

Stylus	Diamond tip Tip radius = 1.5 - 2.5 um Stylus force = 0.7 - 1.0 mN
Filter type	ISO 2CR
Cut-off	0.8 mm
Form compensation	Least squares arc

Table 5.7 - Surface Finish Measurement Specification of Talysurf

CHAPTER 6

RESULTS AND DISCUSSION

6.1 POLISHING CONDITIONS AND RESULTS

Two separate batches of 3/4-inch diameter Si_3N_4 balls, 46 each, have been polished - recorded as batch A and batch B. Batch A served initially as a test to determine the optimum parameters while batch B served as the demonstration to try out these and obtain the best possible results. Altogether, a total of 37 runs were made on batch A and 39 runs on batch B. These results are given in Tables 6.1 and 6.2. Tables 6.3 and 6.4 show the same results as sorted by run parameters; in the order of abrasive type, abrasive size, load, abrasive concentration, run duration, and speed. This reflects the significance of each parameter on MRR; as can be seen in the values for MRR as they descend from generally higher to lower values.

6.2 DESCRIPTION OF BATCH A AND B POLISHING RUNS

This section will give an outline for both batches to show the approach and reasoning taken for each of the runs as well as a general description of the results obtained.

Run Parameters							Results								
Run	Abr. Type	Abr. Size	Load	Abr. Conc.	Time	Speed	Dia.	ΔDia.	Batch Weight **	ΔWeight	Avg. Batch Sphericity	Sphericity Std. Dev.	Surface Finish - Ra	MRR	MRR
		(grit)	*(N/ball)*	*(%)*	*(min)*	*(rpm)*	*(in)*	*(in)*	*(g)*	*(mg)*	*(μm)*	*(μm)*	*(nm)*	*(μm/min)*	*(mg/min)*
0							0.785 1		602.7771		27.35	10.29	865		
1*	B_4C	500	0.75	5	60	400	0.784 5	0.000 6	601.3791	1398.0	16.80	3.50	451	-	-
2	B_4C	500	1	5	60	400	0.782 6	0.001 9	597.0251	4354.0	14.28	10.71	93	0.803	72.6
3	B_4C	500	1	5	60	400	0.780 5	0.002 1	592.3178	4707.3	8.14	5.40	-	0.873	78.5
4	B_4C	500	0.5	5	45	300	0.780 0	0.000 5	591.1222	1195.6	9.83	6.08	-	0.297	26.6
5*	B_4C	500	0.5	5	60	300	0.779 3	0.000 7	589.5197	1602.5	-	-	-	-	-
6*	B_4C	500	0.5	10	60	400	0.779 0	0.000 3	588.8361	683.6	-	-	-	-	-
7	B_4C	500	0.5	10	60	400	0.777 1	0.001 9	584.5974	4238.7	-	-	-	0.793	70.6
8	B_4C	500	0.5	20	60	550	0.775 8	0.001 3	581.6003	2997.1	-	-	-	0.563	50.0
9	B_4C	500	1	5	60	400	0.774 2	0.001 5	578.1251	3475.2	-	-	-	0.655	57.9
10	B_4C	500	1	10	60	550	0.771 8	0.002 4	572.7309	5394.2	1.77	0.81	-	1.023	89.9
11	B_4C	500	1	20	60	300	0.769 3	0.002 5	567.1291	5601.8	-	-	-	1.069	93.4
12	B_4C	500	1.5	5	60	550	0.766 9	0.002 4	561.7979	5331.2	-	-	-	1.024	88.9
13	B_4C	500	1.5	10	60	300	0.765 4	0.001 5	558.5499	3248.0	-	-	-	0.627	54.1
14	B_4C	500	1.5	20	60	400	0.761 7	0.003 7	550.5251	8024.8	-	-	-	1.559	133.7
15	B_4C	500	0.5	5	60	300	0.760 9	0.000 8	548.8180	1707.1	2.23	0.72	-	0.334	28.5
16	B_4C	500	1.5	10	120	400	0.755 3	0.005 6	536.7645	12053.5	-	-	-	1.188	100.4
17	B_4C	500	1.5	10	48	400	0.752 5	0.002 8	530.8125	5952.0	-	-	-	1.483	124.0
18	B_4C	500	1.5	5	54	400	0.750 9	0.001 6	527.4891	3323.4	3.05	1.20	71	0.740	61.5
19	B_4C	1500	1	10	90	400	0.750 8	0.000 1	527.2621	227.0	1.78	0.16	33	0.030	2.5
20	B_4C	1500	0.5	5	60	350	0.750 8	0.000 0	527.1995	62.6	2.14	0.62	32	0.013	1.0
21	B_4C	1500	0.75	10	61	400	0.750 7	0.000 1	527.0546	144.9	1.73	0.30	33	0.029	2.4
22	B_4C	1500	0.5	15	60	450	0.750 7	0.000 0	527.0143	40.3	1.46	0.21	34	0.008	0.7
23	B_4C	1000	1	10	20	400	0.750 2	0.000 6	525.8511	1163.2	1.25	0.36	79	0.702	58.2
24	B_4C	1500	0.5	10	60	400	0.750 1	0.000 0	525.7991	52.0	1.50	0.31	-	0.010	0.9
25	SiC	8000	1.5	20	63	400	0.750 0	0.000 1	525.5981	201.0	1.28	0.29	21	0.039	3.2
26	SiC	1200	1	10	90	400	0.749 7	0.000 3	524.9663	631.8	1.28	0.25	-	0.085	7.0
27	SiC	1200	1	10	60	400	0.749 4	0.000 4	524.2253	741.0	1.12	0.21	-	0.149	12.4
28	SiC	1200	1	10	60	400	0.749 1	0.000 3	523.5935	631.8	1.50	-	-	0.127	10.5
29	SiC	1200	1	10	32	400	0.749 0	0.000 1	523.3405	253.0	1.03	0.34	-	0.096	7.9
30	B_4C	500	1	10	60	400	0.746 9	0.002 1	518.9581	4382.4	1.11	0.21	-	0.887	73.0
31*	B_4C	500	0.5	10	72	400	0.746 9	0.000 0	518.6084	349.7	1.87	0.27	-	-	-
32	B_4C	1000	0.75	10	60	400	0.745 5	0.001 4	516.1334	2475.0	1.81	0.39	-	0.575	41.2
33	B_4C	1000	0.75	10	76	400	0.744 0	0.001 5	513.0401	3093.3	1.71	0.41	-	0.499	40.7
34	SiC	1200	0.75	10	60	400	0.743 8	0.000 2	512.6371	403.0	1.15	0.17	44	0.082	6.7
35	SiC	1200	0.5	5	60	400	0.743 7	0.000 1	512.4555	181.6	0.90	0.20	-	0.037	3.0
36	SiC	1200	0.5	5	60	400	0.743 6	0.000 1	512.2885	167.0	0.88	0.19	45	0.034	2.8
37	CeO_2	< 5 μm	0.5	5	90	400	0.743 6	0.000 0	512.2783	10.2	0.81	0.14	35	0.001	0.1

