FINISHING OF GLASS BALLS BY CHEMICAL MECHANICAL POLISHING (CMP) USING CERIUM OXIDE – EXPANDING THE PROCESS CAPABILITIES OF MAGNETIC FLOAT POLISHING (MFP) TECHNOLOGY

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PREFACE

Finishing of brittle materials requires the use of “gentle” conditions that result in minimal or no surface and subsurface damage. Conventional polishing processes make use of diamond and other hard abrasive materials, which leads to scratching and brittle fracture on the surface. While some scratches can be extremely fine, others can produce micro-cracks that could further lead to catastrophic failure of the brittle work material. This is so especially in the case of the glass finishing process where the parameters used (abrasive, polishing load, etc.) should be gentle enough to avoid brittle fracture of the surface.

Magnetic Float Polishing (MFP) technology is most suitable for finishing hard and brittle materials, like ceramics and glasses. It is a “gentle” finishing process that offers flexibility and a wide range of process capabilities. This investigation stresses an extension of this technology to finish glass spheres. Due to its excellent optical properties, finished sections of glass balls are widely used in optical and medical instruments, lenses, laser and fiber optics. Glass can achieve an excellent surface finish and is also chemically resistant to a variety of materials. The finished surface of glass can provide a good seal and, hence, glass balls find wide applications in valves, pumps, flow meters, liquid dispensers, and also in special ball bearings. It is through technological

advancements in chemical mechanical polishing (CMP) that the achievable level of surface finish and other parameters, such as form and sphericity, can be improved significantly.

In this investigation, a methodology for finishing glass balls, MFP, with a high level of surface finish is developed. The Taguchi technique is used to determine the optimum polishing conditions for best finish and to analyze the influence of individual parameters and their levels on the polishing process.

Three distinct stages in the polishing process are identified as: the first stage with emphasis on material removal rate but low surface and subsurface damage, the second semi-finishing stage with reasonable material removal rates with control over size and sphericity with again minimal or no surface damage, and the third stage of final finishing involving CMP using softer (relative to hardness of glass) cerium oxide abrasive. The use of polishing pad (lap) is introduced into the MFP system that will improve the surface finish of the glass balls significantly. Surface finish - average roughness, Ra, of 10 nm (= 100 A° as measured by Talysurf - characterization length of 1.5 mm) or 4.3 nm Ra (= 43 A° as measured by AFM) can be obtained using a chemically resistant synthetic polishing pad with proper combination of other process parameters derived from the Taguchi experimental design.

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The experimental work was jointly conducted with Mr. Naga Chandrasekaran. The surface characterization of the glass balls, as well as the analysis of the results derived from the Taguchi experimental design, was performed individually for comparison. I am grateful to him for his valuable discussions and help as a research team partner.

I am thankful to Dr. Jiang Ming and Mr. Peijun Cao, former research assistants at MAERL, OSU, for sharing their experiences and teaching me the basics of the magnetic float polishing (MFP) technology. I would also like to thank my colleagues Mr. Ashok Lakshmanan and Mr. Srihari Rao for their co-operation and help.

On a personal note, I wish to acknowledge the support and encouragement of my family at all times. I am also grateful to my colleagues and friends at MAERL.

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Chapter 1

Introduction

Due to its excellent optical properties, sections of finished glass balls are widely used in optical and medical instruments, lenses, laser and fiber optics. Glass can achieve an excellent surface finish and is also chemically resistant to a variety of materials. The finished surface of glass can provide a good seal and, hence, glass balls find wide applications in valves, pumps, flow meters, liquid dispensers, and also in special bearings. It is through modern technological advancements that the achievable level of surface finish and other parameters, such as sphericity, can be improved significantly.

Figure 1.1 Finished Glass Balls

Finishing of glass balls in industry is done using conventional lapping and polishing methods, where material removal is generally by brittle fracture. This often leads to surface and subsurface damage that can further cause catastrophic failure of the finished glass balls.

Generally, the initial stages of roughing and semi-finishing require high material removal rates. The higher the material removal rate, the faster is the process of finishing the product to its final dimensions. The industry practice is to use high loads and harder abrasives, like diamond, which can damage the workmaterial. Though reasonable form accuracy and surface finish are achieved by this process, it is not quite suitable for glass. The finishing time is generally long because of the severe abuse in the initial roughing stages for high material removal. It takes a few days, sometimes several weeks to finish the glass balls. For this reason, as well as the high cost of diamond abrasive used, the cost of finishing is high.

The current technology offers commercial manufacturers a process and methodology to finish glass balls to grades 48V, 100V, 200V and 500V. Grade 48V requires, apart from other parameters, sphericity value of 1.2μm and a surface roughness (Ra) value of 76nm.

The present study deals with the development of the MFP technology that is better suited for finishing glass balls. MFP technology was used successfully for finishing silicon nitride ceramic balls as well as other brittle materials. MFP offers a wide range of process capabilities and can be extended to finish other brittle materials, like glass.

In MFP, the loads used for polishing are extremely small (of the order of 1N/ball or less) and the abrasives used for the final finishing are softer than the work material. In addition, the float offers great flexibility to the polishing system i.e. the work material, polishing shaft, and abrasive slurry. As discussed in the following chapters, the float supports the work material against the load applied by the polishing shaft, by imparting buoyancy forces caused by the magnetic fluid. Freedom of controlled movement in the vertical plane allows the float and the work material to adjust to any excessive forces or vibrations. This phenomenon can be compared to a spring-loaded mechanism, eg. a shock absorber.

These features make the MFP a "gentle" finishing process offering least amount of surface and sub-surface damage. Thus, investigation of the potential of the MFP technology indicates possible expansion of the technology to various brittle work materials, like glass. Finishing of brittle materials requires the use of gentle conditions that result in minimal or no surface and subsurface damage. Especially, in the case of glass, the finishing process and its parameters (abrasive, load, etc.) should be gentle enough to avoid excessive scratching of the surface.

The present investigation deals with developing a methodology for finishing glass balls by MFP with a high level of finish and form accuracy. The Taguchi method is implemented to determine the optimum polishing conditions for good finish, high removal rate, and good sphericity, to analyze the influence of individual parameters and their levels.

Three distinct stages in the polishing process are identified, the first stage with emphasis on high material removal rates and low surface and subsurface damage; an intermediate semi-finishing stage with minimum damage as well as correcting for any damage from the previous stage, also to control and strictly monitor sphericity and surface roughness; and a final finishing stage for good sphericity and finish with minimum or no damage. The final stage involves CMP using softer (relative to hardness of glass) cerium oxide abrasive.

The concept of polishing pad (lap) is introduced into the MFP system that very much improves the surface finish of the glass balls. A surface finish of 10 nm Ra (=100A° as measured by Talysurf - characterization length of 1.5mm) or 4.3nm Ra (=43A° as measured by AFM) is obtainable with the use of a chemically resistant synthetic polishing pad.

Chapter 2

Literature Review

The present study involves CMP of glass balls using MFP technology. Hence, CMP and MFP are also discussed in this chapter. A brief historical review is presented that gives the status of the basic understanding of the process and it's various components and parameters. Also, the apparatus used at Oklahoma State University in previous years was rather simple without complex controls. An attempt is made to trace the process development over the years, beginning from the early 1940s, when the initial patents were issued.

2.1 Ball Lapping/Polishing Technology:

Finishing of spherical objects was known to man from several centuries due to the extensive use of these objects as rolling elements and aesthetic components. It was only in this century that machines were developed to finish objects in spherical form to a high level of finish characterized by good surface roughness (low values of Ra and Rt) and good sphericity (low values of out-of-roundness). Finishing of spherical blanks requires precise and controlled material removal, such that sphericity is further improved. This can be achieved by the proper rolling motion of the balls during grinding and subsequent polishing.