* Run not considered due to setup error ** Specific weight of ball: 51.72 g/in^3

Table 6.1 - Batch A Results

Run	Abr. Type	Abr. Size	Load	Abr. Conc.	Time	Speed	Dia.	ΔDia.	Batch Weight	ΔWeight	Avg. Batch Sphericity	Sphericity Std. Dev.	Surface Finish - Ra	MRR	MRR
	Run Parameters						Results								
		(grit)	(N/ball)	(%)	(min)	(rpm)	(in)	(in)	(g)	(mg)	(μm)	(μm)	(nm)	(μm/min)	(mg/min)
0							0.784 9		602.4414		29.38	6.21	-		
1	B_4C	500	1	10	90	400	0.781 9	0.003 1	595.3990	7042.4	5.37	3.33	-	0.867	78.2
2	B_4C	500	1	10	62	400	0.779 5	0.002 3	590.1079	5291.1	4.49	1.65	-	0.952	85.3
3	B_4C	1000	1	10	60	400	0.778 1	0.001 4	586.8681	3239.8	1.91	0.35	-	0.605	54.0
4	B_4C	1000	1	10	58	400	0.777 0	0.001 1	584.3210	2547.1	2.26	0.49	-	0.494	43.9
5	B_4C	1000	1.5	10	45	400	0.776 3	0.000 7	582.7509	1570.1	2.99	1.02	-	0.393	34.9
6	B_4C	1000	0.75	10	66	400	0.775 0	0.001 3	579.8380	2912.9	1.67	0.32	-	0.499	44.1
7	B_4C	1000	0.75	5	60	400	0.774 5	0.000 5	578.7385	1099.5	0.95	0.21	-	0.208	18.3
8	B_4C	1000	0.75	5	61	400	0.773 5	0.001 0	576.5897	2148.8	1.34	0.27	-	0.400	35.2
9	B_4C	1000	0.75	5	75	400	0.772 8	0.000 7	575.0027	1587.0	20	10.00	-	0.241	21.2
10	B_4C	1000	0.65	5	90	400	0.771 9	0.000 9	572.9079	2094.8	1.07	0.32	-	0.265	23.3
11	B_4C	1000	0.65	5	90	400	0.770 7	0.001 2	570.2049	2703.0	1.04	0.19	-	0.343	30.0
12	B_4C	1000	0.65	7	64	400	0.769 8	0.000 8	568.3483	1856.6	1.40	0.24	-	0.332	29.0
13	SiC	1200	0.65	5	55	400	0.769 7	0.000 1	568.0455	302.8	1.21	0.25	-	0.063	5.5
14	SiC	1200	0.75	5	75	400	0.769 6	0.000 1	567.7214	324.1	0.80	0.21	48	0.050	4.3
15	SiC	1200	0.75	5	75	400	0.769 4	0.000 2	567.3327	388.7	0.82	0.35	47	0.059	5.2
16	SiC	1200	0.75	5	75	400	0.769 2	0.000 2	566.9252	407.5	0.74	0.27	45	0.062	5.4
17	SiC	1200	0.75	5	70	400	0.769 0	0.000 2	566.5612	364.0	0.74	0.15	-	0.060	5.2
18	B_4C	500	1.5	8	55	400	0.766 5	0.002 5	561.0844	5476.8	3.16	0.79	-	1.148	99.6
19	B_4C	500	1	20	30	400	0.765 9	0.000 7	559.6171	1467.3	4.50	3.54	-	0.566	48.9
20	SiC	600	0.75	10	125	400	0.763 7	0.002 2	554.8610	4756.1	1.33	0.23	-	0.442	38.0
21	B_4C	500	1.5	10	105	400	0.759 6	0.004 1	546.0550	8806.0	3.37	1.06	-	0.983	83.9
22	SiC	600	0.75	15	120	400	0.757 4	0.002 3	541.1795	4875.5	1.14	0.18	72	0.480	40.6
23	SiC	600	0.75	5	120	400	0.756 2	0.001 2	538.6188	2560.7	1.90	0.58	-	0.253	21.3
24	SiC	600	0.75	10	90	400	0.754 3	0.001 9	534.6688	3950.0	1.26	0.35	86	0.523	43.9
25	SiC	600	0.75	15	60	400	0.752 8	0.001 5	531.4862	3182.6	1.31	0.28	88	0.635	53.0
26	SiC	600	0.5	5	60	400	0.752 1	0.000 7	530.0518	1434.4	1.06	0.25	85	0.287	23.9
27	SiC	600	0.5	15	60	400	0.751 4	0.000 8	528.3841	1667.7	0.88	0.17	120	0.334	27.8
28	SiC	1200	0.5	15	92	400	0.751 2	0.000 2	528.0631	321.0	1.58	0.80	77	0.042	3.5
29	B_4C	1000	0.5	5	60	400	0.750 7	0.000 5	527.0269	1036.2	1.28	0.56	57	0.208	17.3
30	SiC	1200	0.75	15	60	400	0.750 4	0.000 4	526.2707	756.2	1.23	0.43	55	0.152	12.6
31	SiC	1200	0.75	5	60	400	0.750 2	0.000 2	525.9461	324.6	1.02	0.34	41	0.065	5.4
32	SiC	1200	0.45	5	45	400	0.750 1	0.000 1	525.8406	105.5	0.62	0.15	65	0.028	2.3
33	SiC	8000	0.7	5	60	400	0.750 1	0.000 0	525.8121	28.5	0.86	0.30	53	0.006	0.5
34	SiC	8000	0.75	5	60	400	0.750 0	0.000 1	525.5669	245.2	1.27	0.62	64	0.049	4.1
35	SiC	1200	0.7	5	60	400	0.749 9	0.000 1	525.3450	221.9	0.69	0.11	55	0.045	3.7
36	SiC	8000	0.75	10	60	400	0.749 9	0.000 0	525.2658	79.2	1.79	0.63	45	0.016	1.3
37	SiC	10000	1	10	90	400	0.749 9	0.000 0	525.2382	27.6	0.83	0.46	15	0.004	0.3
38	SiC	10000	1	10	90	400	0.749 8	0.000 0	525.1626	75.6	1.89	1.02	12	0.010	0.8
39	SiC	1200	0.5	5	60	400	0.749 7	0.000 1	524.9841	178.5	2.54	1.28	45	0.036	3.0

Table 6.2 - Batch B Results

Run Parameters							Results								
Run	Abr. Type	Abr. Size (grit)	Load (N/ball)	Abr. Conc. (%)	Time (min)	Speed (rpm)	Dia. (in)	ΔDia. (in)	Weight (g)	ΔWeight (mg)	Avg. Batch Sphericity (μm)	Sphericity Std. Dev. (μm)	Surface Finish - Ra (nm)	MRR (μm/min)	MRR (mg/min)
0							0.785 1		602.7771		27.35	10.29	865		
14	B_4C	500	1.5	20	60	400	0.761 7	0.003 7	550.5251	8024.8	-	-	-	1.559	133.7
16	B_4C	500	1.5	10	120	400	0.755 3	0.005 6	536.7645	12053.5	-	-	-	1.188	100.4
13	B_4C	500	1.5	10	60	300	0.765 4	0.001 5	558.5499	3248.0	-	-	-	0.627	54.1
17	B_4C	500	1.5	10	48	400	0.752 5	0.002 8	530.8125	5952.0	-	-	-	1.483	124.0
12	B_4C	500	1.5	5	60	550	0.766 9	0.002 4	561.7979	5331.2	-	-	-	1.024	88.9
18	B_4C	500	1.5	5	54	400	0.750 9	0.001 6	527.4891	3323.4	3.05	1.20	71	0.740	61.5
11	B_4C	500	1	20	60	300	0.769 3	0.002 5	567.1291	5601.8	-	-	-	1.069	93.4
10	B_4C	500	1	10	60	550	0.771 8	0.002 4	572.7309	5394.2	1.77	0.81	-	1.023	89.9
30	B_4C	500	1	10	60	400	0.746 9	0.002 1	518.9581	4382.4	1.11	0.21	-	0.887	73.0
2	B_4C	500	1	5	60	400	0.782 6	0.001 9	597.0251	4354.0	14.28	10.71	93	0.803	72.6
3	B_4C	500	1	5	60	400	0.780 5	0.002 1	592.3178	4707.3	8.14	5.40	-	0.873	78.5
9	B_4C	500	1	5	60	400	0.774 2	0.001 5	578.1251	3475.2	-	-	-	0.655	57.9
1	B_4C	500	0.75	5	60	400	0.784 5	0.000 6	601.3791	1398.0	16.80	3.50	451	-	-
8	B_4C	500	0.5	20	60	550	0.775 8	0.001 3	581.6003	2997.1	-	-	-	0.563	50.0
31	B_4C	500	0.5	10	72	400	0.746 9	0.000 0	518.6084	349.7	1.87	0.27	-	-	-
6	B_4C	500	0.5	10	60	400	0.779 0	0.000 3	588.8361	683.6	-	-	-	-	-
7	B_4C	500	0.5	10	60	400	0.777 1	0.001 9	584.5974	4238.7	-	-	-	0.793	70.6
5	B_4C	500	0.5	5	60	300	0.779 3	0.000 7	589.5197	1602.5	-	-	-	-	-
15	B_4C	500	0.5	5	60	300	0.760 9	0.000 8	548.8180	1707.1	2.23	0.72	-	0.334	28.5
4	B_4C	500	0.5	5	45	300	0.780 0	0.000 5	591.1222	1195.6	9.83	6.08	-	0.297	26.6
23	B_4C	1000	1	10	20	400	0.750 2	0.000 6	525.8511	1163.2	1.25	0.36	79	0.702	58.2
33	B_4C	1000	0.75	10	76	400	0.744 0	0.001 5	513.0401	3093.3	1.71	0.41	-	0.499	40.7
32	B_4C	1000	0.75	10	60	400	0.745 5	0.001 4	516.1334	2475.0	1.81	0.39	-	0.575	41.2
19	B_4C	1500	1	10	90	400	0.750 8	0.000 1	527.2621	227.0	1.78	0.16	33	0.030	2.5
21	B_4C	1500	0.75	10	61	400	0.750 7	0.000 1	527.0546	144.9	1.73	0.30	33	0.029	2.4
22	B_4C	1500	0.5	15	60	450	0.750 7	0.000 0	527.0143	40.3	1.46	0.21	34	0.008	0.7
24	B_4C	1500	0.5	10	60	400	0.750 1	0.000 0	525.7991	52.0	1.50	0.31	-	0.010	0.9
20	B_4C	1500	0.5	5	60	350	0.750 8	0.000 0	527.1995	62.6	2.14	0.62	32	0.013	1.0
26	SiC	1200	1	10	90	400	0.749 7	0.000 3	524.9663	631.8	1.28	0.25	-	0.085	7.0
27	SiC	1200	1	10	60	400	0.749 4	0.000 4	524.2253	741.0	1.12	0.21	-	0.149	12.4
28	SiC	1200	1	10	60	400	0.749 1	0.000 3	523.5935	631.8	1.50	-	-	0.127	10.5
29	SiC	1200	1	10	32	400	0.749 0	0.000 1	523.3405	253.0	1.03	0.34	-	0.096	7.9
34	SiC	1200	0.75	10	60	400	0.743 8	0.000 2	512.6371	403.0	1.15	0.17	44	0.082	6.7
35	SiC	1200	0.5	5	60	400	0.743 7	0.000 1	512.4555	181.6	0.90	0.20	-	0.037	3.0
36	SiC	1200	0.5	5	60	400	0.743 6	0.000 1	512.2885	167.0	0.88	0.19	45	0.034	2.8
25	SiC	8000	1.5	20	63	400	0.750 0	0.000 1	525.5981	201.0	1.28	0.29	21	0.039	3.2
37	CeO_2	< 5 μm	0.5	5	90	400	0.743 6	0.000 0	512.2783	10.2	0.81	0.14	35	0.001	0.1

Table 6.3 - Batch A Results Sorted by Run Parameters

Run Parameters							Results									
Run	Abr. Type	Abr. Size	Load	Abr. Conc.	Time	Speed	Dia.	ΔDia.	Weight	ΔWeight	Avg. Batch Sphericity	Sphericity Std. Dev.	Surface Finish - Ra	MRR	MRR
		(grit)	(N/ball)	(%)	(min)	(rpm)	(in)	(in)	(g)	(mg)	(μm)	(μm)	(nm)	(μm/min)	(mg/min)
0							0.784 9		602.4414		29.38	6.21	-		
21	B_4C	500	1.5	10	105	400	0.759 6	0.004 1	546.0550	8806.0	3.37	1.06	-	0.983	83.9
18	B_4C	500	1.5	8	55	400	0.766 5	0.002 5	561.0844	5476.8	3.16	0.79	-	1.148	99.6
19	B_4C	500	1	20	30	400	0.765 9	0.000 7	559.6171	1467.3	4.50	3.54	-	0.566	48.9
1	B_4C	500	1	10	90	400	0.781 9	0.003 1	595.3990	7042.4	5.37	3.33	-	0.867	78.2
2	B_4C	500	1	10	62	400	0.779 5	0.002 3	590.1079	5291.1	4.49	1.65	-	0.952	85.3
5	B_4C	1000	1.5	10	45	400	0.776 3	0.000 7	582.7509	1570.1	2.99	1.02	-	0.393	34.9
3	B_4C	1000	1	10	60	400	0.778 1	0.001 4	586.8681	3239.8	1.91	0.35	-	0.605	54.0
4	B_4C	1000	1	10	58	400	0.777 0	0.001 1	584.3210	2547.1	2.26	0.49	-	0.494	43.9
6	B_4C	1000	0.75	10	66	400	0.775 0	0.001 3	579.8380	2912.9	1.67	0.32	-	0.499	44.1
9	B_4C	1000	0.75	5	75	400	0.772 8	0.000 7	575.0027	1587.0	20	10.00	-	0.241	21.2
8	B_4C	1000	0.75	5	61	400	0.773 5	0.001 0	576.5897	2148.8	1.34	0.27	-	0.400	35.2
7	B_4C	1000	0.75	5	60	400	0.774 5	0.000 5	578.7385	1099.5	0.95	0.21	-	0.208	18.3
12	B_4C	1000	0.65	7	64	400	0.769 8	0.000 8	568.3483	1856.6	1.40	0.24	-	0.332	29.0
10	B_4C	1000	0.65	5	90	400	0.771 9	0.000 9	572.9079	2094.8	1.07	0.32	-	0.265	23.3
11	B_4C	1000	0.65	5	90	400	0.770 7	0.001 2	570.2049	2703.0	1.04	0.19	-	0.343	30.0
29	B_4C	1000	0.5	5	60	400	0.750 7	0.000 5	527.0269	1036.2	1.28	0.56	57	0.208	17.3
22	SiC	600	0.75	15	120	400	0.757 4	0.002 3	541.1795	4875.5	1.14	0.18	72	0.480	40.6
25	SiC	600	0.75	15	60	400	0.752 8	0.001 5	531.4862	3182.6	1.31	0.28	88	0.635	53.0
20	SiC	600	0.75	10	125	400	0.763 7	0.002 2	554.8610	4756.1	1.33	0.23	-	0.442	38.0
24	SiC	600	0.75	10	90	400	0.754 3	0.001 9	534.6688	3950.0	1.26	0.35	86	0.523	43.9
23	SiC	600	0.75	5	120	400	0.756 2	0.001 2	538.6188	2560.7	1.90	0.58	-	0.253	21.3
27	SiC	600	0.5	15	60	400	0.751 4	0.000 8	528.3841	1667.7	0.88	0.17	120	0.334	27.8
26	SiC	600	0.5	5	60	400	0.752 1	0.000 7	530.0518	1434.4	1.06	0.25	85	0.287	23.9
30	SiC	1200	0.75	15	60	400	0.750 4	0.000 4	526.2707	756.2	1.23	0.43	55	0.152	12.6
14	SiC	1200	0.75	5	75	400	0.769 6	0.000 1	567.7214	324.1	0.80	0.21	48	0.050	4.3
15	SiC	1200	0.75	5	75	400	0.769 4	0.000 2	567.3327	388.7	0.82	0.35	47	0.059	5.2
16	SiC	1200	0.75	5	75	400	0.769 2	0.000 2	566.9252	407.5	0.74	0.27	45	0.062	5.4
17	SiC	1200	0.75	5	70	400	0.769 0	0.000 2	566.5612	364.0	0.74	0.15	-	0.060	5.2
31	SiC	1200	0.75	5	60	400	0.750 2	0.000 2	525.9461	324.6	1.02	0.34	41	0.065	5.4
35	SiC	1200	0.7	5	60	400	0.749 9	0.000 1	525.3450	221.9	0.69	0.11	55	0.045	3.7
13	SiC	1200	0.65	5	55	400	0.769 7	0.000 1	568.0455	302.8	1.21	0.25	-	0.063	5.5
28	SiC	1200	0.5	15	92	400	0.751 2	0.000 2	528.0631	321.0	1.58	0.80	77	0.042	3.5
39	SiC	1200	0.5	5	60	400	0.749 7	0.000 1	524.9841	178.5	2.54	1.28	45	0.036	3.0
32	SiC	1200	0.45	5	45	400	0.750 1	0.000 1	525.8406	105.5	0.62	0.15	65	0.028	2.3
36	SiC	8000	0.75	10	60	400	0.749 9	0.000 0	525.2658	79.2	1.79	0.63	45	0.016	1.3
34	SiC	8000	0.75	5	60	400	0.750 0	0.000 1	525.5669	245.2	1.27	0.62	64	0.049	4.1
33	SiC	8000	0.7	5	60	400	0.750 1	0.000 0	525.8121	28.5	0.86	0.30	53	0.006	0.5
37	SiC	10000	1	10	90	400	0.749 9	0.000 0	525.2382	27.6	0.83	0.46	15	0.004	0.3
38	SiC	10000	1	10	90	400	0.749 8	0.000 0	525.1626	75.6	1.89	1.02	12	0.010	0.8