The basic method in grinding and polishing or lapping of spherical objects is that the spheres are processed in between two plates that have relative rotational motion. The plates are horizontal in certain types of ball lapping machines, or vertical, or inclined at an appropriate angle. The material removal rates and other parameters can then be controlled by selecting proper levels of variable parameters like load on the plates, rotational speed of the plates, type and volume percent of abrasives, ball material to be finished, abrasive slurry medium, etc. In the following, selected patents are discussed that relate to the ball finishing technique and disclose the apparatus used for the same.

The figures are derived from the actual patents, in which several parts of the apparatus are labeled and numbered. However, in the following description, only the main parts are mentioned. For detailed description of the patents and drawings, the actual patent can be read.

US Patent No. 3,924,356, issued to Kitchel in December 1975, discloses a methodology to grind and polish beads and marbles. The apparatus is shown in Figure 2.1. It is simple, consisting of upper and lower wear plates (numbered 40 and 42 in Figure 2.1) in between which balls of generally spherical shape (item 50 as in Figure 2.1) and the abrasive slurry (item 52) are placed. These wear plates are rotated relative to each other. A drag sleeve (54) that is concentric to the center shaft (46), that holds the upper wear plate, adjusts the clearance between the plates. This clearance is set to the finished diameter of the ball at every stage. The end point of any finishing stage is detected once the set diameter is reached as, at that time, the upper wear plate would rest on the sleeve causing no grinding/polishing action.

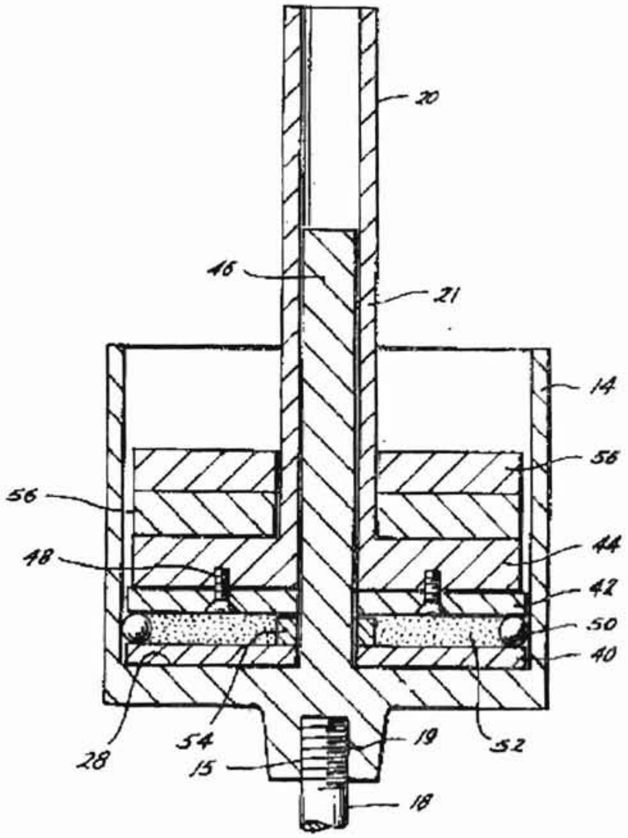


Figure 2.1 Schematic of Grinding/Polishing Apparatus

(US Pat.No. 3,924,356 to Kitchel)

Before this invention, crown bead mill was used for grinding and polishing of the balls. The device is mounted on six coil springs and does not rotate, while a center shaft rotates the upper wear plate. However, the device had some limitations and disadvantages. The main disadvantage being that the abrasive slurry collects in the center due to the spring action and the rotation of the upper wear plate, while the balls collect around the periphery due to centrifugal forces. Hence, the grinding and polishing actions are not very effective. Also, the grinding action is not even.

The device disclosed in this patent causes both the abrasive slurry and the balls to be moved radially outward such that the polishing zone is restricted, with both the workpiece and the abrasive remaining in contact throughout the operation. In the initial roughing stages, 80-120 mesh carborundum grit is used as the abrasive. Weight disks are placed on the upper wear plates that provide the grinding load. As the grinding proceeds, finer and finer abrasive grit is used until a desired diameter and form is reached for the balls. The chamber (14) is then cleaned, the sleeve is removed and the wear plates are replaced by leather disks. Aluminum oxide or cerium oxide is used for polishing, depending on the hardness and density of the balls. Normally, the polishing process takes about two hours.

Akahane et al. developed a polishing device to polish the surface of hard bodies of metals, rock, glass, and plastics into a perfectly spherical shape. It is disclosed in US Pat. No. 3,961,448, issued on June 8, 1976. The device could also be used to polish lenses and other concave and convex objects. Figure 2.2 shows the apparatus.

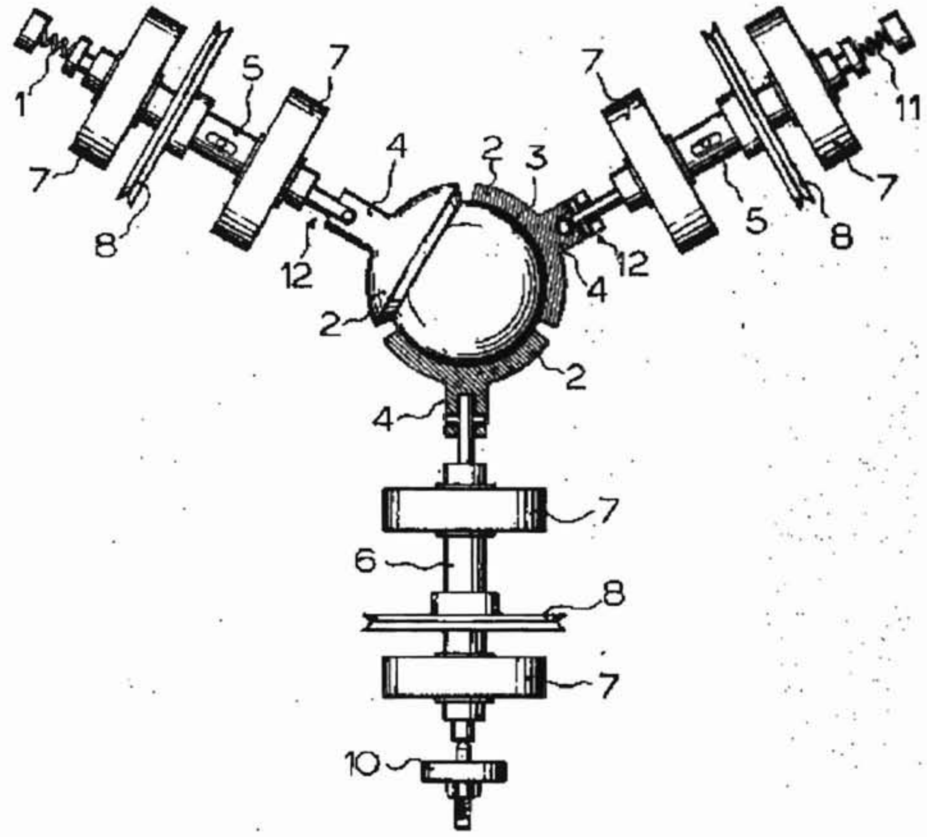


Figure 2.2 Sphere Polishing Device

(US Pat. No. 3,961,448 to Akahane)

The device mainly consists of three identical polishing dishes (item 2 in Figure 2.2) that are connected to three shafts (5 and 6) journaled in bearings (7), for rotation and movement in the axial direction. These shafts are positioned along three lines radiating from one point, which is also the center for the polishing device/system. The shafts are separated by an angular interval of 120° respectively. A circular brim, a concave dish surface and a dish holder constitute the polishing dish. The sectional arc of the concave dish has a central angle of less than 120°. One of the three polishing dishes is fixed to the rotating shaft, whereas the other two dishes can swing slightly at their ends where they are fixed to the shafts. A spherical object, to be polished, is placed between the three polishing dishes such that its center is coincides with the converging center of the dishes. The polishing dishes are rotated at different speeds, to obtain uniform polishing of the spherical workpiece producing perfect spheres. The rotation rates depend upon the workpiece material and its diameter. Suitable abrasives are used to form the slurry.