Table 6.4 - Batch B Results Sorted by Run Parameters

6.2.1 GENERAL DESCRIPTION OF BATCH A

This was the first set of 3/4" balls polished using the large batch MFP system. Prior to this, four batches of 1/2" Si_3N_4 balls were polished and the experience from these was used as a guide for the larger balls. Table 6.5 gives the objectives, results, and some remarks for the runs of batch A. The final results were a sphericity of 0.81 μm (as an average for the batch), with a standard deviation of 0.14 μm, and a surface finish of 45 nm Ra.

Runs five through fifteen served as the tests for Taguchi's method, where the parameters for the highest MRR were determined. These conditions were used later as the base for stages 1a and 1b. The remaining runs were mainly to find the best possible sphericity. As stated earlier, the biggest challenge to this is the inconsistencies with the setup of the apparatus. Several changes to the original design were made throughout this batch and into batch B (as discussed in Chapter 4). This is the reason for the variation in results from different runs with identical run parameters.

6.2.2 GENERAL DESCRIPTION OF BATCH B

Table 6.6 gives a similar outline of the objectives, results, and general remarks for each of the runs for this batch. Some changes to the apparatus were still being made throughout this batch, but the results began to be more consistent by runs 16 and 17. The best average sphericity for a batch was 0.62 μm, with a standard deviation of 0.15 μm. For a single ball, the best results

Run	Objective	Results *	Remarks
	Initial Measurements	Dia 0.785" Sphericity 27 µm (10.3 µm) Ra 865 nm	
1-4	Initial runs B4C-500, 0.5 - 1.0 N/ball, 300 - 400 rpm, 45 - 60 mins	Dia 0.780" Sphericity 9.83 µm (6.08 µm)	
5-15	Test runs for Taguchi method - Parameters used given in Table 5.4		Obtained highest MRR conditions: B_4C-500, 20%, 1.5 N/ball, 400 rpm MRR = 134 mg/min (1.56 µm/min) (or 0.0037" off Dia per 1 hour run)
16-18	To decrease diameter quickly to 0.001" above nominal size of 0.750", using MRR conditions found from Taguchi's method	Dia 0.7509" Sphericity 3.05 µm (1.2 µm)	
19-24	Switched to B_4C-1500 to improve sphericity at lower MRR	Dia 0.7501" Sphericity 1.5 µm (0.31 µm)	0.0001" above allowable diameter
25	Used SiC-8000 to improve sphericity	Dia 0.750" Sphericity 1.28 µm (0.29 µm) Ra 21 nm	Dia is at lowest allowable size with unacceptable sphericity and Ra values. More diameter should be left for improving sphericity (than the 0.001" from runs 16-18). Remaining runs will focus on sphericity and Ra with no regard for diameter.
26-29	Used SiC-1200, 1 N/ball, 10 % abr, to improve sphericity	Dia 0.749" Sphericity 1.03 µm (0.34 µm)	
30-33	Tried to lower sphericity using B_4C-500 & B_4C-1000	Sphericity 1.71 µm (0.41 µm)	Sphericity increased as well as standard deviation
34	Used SiC-1200, 0.75 N/ball, 10% abr, to improve sphericity	Sphericity 1.15 µm (0.17 µm) Ra 45 nm	The more "Gentle" conditions - softer abr, lower loads, with less concentration - seem to give better results. Will decrease these parameters even further during next runs
35-36	Used SiC-1200, 0.5 N/ball, 5% abr, to improve sphericity	Sphericity 0.88 µm (0.19 µm) Ra 45 nm	Sphericity improved significantly; with a batch avg of 0.88 µm and several balls measuring between 0.5 µm and 0.65 µm
37	Used CeO_2, with particle size of < 5 um, and with 0.5 N/ball and 5% abr	Final Dia 0.743" Sphericity 0.81 µm (0.14 µm) Ra 35 nm	Sphericity improved further with this abrasive, as well as with a lower standard deviation. Surface finish is still higher than allowed (of 4-10 nm), but can be improved with a few more runs at these parameters

* Sphericity standard deviation in ( )

Table 6.5 - Outline of Batch A Runs

Run	Objective	Results *	Remarks
	Initial Measurements	Dia 0.786” Sphericity 29.4 μm (6.2 μm) Ra ~ 850 nm	
1-2	Used B_4C-1000 to lower diameter and sphericity quickly	Dia 0.779” Sphericity 4.49 μm (1.65 μm)	
3-12	Used B_4C-1000. Goal is to obtain the best sphericity. Improvements are still being made to apparatus design and setup. MRR not a concern now.	Sphericity 1.4 μm (0.24 μm)	Different results were obtained under same parameters. This is due to setup variations. Main thrust is to standardize this setup.
13-17	Switched to SiC-1200, 0.75 N/ball to further improve sphericity	Dia 0.769” Sphericity 0.74 μm (0.15 μm)	Sphericity improved significantly as well as the standard deviation. Results from runs 16 & 17 were the same at 0.74 μm sphericity, with equal MRRs also; indicating that the setup and design are becoming more consistent. With the remaining runs, the ideology is to essentially start the process over, returning to Stage 1 to quickly decrease the diameter, followed by Stage 2 parameters for lower MRRs and improvements in sphericity
18-19	Switched back to B_4C-500 to quickly decrease diameter	Dia 0.766” Sphericity 4.5 μm	
20	Used SiC-600 to improve sphericity	Dia 0.764” Sphericity 1.33 μm (0.23 μm)	Used SiC-600 for the first time. Proved to be good for Stage 1b
21	Switched back to B_4C-500 since there’s still 0.014” to remove from the diameter. SiC-600 would require too many runs to be practical for this Stage 1a	Dia 0.760” Sphericity 3.37 μm	Sphericity again increased
22-27	With a diameter of 0.760”, this marks the end of Stage 1a processing and begins Stage 1b – using SiC-600 for improving sphericity at moderate MRRs	Dia 0.7514” Sphericity 0.88 μm (0.17 μm)	End of Stage 1b processing. Good final results for this stage
28-32	Stage 2a: Using SiC-1200 for improved sphericity at low MRR. Abr: 5-15%, Load: 0.45-0.75 N/b	Dia 0.7501” Sphericity 0.62 μm (0.15 μm) Ra 65 nm	End of Stage 2a processing. Good final results for this stage
33-34	Stage 2b: Using SiC-8000 to further improve sphericity as well as Ra. 5% abr & 0.7-0.75 N/ball	Dia 0.7500” Sphericity 1.27 μm (0.62 μm) Ra 64 nm	Sphericity increased with no improvements in Ra.
35	Switched back to SiC-1200 to recover sphericity (Stage 2a conditions)	Dia 0.7449” Sphericity 0.69 μm (0.11 μm) Ra 55 nm	Diameter fell below 0.750”, Sphericity and Ra improved. Remaining runs will focus on sphericity and Ra, with no regard for diameter
36	Switched back to SiC-8000 again to improve sphericity and Ra (Stage 2b conditions – as in runs 33-34)	Sphericity 1.79 μm Ra 45 nm	Sphericity again increased. May have problems with this abrasive
37-38	Switched to SiC-10,000	Sphericity 1.89 μm (1.02 μm) Ra 10-12 nm	Sphericity again increased
39	Tried SiC-1200 to recover sphericity	Final Dia 0.7497” Sphericity 2.54 μm (1.28 μm) Ra 45 nm	Stopped runs for this batch

* Sphericity standard deviation in ( )

Table 6.6 - Outline of Batch B Runs

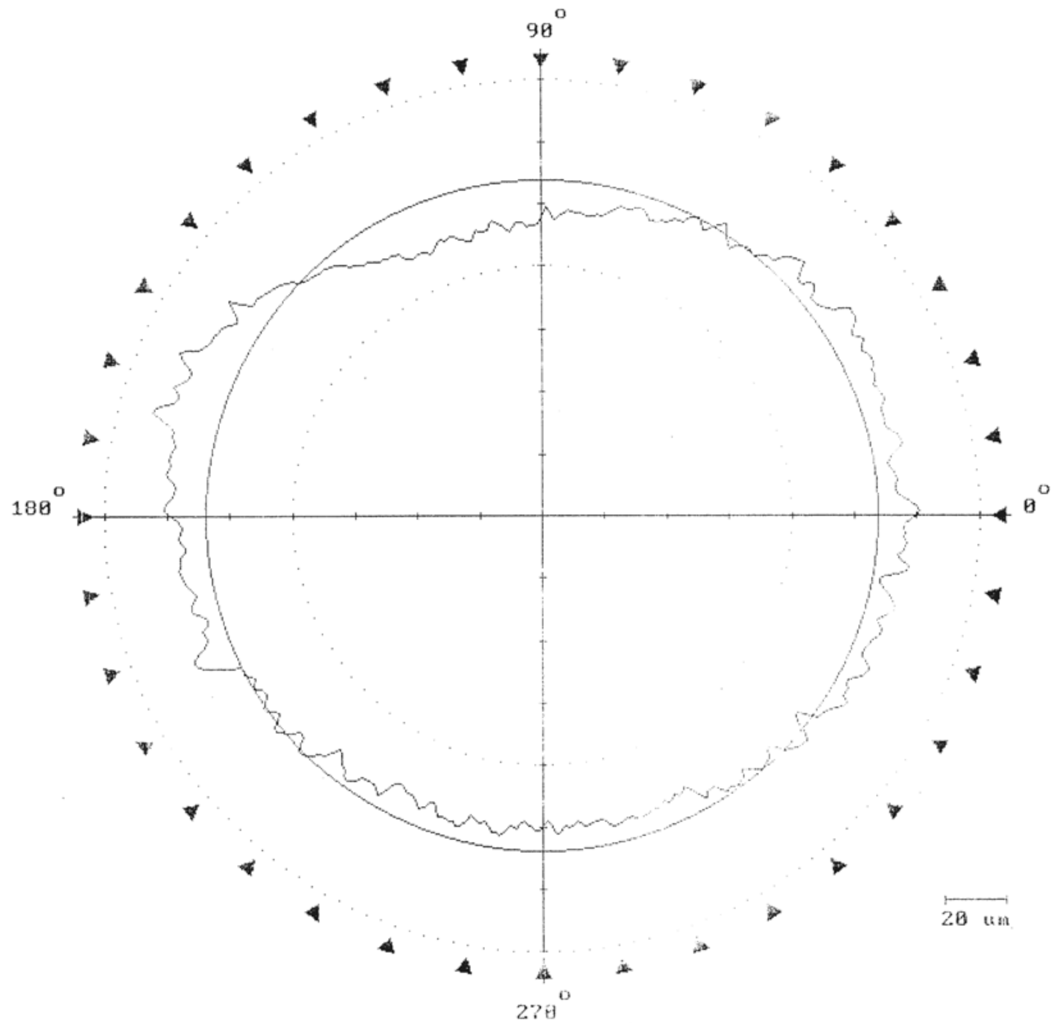


Figure 6.1 - Initial Sphericity Profile (As-received Condition)
Sphericity: 38.15 μm