US Patent No. 4,965,967 issued to London in October 1990 discloses an apparatus for low stress polishing of spherical objects. The apparatus consists of two plates parallel to each other with a clearance between them to place the spherical objects to be polished. Figure 2.3 shows the polishing device.

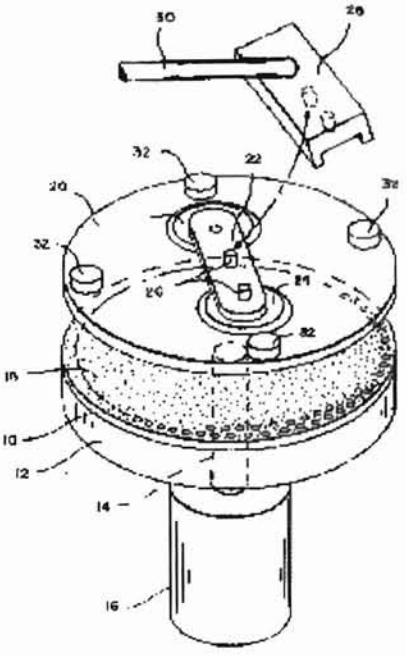


Figure 2.3 Apparatus for Low Stress Polishing of Spherical Objects

(US Pat. No. 4,965,967 to London)

The face of the plates is smooth. The top plate is made of ceramic material and includes a transparent plate, so that the process can be monitored even by viewing. There are radially concave grooves on the top plate, in which the balls to be polished can be mixed during polishing. The bottom plate is rotated to cause polishing action. Magnets are placed on the top plate to restrict the motion of the balls out of the polishing zone. Thus, it limits the path of travel as the bottom plate rotates. The magnets also help in keeping the balls within the polishing chamber. Metal balls, YIG (Yttrium-Iron-Garnet) crystals, and the like can be polished using a slurry consisting of glycol mixed with fine diamond powder.

The polishing load used is very low of the order of several hundred grams. The rotational speeds of the polishing plates are also low, ranging from 5-60rpm. One polishing lot holds up to 500 to 3000 balls, depending upon the ball blank diameter. The magnets used in this device create a magnetic field over the balls, which promotes ball rotation around an infinite number of axis, redistributes the balls randomly relative to their radius from the center of the lapping plate. Thus, a uniform polishing is affected, giving a superior degree of sphericity. Also, since all the balls travel the same distance in the lapping process, the diameter of the polished balls remains highly uniform. The polishing process allows the system to be tolerant of balls that are divergent from the norm (e.g. smaller, larger, high level of out-of-roundness). The polishing action is more on balls that are larger in diameter, and less on those that are smaller in diameter. This continues until all the balls are of the same diameter and sphericity. This results in non-breakage of balls in the grooves during the process. Thus, further damage to other good balls is also avoided. Compared to the previous device, the removal rates are very low, which acts in favor of the polishing process with respect to more than just the gentle polishing conditions (namely - finer abrasives, low loads and speeds, enhanced random motion). The polishing process can be carried on continuously for 24 hours with considerably less operator attention. In this way, the average time to complete a lot decreases from 23 to 10 days.

Figure 2.4 shows the conventional ball-lapping machine as described in US Pat. No. 5,301,470. The lapping plates (1 and 2) are vertical. The plate 2 is stationary and facilitates loading and unloading of balls 3 and abrasive slurry into the grooves (5). The plate 1 rotates causing the balls to be lapped.

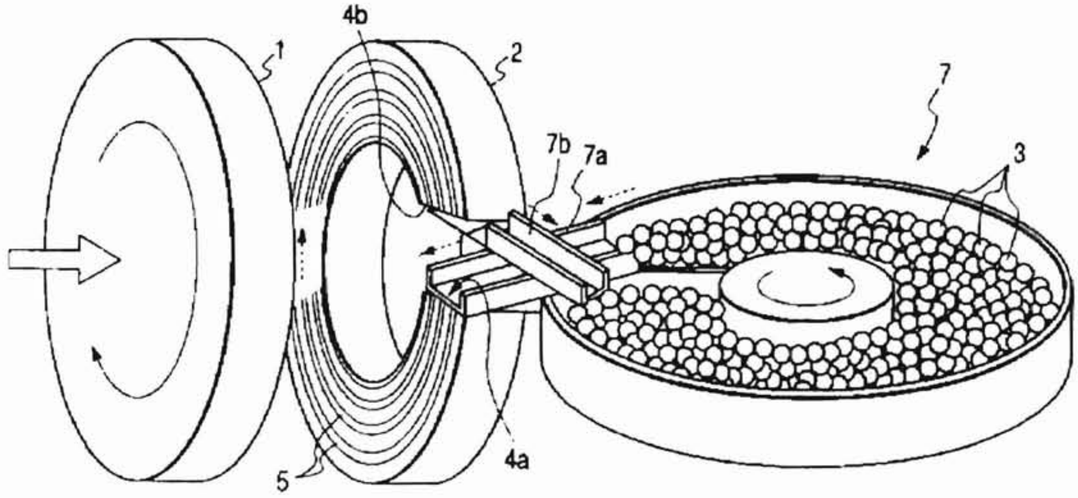


Figure 2.4 Conventional Ball Lapping Machine (US Pat. No. 5,301,470)

Some of the disadvantages of the conventional lapping machine are mentioned briefly in the following. The circulatory motion of the balls is not smooth and also the abrasive particles and wear debris get collected in the grooves on the lower side. This scratches the ball surface while lapping. Also, the structure is such that support to both the plates is provided from the reverse side of each disc, that causes the polishing discs to be affected by the heat generated in the rotating spindle. Due to this, the temperature of the lapping liquid rises, concentricity of the grooves (item 5) changes, and the parallelism of the discs with respect to each other is affected. These factors degrade the sphericity and surface roughness of the balls. Similar adverse effects are also seen, due to the load exerted on the discs. These issues are considered and corrected in the modified apparatus developed by Sato [1994].

Sato developed an apparatus for lapping of balls, which is a modification of the conventional lapping machine (as shown in Figure 2.4). US Pat. No. 5,301,470 issued in April 1994 discloses the modified lapping machine. The lapping plates in this invention are tilted at an angle (α) during the lapping process, while the plates stay horizontal when loading and unloading of the balls. Figure 2.5 shows the schematic of the ball-lapping machine. The stationary plate (5) of the lapping machine is mounted on a central shaft and the rotating plate (4) is mounted on a sleeve, with it's axial center allowed to incline at an angle to the vertical.