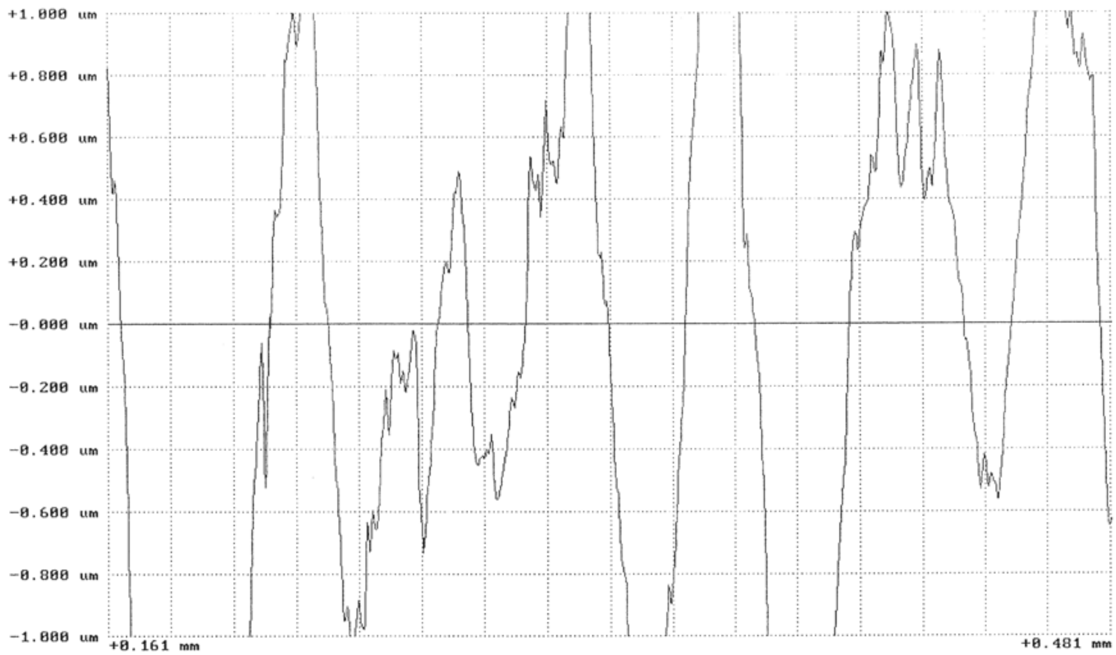


Figure 6.2 - Initial Surface Finish Profile (As-received Condition)
Surface Finish: 909.8 nm

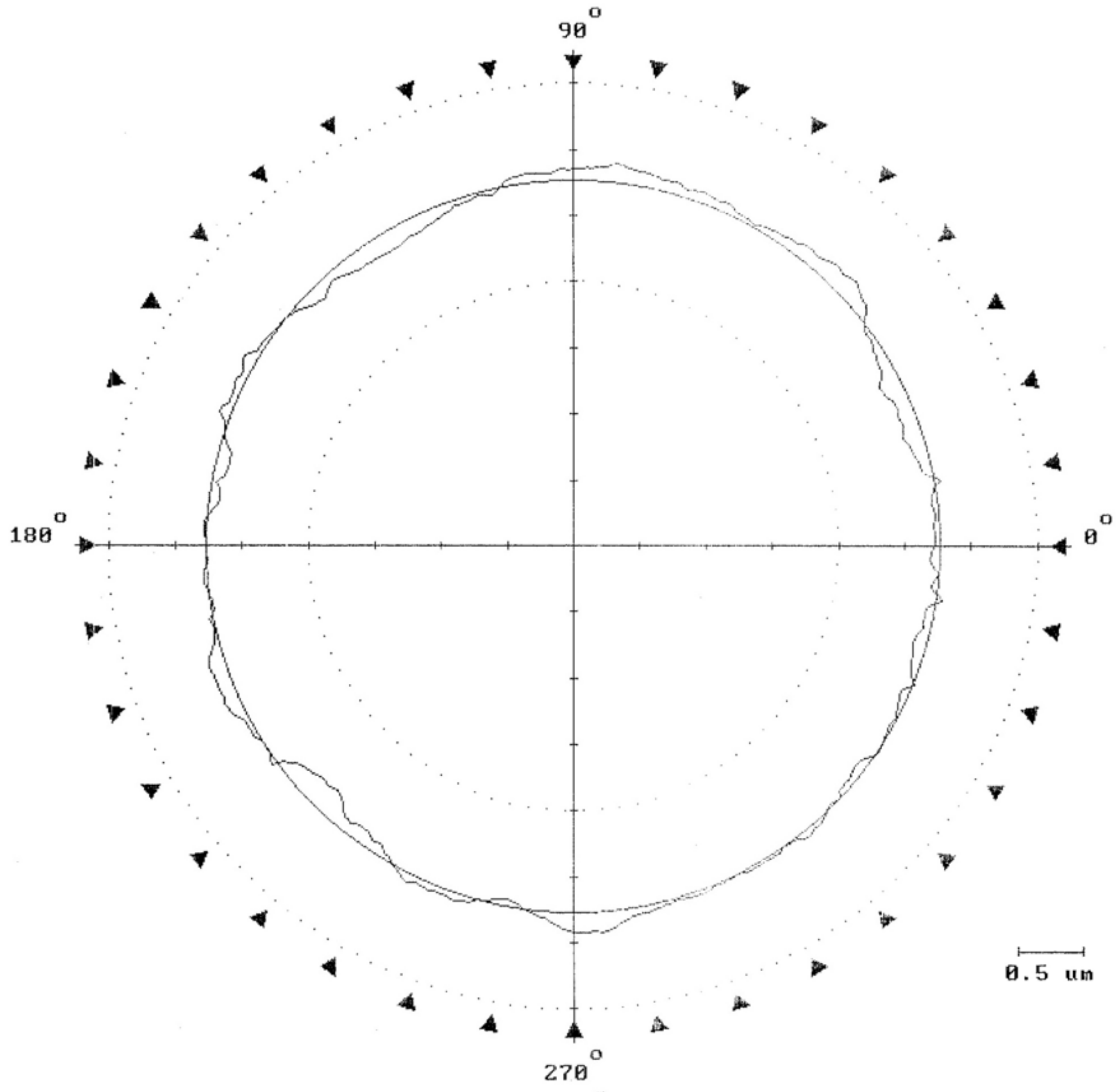


Figure 6.3 - Profile of Best Sphericity Obtained (Batch B, Run 37)
Sphericity: 0.35 μm

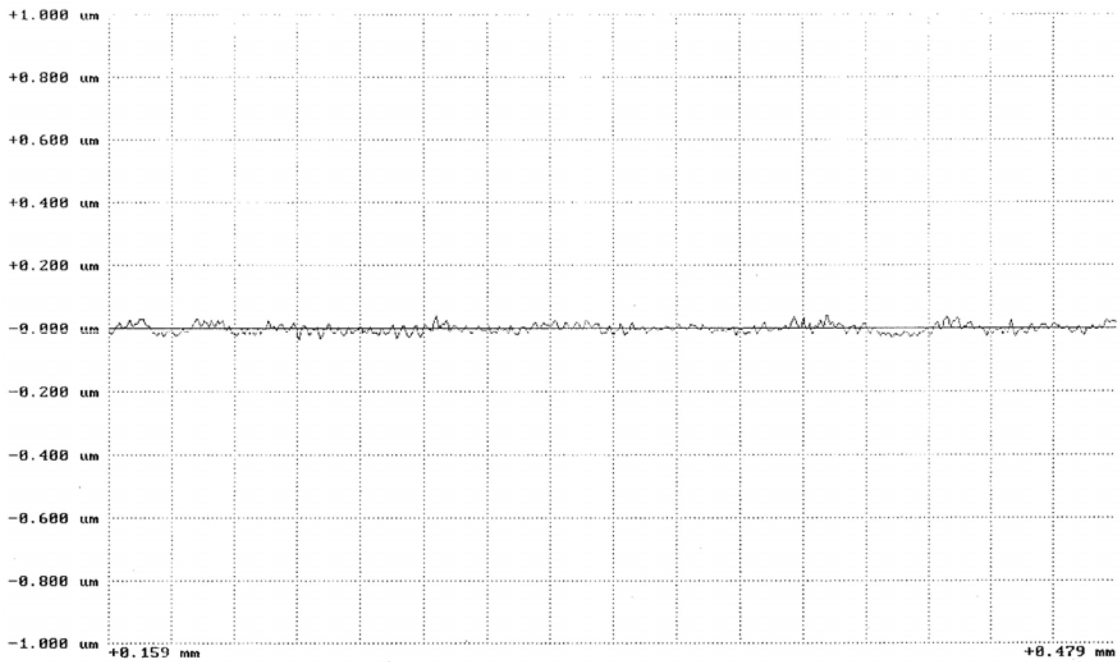


Figure 6.4 - Profile of Best Surface Finish Obtained (Batch B, Run 38)
Surface Finish: 10.6 nm

obtained was a sphericity of 0.35 μm and a surface finish of 10.6 nm Ra, as shown in Figures 6.3 and 6.4 respectively, along with the as-received sphericity profile in Figure 6.1 and as-received surface finish profile in Figure 6.2.