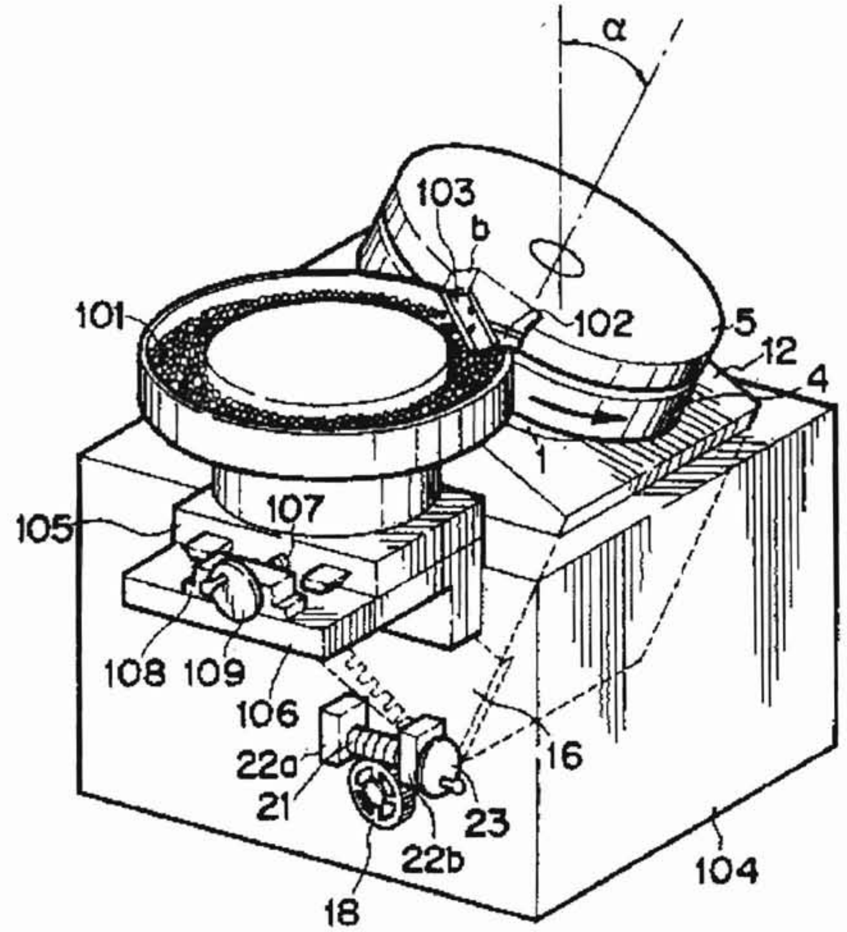


Figure 2.5 Ball-lapping Machine

(US Pat. No. 5,301,470 to Sato)

In this device, the plates are kept horizontal while loading the balls. They are then tilted at an appropriate angle, as shown in Figure 2.5. The supports to both the plates are provided on the same side, which avoids the plates getting affected by the heat generated from the rotating spindle. This further avoids any change in the groove geometry and it's alignment – concentricity and parallelism – with respect to the groove on the other disc. The abrasive particles and the wear debris do not get accumulated, as these are dropped out from the space between the discs. Thus, no scratching of the ball surface occurs and the ball motion is uniform without any hindrance. (All the machines as shown by Figures 2.4, 2.5 and 2.6 are developed at NSK Lt., Tokyo, Japan, and hence are similar in certain respects)

US Patent No. 5,913,717 to Tonooka et al. issued on June 22nd, 1999 discloses an apparatus for polishing of balls. The invention gives more uniform polishing of the balls, caused by modification in the lapping plates of the conventional lapping machine and is shown by Figure 2.5.

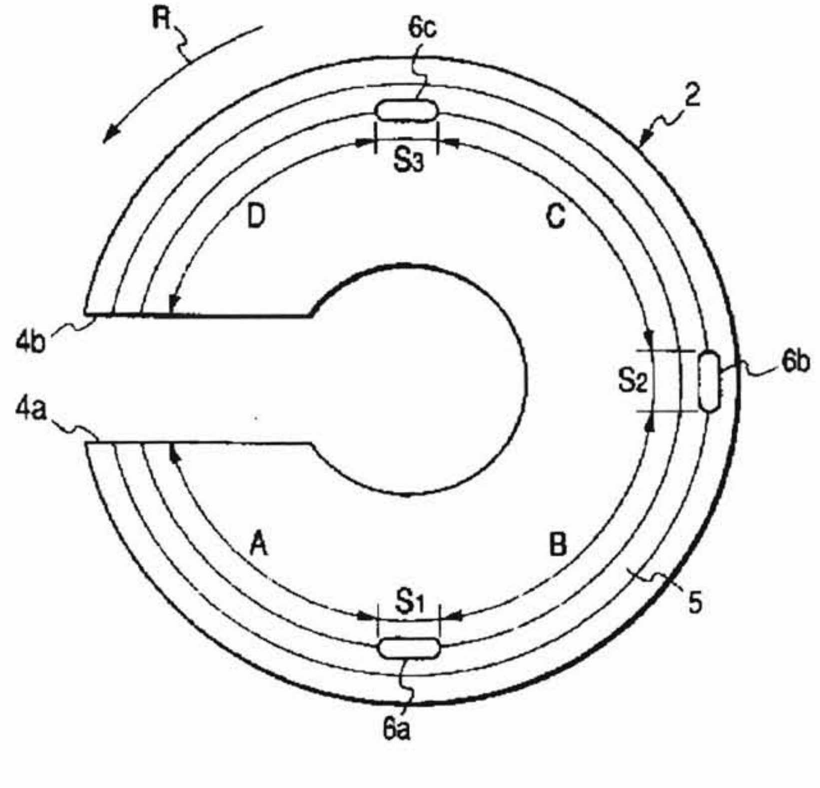


Figure 2.6 Lapping Plate with Relief Grooves

(US Pat. No. 5,913,717 to Tonooka et al.)

As shown in figure 2.6, relief grooves 6a, 6b, and 6c are formed on to the stationary plate 2. These grooves facilitate changing the inclination of the rotating axis of the balls that pass through the groove (in between the two lapping plates 1 and 2). The positions and lengths of the grooves are so determined that the inclination of the rotating axis of the ball changes whenever it passes through the grooves 6a, 6b, and 6c. Thus, in one pass, each ball changes the inclination of the axis of rotation (rotation around its own axis) thrice while passing through the groove in between the plates. Due to this, the balls are more uniformly polished resulting in a superior finish and sphericity.

US Patent No. 5,449,313 issued in September 1995 and US Pat. No. 5,839,944 issued in November 1998 to Kordonsky et al. disclose magnetorheological polishing devices and methods. This technique is similar to MFP in several ways. It uses a magnetic fluid mixed with abrasives to form an abrasive slurry. The workpiece and the abrasive slurry are placed in a chamber that is in proximity to a strong magnetic. The magnetic field acting on the chamber causes the magnetic fluid to be attracted in one direction, pushing the non-magnetic abrasives and workpiece in the other direction, thus, creating a significantly improved polishing zone. The workpiece is moved against the slurry in some devices whereas, the magnetic fluid is moved across the workpiece in some other devices. A wide range of workpiece geometries (flat, curved, hemi-spherical, spherical) can be polished using this technique.

However, the apparatus for each one of these applications is different and suited to a particular application only. Figure 2.7 shows an apparatus for polishing spherical objects. The magnetic fluid 3002 and the spherical objects 3004a and 3004b are placed in the channel-like polishing chamber 3025. The channel is defined by the gap between the top vessel 3001b and the bottom vessel 3001a. The two vessels are rotated in opposite directions relative to each other, during the polishing process. The magnetic field, applied by the electromagnets 3006a and 3006b, pulls the magnetic fluid in one direction and the abrasives and spherical objects move relative to each other causing a polishing action. Thus, a more efficient polishing zone is created for polishing the spherical objects.

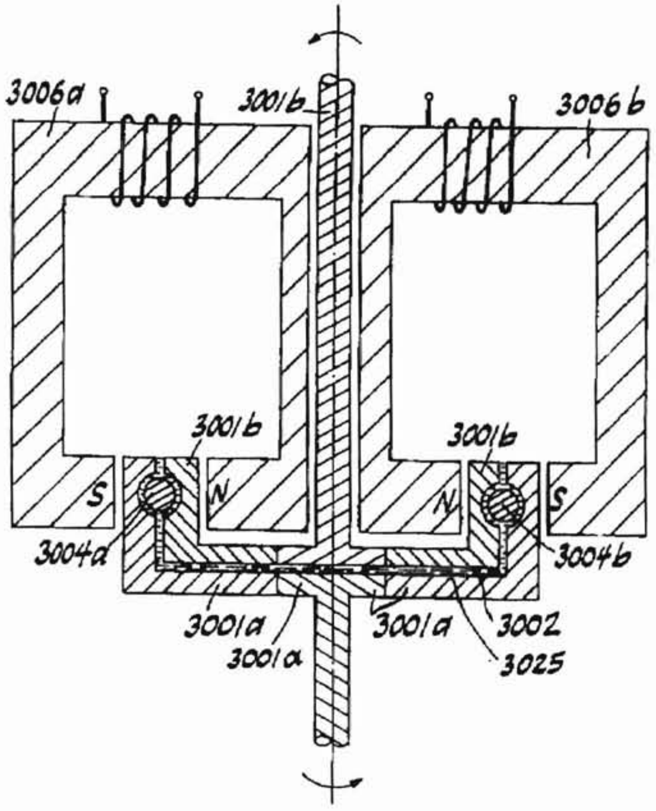


Figure 2.7 Apparatus for Polishing Spherical Objects

(US Pat. No. 5,449,313 to Kordonsky et al.)

US Pat. No. 5,957,753 to Komanduri et al. issued in September 1999 discloses the MFP apparatus. In the MFP technique, magnetic fluid mixed with abrasives is used as the abrasive slurry to polish a wide range of materials to a superior finish and sphericity. The process is significantly faster than conventional methods. The apparatus and polishing process are discussed in detail later in this chapter and in chapters 3 and 5.

2.2 Magnetic Field Assisted Finishing:

Magnetic field assisted finishing can be broadly classified in to two groups: Magnetic Abrasive Finishing (MAF) and Magnetic Float Polishing (MFP). In MFP, a magnetic fluid mixed with non-magnetic abrasive forms the abrasive slurry. The workmaterial is suspended in this abrasive slurry and supports itself by the buoyant force. In MAF, an abrasive with fine iron particles is used instead of the magnetic fluid. The magnetic iron particles get oriented as per the magnetic poles and form a 'brush' over which the workpiece is moved/rotated. The surface of the workpiece is polished by the action of such an abrasive brush. This method can be used to finish internal and external cylindrical surfaces, as well as flat surfaces, very effectively [Shinmura et al., 1990; Fox et al., 1994; Fox, 1990; Thomas, 1997]

2.2.1 Magnetic Float Polishing (MFP):

MFP process was developed recently with certain modifications in the existing technology of magnetic field assisted finishing. The development of the latter process can be traced to the 1940's when it was used in the U.S. to polish gun barrels [Coats 1940]. The process gained importance as a non-traditional machining process, as it was used to finish materials that were difficult to finish by conventional methods. The process was developed extensively in the USSR in the late 50's and early 60's and was used to finish large workpieces and difficult to machine materials [Baron, 1975]. This technique was further developed by Japanese researchers, mainly Prof. Shinmura of the Utsunomia University in Utsunomia, Japan and Prof. Kato of the Tohoku University in Sendai, Japan [Shinmura et al, 1990; Kato and Umehara, 1990]. The magnetic field assisted finishing technique was employed to finish optical glass (lenses), silicon, germanium, and gallium arsenide wafers and, in general, other brittle materials.

In the early 1990's, the technology was applied to finish silicon nitride, zirconia, and alumina balls by Childs et al in the U.K. [1994, 1995]. It gained importance due to its ability to finish hard and brittle materials, like advanced ceramics. MFP emerged as a promising technology that was a modification of the magnetic field assisted finishing. The MFP process uses a float to support the work material that increased the flexibility and effectiveness of the process.

In the late 1990's MFP research activities were extensively carried out by Komanduri et al. [1996; Bhagvatula and Komanduri, 1996; Umehara and Komanduri, 1996; Raghunandan and Komanduri, 1997 a, b; Jiang and Komanduri, 1997 a, b, c; Hou and Komanduri, 1998 a, b, c]. In the research by Komanduri et al. [1996; Jiang and Komanduri, 1998], CMP of different work materials during MFP was investigated and developed. MFP, involving CMP, offered wide range of process capabilities with respect to work materials to be finished and the level of finish to be achieved.

MFP was developed by Umehara and Kato [1990]. An acrylic float was introduced in-between the base of the polishing chamber and the workpiece. The float offered more polishing force as well as flexible support to the workpiece and drastically improved the efficiency of the process in terms of material removal rates. Experiments conducted using the float showed an improvement in the finish of the workpiece. This was attributed to the gentle polishing conditions, as well as the use of a flexible support system. The balls are held in three point contact between the polishing shaft and the side of the interior of the chamber and the float, such that motion of the ball is a combination of the rotation of the ball around its own axis as well as the rotation around the spindle axis. This results in better sphericity of the balls.

In the MFP technique, the workpiece, the non-magnetic abrasives, and the float are acted upon by the buoyant force. The workpiece itself being non-magnetic, the levitation force further increases. This causes the polishing system - abrasives and workpiece - to be pushed against the polishing shaft that is driven at high speeds. The polishing load also acts through the polishing shaft. Material removal is caused by relative movement of the workpiece and the polishing shaft. The forces applied by the abrasives and the polishing shaft to the workpiece are extremely small and highly controllable. The method is very useful to finish surfaces of hard and brittle materials of any geometry - flat, cylindrical, tapered, spherical, as well as curved surfaces. [Kato and Umehara, 1990; Umehara, 1990; Childs et al., 1994, 1995; Komanduri et al., 1996; Bhagvatula and Komanduri, 1996; Umehara and Komanduri, 1996; Raghunandan and Komanduri, 1997 a, b; Jiang and Komanduri, 1997 a, b, c; Hou and Komanduri, 1998 a, b, c].

MFP was initially introduced by Tani et al., [1984] but could polish only extremely soft materials, such as acrylic resin. The removal rates due to very low forces applied on these soft materials were low (~2μm/min) with SiC abrasive (grain size: 4μm). In this mode it is extremely difficult to apply the process for hard and brittle materials like glass, ceramics, and steels.

Research on MFP to finish ceramic rolling components (balls and rollers) was conducted in Japan by Kato's group, in the UK by Childs and his group, and in the USA by Komanduri's group. More recently the technology was extended at Oklahoma State University to finish glass balls. The polishing shaft was used with a polishing pad and the abrasive used was cerium oxide [Dock and Komanduri]. The following tables briefly review the work done in this field by several researchers from the three groups.

Table 2.1 MFP research work by Kato and Umehara's group in Japan [after Jiang, 1998]

Professor Kato's Research Team (Japan) N. Umehara B. Zhang K. Kato	**Work Materials:** • Balls: sintered silicon nitride (1990, 1994) • Rollers: silicon nitride (1992) • Plates: alumina (1992), stainless steel (1993) **Activities:** • Introduced float increasing polishing load and the material removal rate (1990) • Investigated the effect of stiffness of float on the polishing performance (1990, 1994) • Developed a dynamic model for MFP (1996) • Developed an eccentric apparatus to obtain balls with good sphericity (1996)

Table 2.2 MFP research work by Childs' group in the UK [after Jiang, 1998]

Professor Childs' Research Team (UK) S. Mahmood H.J. Yoon T.H.C. Childs	Work Materials: • Balls: silicon nitride, zirconia, alumina (1994, 1995) Activities: • Design of the magnetic float grinding cell (1992) • Kinematics of the ball motion (1994) • Mechanism of material removal (1995)

Table 2.3 MFP research work by Komanduri's group in the US [after Jiang, 1998]

Professor Komanduri's Research Team (USA) M. Raghunandan Jiang Ming S.R. Baghavatula N. Chandrasekaran Ashutosh Khuperkar Srihari Rao M. J. Fox M. Dock Asif Patel Vinoo Thomas Cetin Murat Ali Noori-Khajavi Zhen-Bing Hou N. Umehara T. Shinmura R. Komanduri	**Work Materials:** • Balls: silicon nitride, zirconia, stainless steel, glass • Rollers: silicon nitride, stainless steel • Tubes: Stainless steel **Activities:** • Electromagnet apparatus (1994, 1997) • Permanent magnet apparatus -FEM analysis (1996) • Mechanisms of material removal (1996) • Chemo-mechanical polishing (1996, 1997) • Thermal analysis of MFP (1997 a, b, c) • Methodology for finishing ceramic balls for bearing applications with good sphericity and surface finish using Cr_2O_3 and CeO_2 abrasives (1996, 1997) • Development of equipment for the finishing of large batch balls (1998) • Finishing of ceramic balls for hybrid bearings that meet the requirements of industry (1998) • Online vibration monitoring and control (1999) • Expanding process capabilities of MFP to finish glass balls by CMP using cerium oxide (1999), and process optimization.