6.3 EFFECT OF PARAMETERS ON SPHERICITY, SURFACE FINISH, AND MRR

The parameters used were given above in Table 5.1 and are discussed here as to their significance to the final results.

6.3.1 ABRASIVES

The abrasives used are boron carbide (B_4C), silicon carbide (SiC), and cerium oxide (CeO_2), with particle sizes ranging from < 5 μm in diameter to 10,000 grit. Concentration level for these varied from 5 to 20% - by volume. In general, the harder, larger abrasives are most effective for high material removal rates, while softer, smaller abrasives tend to produce better surface finishes and sphericities. The abrasive-grit combinations that proved to be most significant are as follows:

- **B_4C-500** gives the highest MRR (greater than 133 mg/min, or 0.008 inches removed from the diameter per run), and is suited for the initial "roughing" - stage 1a. But there seems to be a limit to the sphericity obtainable: ~1 μm sphericity and ~70 nm Ra surface finish.
- **SiC-600** gives good MRR (up to 53 mg/min - in this study), with better sphericity: limits ~0.88 μm sphericity and 70 nm Ra surface finish.

Therefore this combination would be adequate for stage 1b polishing where MRR is a concern followed by sphericity as a second priority.

- **SiC-1200** gives lower MRR (maximum ~12 mg/min), but with the best sphericity obtained during this study: 0.35 μm for a single ball and 0.62 μm for an entire run average.
- **SiC-8000** damaged the roundness when used. This could be the result of either a poor combination with other parameters (load, speed, etc.) or contamination with other abrasives.
- **SiC-10000** gave a very good surface finish (~10 nm Ra), but it also damaged the roundness. This could be from the same reasoning as with SiC-8000.
- **CeO_2** improved both the sphericity and the surface finish. The MRR was extremely low, ~0.1 mg/min, and so is useful only for the final stage of polishing (stage 3). For optimal use this abrasive should be used after the balls have reached a surface finish of 10 nm Ra or less and when an acceptable sphericity has already been reached (it shouldn't be relied on to improve the sphericity more than ~0.05 μm)

The abrasives of interest as they apply to the five stages of polishing are:

- Stage 1a: B_4C-500
- Stage 1b: SiC-600
- Stage 2a: SiC-1200
- Stage 2b: SiC-1200
- Stage 3: CeO_2 (< 5 μm size particles)

Regarding abrasive concentration level, the results from Taguchi's method show that increasing the volume percent of the abrasive will result in an increase in MRR. This is shown in Figure 5.1b and is verified throughout the polishing results of both batches. For final stages, where sphericity is more important, lower concentrations have proven to give better results. In batch A, runs 34 through 36, it is seen that decreasing only the concentration caused the sphericity to decrease by 0.37 µm. This is also the case with surface finish. Decreasing the concentration gives better finish. Batch B, runs 30 and 31 is one example.

6.3.2 LOAD

Taguchi's method also showed that increasing the load causes the MRR to increase (Figure 5.1a). The higher loads are also better for improving surface finish; but lower loads tend to give better sphericities. This is seen in the present results and is also the same conclusions reached by previous researches (Jaing, 1998; Raghunandan and Komanduri, 1997). Therefore at final stages, the load must be chosen carefully in order to improve both. For this reason, the 0.75 N/ball load was used as a compromise during intermediate stages.

6.3.3 SPEED

Figure 5.1c shows the results of Taguchi's method based on speed. Here it is shown that a speed of 400 rpm is optimum for highest MRR. This corresponds fairly well with the results. Also, 400 rpm seemed to give the best sphericity, based on some initial runs. So, this speed was chosen for the remainder of the research - from batch A, run 23 onward.

Jaing (1998) investigated thoroughly the effect of speed on surface finish with the conclusions that higher speeds give better surface finish values. At lower speeds it is believed that the type of material removal mechanism is 3-body abrasion; where the abrasives cause pitting on the surface of the ball - or a "fracture and remove" process. As the speeds increase the mechanism shifts to 2-body abrasion; where the abrasive particles become embedded in the spindle and cause uniform scratching over the ball surfaces, resulting in a better finish.

6.3.4 DURATION

The results show that the MRR decreases with run duration. And so under similar conditions, a run with a duration of 60 minutes will have a higher MRR than one running for 90 minutes; although the amount of material removed is still greater for the latter. For this reason initial stages should be allowed to run longer in order to remove as much material as possible per run. This conserves consumables, such as magnetic fluid, floats, abrasives, liners, etc., as well as decreases the number of runs and overall time needed to polish a batch. An appropriate duration for initial stages is 180 minutes.

For later stages the duration should be lower - 90 to 120 minutes for intermediate stages and 45 to 75 minutes for final stages. This is due to the sludge buildup at the bottom of the chamber as material is removed from the ball. It is thought that the sludge builds up unevenly and causes the float to become tilted with respect to the chamber base. This directly effects the circulation of the float and balls and the forces acting on them; which degrades the sphericity. Other factors are also involved which change with duration including viscosity of the magnetic fluid, the wear of the spindle, float, and liner, temperature of fluid, and concentration level of the abrasive - due to the evaporation of the water from the magnetic fluid. Therefore, for these reasons, it is best to lower the duration from stage to stage of polishing.

6.4 ON MATERIAL REMOVAL RATE

The effect of various parameters on the MRR has been reviewed in the previous sections. In general, high MRRs are desired during initial stages and low MRRs in the final stages, since it corresponds directly to the quality of the results obtained. Aggressive conditions give high MRR but poor sphericity and finish; while softer, more "gentle" conditions give lower MRR but better sphericity and surface finish. Figure 6.5 gives the ranges of MRRs for the abrasives and grit sizes used; the other parameter of load, speed, concentration, and duration are not factored out.

6.5 ON DIAMETER

Obtaining the diameter according to the AFBMA specifications is quite challenging. Having a good source of data on the MRRs for different abrasive-load-speed-duration combinations is the key. While B_4C, 500 grit, can remove greater than 0.006 inches from the diameter per run, less aggressive conditions such as SiC, 10000 grit, can polish for 60 minutes with hardly any noticeable change in diameter. The major difficulty lies in getting to the correct diameter, roundness, and surface finish simultaneously. To accomplish this, all three must meet certain milestones during the polishing sequences (stage-to-stage). If not, for instance, if at stage 3 the sphericity is still at 1 μm with less than 0.0001 inches remaining to be removed from the diameter, it will be impossible to obtain a sphericity below roughly 0.8 μm using any combination of conditions. A good plan must therefore be mapped out beforehand.

6.6 RECIPE FOR POLISHING

Based on the data gathered throughout this study, the procedure shown in Table 6.7 is suggested for polishing a batch of 46, 3/4" balls.