The exact ball motion and the mechanism of material removal during polishing is difficult to study. Childs et al., [1994] developed a kinematic model of the ball motion during MFP of ceramic balls. Wear coefficients and sliding speeds were estimated. Based on the wear coefficients (0.04~0.08), they concluded that abrasives get embedded in the shaft leading to the material removal by two-body abrasion, as shown in Figure 2.8.

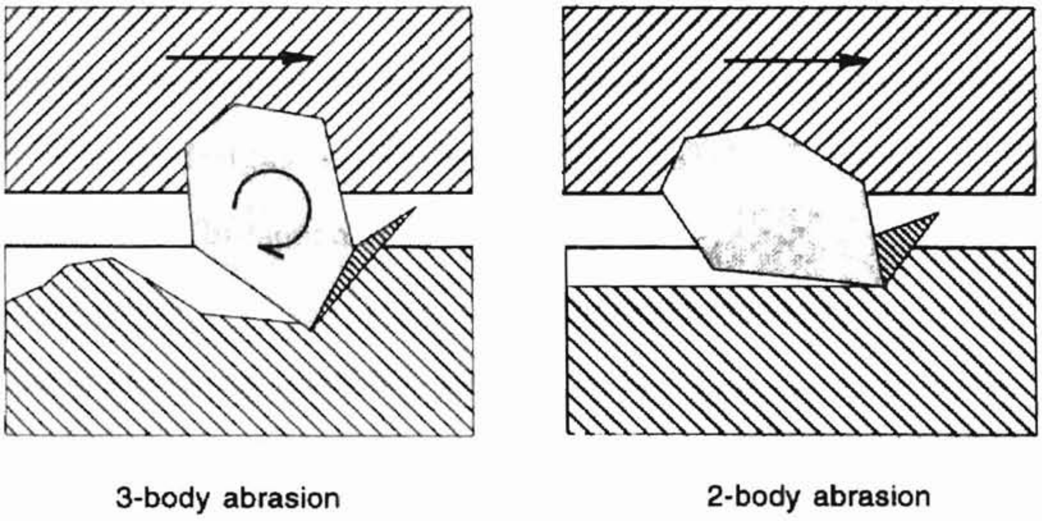


Figure 2.8 Schematic of two-body abrasion.

Umehara and Kato [1990] and Umehara [1990] introduced the float that resulted in a more uniformly distributed polishing force. As mentioned earlier, the use of the float improved the sphericity of the balls significantly along with higher material removal rates. Zhang, Umehara, and Kato [1996] studied a dynamic model for the MFP of ceramic balls. They found material removal rates to be high when larger diameter portions of ball enter the contact area (with polishing shaft and guide ring). This was believed to be due to a higher polishing load acting on that portion of the ball.

Zhang et al., [1997] investigated the motion of the ball during polishing and the various forces acting upon it. They believed that if the polishing action is uniformly distributed over the ball surface, the resultant sphericity would be low. To study these effects, they developed an eccentric polishing apparatus where, as the name implies, the polishing shaft is eccentric with the polishing chamber. This would facilitate uniform contact track distribution resulting in proper feed motion of the ball for polishing.

Jiang and Komanduri [1997] identified three stages for polishing of silicon nitride (Si_3N_4) balls by MFP. They are: 1) an initial roughing stage where the material removal rate is high, with minimal surface or subsurface damage; 2) an intermediate semi-finishing stage, where material removal rates are reasonable and sphericity and surface roughness are closely monitored; 3) the final finishing stage, where material removal rates are very low or negligible and emphasis is on the desired size (diameter), form (sphericity), and finish (surface roughness). The use of harder abrasives, like B_4C and SiC, during the initial stages of polishing yields high material removal rates (1μm/min) with minimal subsurface damage. This is due to rapid accumulation of minute amounts of material removed by mechanical micro-fracture at high polishing speeds and low loads.

Jiang and Komanduri [1998] implemented the Taguchi method for optimization of the MFP process, to finish silicon nitride ceramic balls. An orthogonal array was used for the tests. The three variable process parameters identified were polishing force, abrasive concentration in the slurry, and polishing speed. It was found that polishing force was the most significant factor for overall surface finish. Optimum polishing conditions for polishing were obtained. Within the range of parameters evaluated, the Taguchi experimental design indicated that a high level of polishing force (1.4N/ball), a low level of abrasive concentration (5%), and a high level of polishing speed (7000 rpm) are optimal for improving surface finish, both Ra and Rt. Using 1μm size SiC abrasive, surface finish of 15nm Ra and 150nm Rt was obtainable. CMP using CeO_2 further improved the surface finish. Figures 2.9 (a) & (b), and 2.10 (a) & (b) show the results of the Taguchi experimental design work.

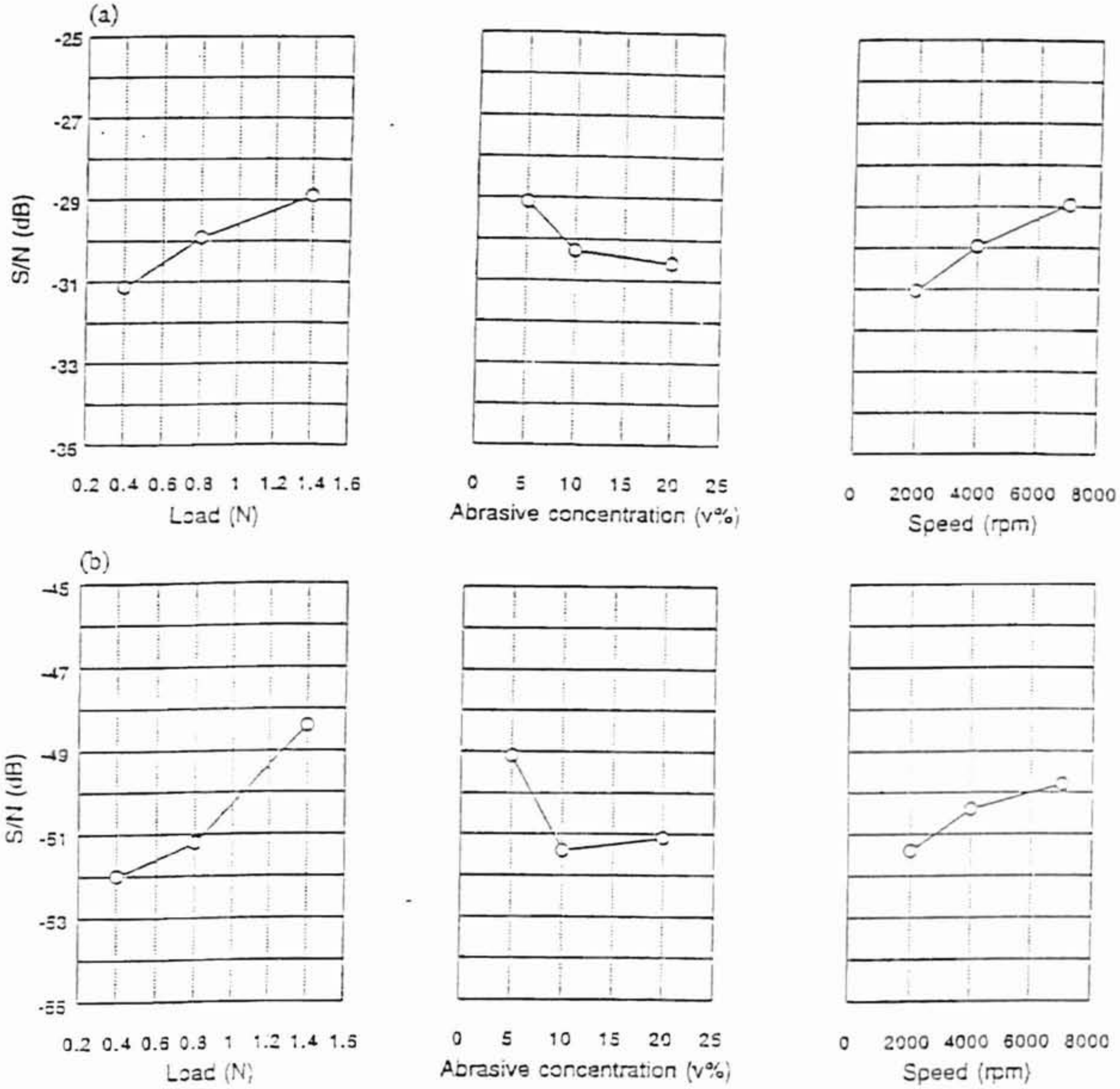


Figure 2.9 (a) Plots of the response of each polishing parameter level on Ra.

(b) Plots of the response of each polishing parameter level on Rt.

[Jiang and Komanduri, 1998]

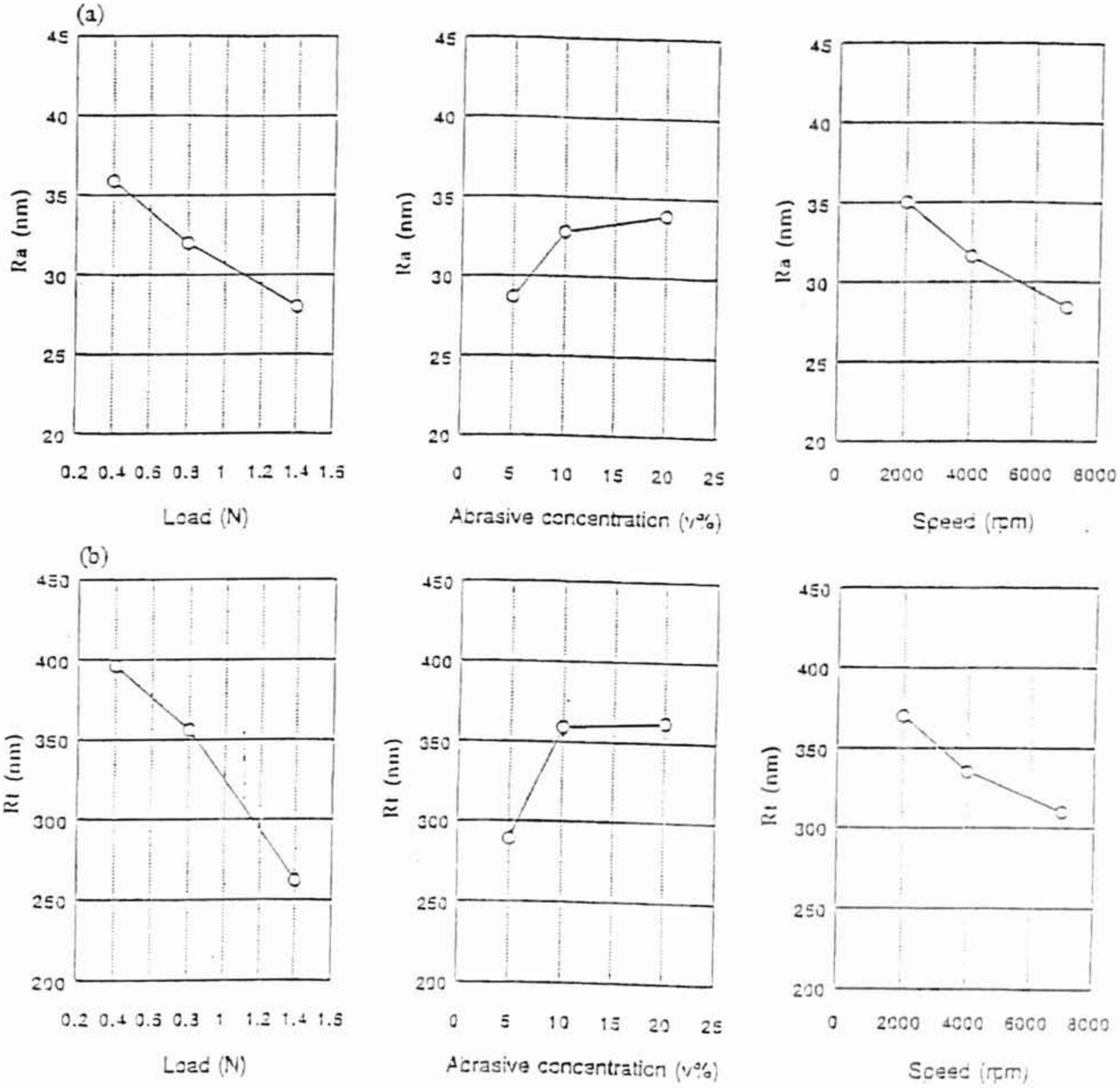


Figure 2.10 (a) Plots of Signal-to-noise (S/N) ratios showing the effect of each parameter level on the surface finish - Ra.

(b) Plots of S/N ratios showing the effect of each parameter level on the surface finish – Rt. [Jiang and Komanduri, 1998]

2.3 Chemical Mechanical Polishing (CMP):

CMP is the process of subjecting the workmaterial to a chemically reactive environment to allow the surface of the workmaterial to react and form a weaker reaction product layer, that is removed by gentle mechanical action. CMP achieves planarization of non-planarized surfaces. The process can be controlled very precisely and is a very effective finishing process, due to the combination of gentle chemical and mechanical actions. Yasugana et al. [1977-79] first reported CMP in the polishing of single crystals of silicon, using a soft abrasive. A model of the CMP is shown in Figure 2.11.

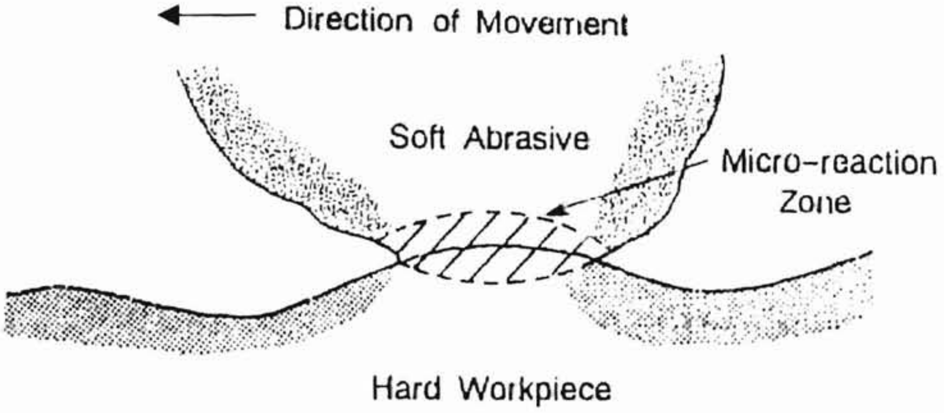


Figure 2.11 Principle of CMP [Yasaguna, Imanaka, et al., 1978]

According to their theory, high temperatures and pressures are generated in the micro-reaction zone. The effectiveness of the process is dependent on the proper choice of the abrasive for a given workmaterial, and sliding conditions such as polishing load, contact temperature, and sliding speed. The sliding conditions are particularly important as they cause actual removal of the reaction product layer over the workmaterial by the mechanical action of the abrasive.