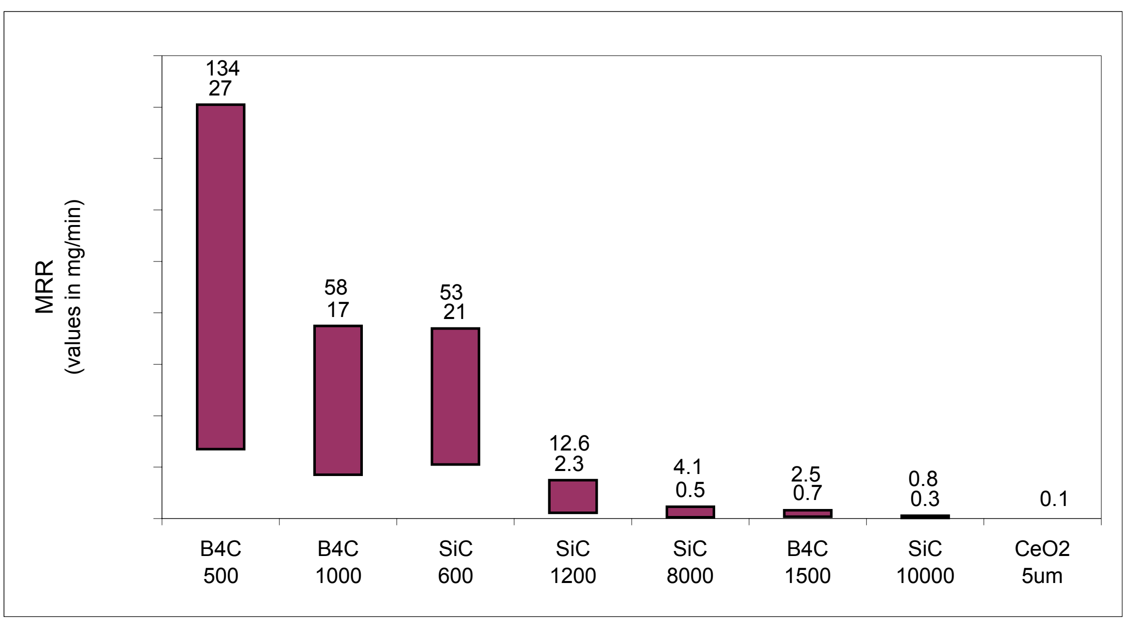


Figure 6.5 - Ranges of MRR for the Abrasive-Grit Size Combinations Used

		Run Parameters **					Expected Results			
Stage	Run	Abr. Type	Abr. Size *grit*	Abr. Conc. *%*	Load *N/ball*	Duration *min*	MRR *mils/run*	Final Dia. *in*	Final S.F. *Ra (nm)*	Final Sphericity *μm*
Stage 1a	1-4	B_4C	500	20	1.5	180	0.007	0.757	< 100	< 10
Stage 1b	5-6	SiC	600	10	0.75	120	0.002	0.753	80-90	0.9 - 1.0
	7-8	SiC	600	10	0.75	60	0.001	0.751	70-80	0.8 - 0.9
Stage 2a	9-13	SiC	1200	5	0.45	60	0.00015	0.75025	40-50	0.35 - 0.45
Stage 2b	14-15	SiC	1200	5	0.45	45	0.0001	0.75005	40-50	$\leq$ 0.35
Stage 3	16-20 *	$Ce0_2$	< 5 um	5	0.5	90	-	0.75	4-10	$\leq$ 0.35

* Approximate ** Speed constant at 400 rpm

Table 6.7 - Procedure for Polishing

CHAPTER 7

CONCLUSIONS

This investigation focused on the use of the large batch magnetic float polishing (LBMFP) apparatus to polish Si_3N_4 balls to the best possible sphericity and surface finish. Two batches of 46, 3/4" balls have been polished and the results reported. With the first batch serving as a bench mark for determining the material removal rates, sphericity, and surface finish obtainable with the various parameters involved (load, speed, time, abrasive); the second batch served as a trial using this data to polish under optimum conditions.

The best results achieved were a batch average sphericity of 0.62 μm and 12 nm Ra surface finish. For a single ball, the best results were 0.35 μm sphericity and 10 nm Ra surface finish. This is equivalent to a grade 16 ball , per AFBMA standards; and is not quite at the highest quality level, of say grade 3, or 0.08 μm sphericity.

The conclusions reached for this study indicate that the most significant variables affecting the results, mainly sphericity, is the setup variances of the spindle and chamber. The eccentricity between the spindle-chamber and the tilt of the chamber and spindle with respect to the horizontal plane are considered the most damaging to the sphericity results.

During this study the majority of effort has been devoted to improving the setup of these two components. A self-aligning method was initiated which enabled true alignment between the spindle and the chamber. Following this, a leveling plate was added which aligned the planes of the spindle and chamber. Additional improvements include the newer design of the chamber, to guarantee true roundness, and the addition of the machining post, which allowed for the spindle to be re-machined in place and therefore guaranteed true coaxialty between the CNC axis and spindle (which reduced vibrations considerably). As a result of these improvements, more consistent results were obtained for MRR, sphericity, and surface finish for a particular set of run parameters.

The effects of these can be seen when comparing results of similar run conditions at the beginning and end of the two batches. Initially, during batch A, runs with similar parameters would produce drastically different results, mainly in terms of sphericity. The ideology at this point was that the first step to take to improve results was to study the system, and make any necessary changes, in order to be able to better control the output. With the setup being such a major variable in the results, the effects of different parameters could not be completely relied upon.

With the changes mentioned being made, during the final runs of Batch B, runs under similar conditions gave very close results. This is considered the largest accomplishment of this research, and is only the first step in realizing the capabilities of this large batch system.

The information gathered shows the tolerances allowed for the chamber-spindle setup - shown in Table 7.1.

	Tolerance Used
Chamber Tilt	< 0.01 degrees
Chamber/Spindle Eccentricity	Considered fully aligned with self-aligning method
Chamber Roundness	< 0.003 inches out of roundness (the limiting factor during this study was the polyurethane liner which had a thickness variation of ~0.003")
Spindle Coaxialty to CNC Axis	< 0.0001 inches under static conditions

Table 7.1 - Setup Tolerances Used for Chamber and Spindle

Although these improvements are substantial, the process of setting up the system for a run is still an "art", and, to a large degree, dependent upon the researchers craftsmanship; and therefore there are still inconsistencies involved. Minimizing this, and creating a "foolproof" setup procedure, would greatly reduce these inconsistencies. This would allow a more in-depth study of the parameters involved and their effects. With most of the work of this research devoted to the hardware and system setup, it is certain that far better results can be achieved by optimizing the run parameters.

The results obtained during this research along with the advantages and disadvantages of the LFMFP technology are listed below.

Advantages:

- MRRs of 134 mg/min (1.56 μm/min) allow a batch to be polished in 21 runs or less
- Sphericity of 0.35 μm and surface finish of 10 nm obtainable

Disadvantages:

- High cost of magnetic fluid presents biggest drawback
- The process is labor intensive, requiring 2-3 hours of setup and characterization time per run, with a 3 person team

Future Considerations:

- More effort should be devoted to developing "fool proof" techniques for aligning the spindle and chamber - both coaxially and parallel, since these are thought to be most damaging to sphericity. This would reduce the variations in results
- Process variables should be investigated further. Roundness could be further improved based solely on better conditions. (There was contamination with B_4C-1500, and possibly SiC-8000 and SiC-10000 grit, which prevented their use. These seem to be the ideal abrasives to use)

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