CMP, of silicon nitride ceramic balls in MFP, involves formation of a thin reaction product layer of silica that is removed by the mechanical action. This mechanism is similar to the CMP of silicon wafers, where the wafer surface chemically reacts with the abrasive slurry to form a thin reaction product layer of silica. Wang et al. [1994] pointed out that formation of a thin film (usually less than 100 A° thick) of reaction product – SiO_2, resulted in the easy removal of it without directly abrading the hard surface. This results in high material removal rates and low surface damage, due to the formation of softer surface films.

CMP of glass balls using cerium oxide involves a similar mechanism of material removal. For this reason, a part of the literature review is on the CMP of silicon and silicon nitride work materials to provide a better appreciation of the CMP process for glass using MFP. Vora et al. [1982-83] demonstrated the process capability of CMP to generate a high level of finish in polishing of silicon nitride with Fe_2O_3 and Fe_3O_4 abrasives. Other oxides were studied by Suga et al., [1989] for polishing of silicon nitride, such as CaCO3, MgO, SiO_2, Fe_2O_3, Fe_3O_4, and Cr_2O_3. It was found that Cr_2O_3 was the most effective abrasive, due to its role more as a catalyst than an abrasive.

2.3.1 CMP in MFP:

Komanduri et al [1996] investigated the possibility of chemo-mechanical action in MFP of silicon nitride. Chromium oxide and aluminum oxide were used as abrasives. With chromium oxide as an abrasive, material removal rates were higher and the surface texture was smoother (with fewer pits) as compared to aluminum oxide. Formation of pits due to brittle fracture was believed to be the more predominant mode of material removal, with aluminum oxide abrasive.

Though these two abrasives, Al_2O_3 and Cr_2O_3, have nearly the same hardness, the results were different for the polishing of a silicon nitride workpiece. The difference is believed to be due to chemo-mechanical action with the use of chromium oxide. Higher chemical stability of aluminum oxide abrasive (compared to chromium oxide abrasive) and the known role of chromium oxide as a catalyst for the oxidation of silicon nitride are some of the reasons attributed for this action. The material removal is believed to be at the molecular level and therefore the surface finish generated by the chemo-mechanical action is superior to other methods. Also, the abrasives used in CMP are often softer than the work material and material removal is caused by the removal of reaction product formed over the surface of the work material. In this way, the subsurface of the work material is not scratched or damaged by the softer abrasive. Thus, a very fine finish is achieved by CMP.

Bhagavatula and Komanduri [1996] investigated the chemo-mechanical action in the polishing of Si_3N_4 balls using Cr_2O_3 abrasive and water based magnetic fluid. The wear debris from the polishing process was examined using the scanning electron microscope with an X-ray microanalyser and a small-angle X-ray diffraction apparatus. The analysis showed that Cr_2O_3 and Si_3N_4 form chromium nitride and chromium silicate. The hardness of Cr_2O_3 abrasive and Si_3N_4 balls is nearly same and, hence, it is concluded that the material removal is due to CMP action of the abrasive on the workpiece in the water environment.

Furthermore, a model was developed for the CMP of silicon nitride work material and chromium oxide abrasive in air and water environments. The investigation also shows that oxidation of the silicon nitride balls forms a thin layer of silica (SiO_2) on the workpiece surface that is removed by the mechanical action of polishing. The silica and water form an additional reaction product, that is a hydrated layer of silica forming silicic acid (H_2SiO_3). The reaction of silica and water is given by the equation: $3\,SiO_2 + 6H_2O \rightarrow 3Si(OH)_4$.

Jiang and Komanduri [1998] investigated the CMP of silicon nitride balls by MFP using various abrasives. The aim of that study was to find the effectiveness of each abrasive in producing a good surface finish. Cerium oxide (CeO_2) and ZrO_2 were found to be most effective, followed by Fe_2O_3 and Cr_2O_3. The formation of a SiO_2 layer on the surface of silicon nitride was substantiated by thermodynamic analysis involving Gibbs Free energy of formation. It was observed that water environment from the water based polishing fluid facilitated the formation of silica layer, that increases effectiveness of the CMP process, whereas, oil-based polishing fluid minimized CMP.

Chapter 3

Problem Statement

Finishing of glass balls in industry is done using conventional lapping and polishing methods where material removal is generally by brittle fracture. This often leads to surface and subsurface damage that can further cause catastrophic failure of the finished glass balls. Strategies and experiments were designed to accomplish targets set at every stage. These are outlined in the following:

- Apply MFP technology for finishing glass balls and establish an alternative technology for finishing glass

- For a given diameter of glass ball blank, investigate the characteristics of a finished ball such as sphericity, size, finish, and surface damage

- Set a target for the finished glass balls produced by the MFP process. Sphericity and surface finish should be better than the best grade available in glass balls finished by conventional polishing technique

- Investigate different abrasives suitable for glass finishing with minimal or no surface and sub-surface damage, especially in the final stages

- Achieve reasonable material removal rates to make the process fast and economically viable, and avoid or minimize the damage that may result at high removal rates

- Optimize the process conditions for high removal rate, good sphericity, and good surface finish. Develop conditions for different stages from initial stage of high material removal with minimal damage to final stage of low material removal with good finish and sphericity.

- Modify the apparatus with design changes in the polishing shaft to polish a range of diameters of balls

- Introduce a polishing pad in to the system to improve surface finish

- Develop process capabilities such that it has a precise control over the material removal rates to finish a batch of balls of a given diameter. This is very important from the 'process capability' point of view. If the diameter of the balls approaches the finish diameter, the process should offer precise material removal rates. In other words, the process should cater to a wide range of material removal rates, especially in the micrometer to sub-micrometer regime.

The steps outlined are critical to the finishing of the balls to a particular diameter. As an example, consider a batch of glass balls to be finished to a diameter of 4.50 mm from the as-received ball of diameter 5.012 mm. This is achieved by removing 512 micrometers on the diameter. With the initial stage, a high material removal can be achieved followed by the semi-finishing stage to get close to the finish diameter. This can reduce the diameter to 4.51 mm with several polishing runs leaving the precise removal of the last ten micrometers. At this point, accurate process control becomes critical, as exactly ten micrometers of material have to be removed.

Even after considering certain tolerances, it is crucial to remove material precisely. It is at this point that the process should be capable of offering a wide range of precise material removal rates to reach the exact finish diameter. The process should, ideally, have varied material removal rate capability, by changing and controlling parameters and the choice of effective abrasives.

Chapter 4

Polishing of Glass

4.1 Introduction

In the following different polishing theories and material removal mechanisms are presented to investigate the capabilities of different glass polishing processes. The surface of glass can be polished to a high level of finish giving it a brilliant appearance. Glasses can be made ultra-clear by removing the color forming oxides. On the other hand, oxides such as PbO and K_2O promote the brilliant appearance by facilitating decolorizing and increasing the refractive index, eg. leaded glass (more than 20wt. % PbO). The nominal composition for leaded glass is provided in appendix A.

4.2 Glass Polishing Theories

Glass is a brittle material and hence cannot withstand sudden impact and high polishing loads. The material removal in most polishing processes is by brittle fracture that occurs on the surface as a result of the polishing load and abrasive impact. The bigger the abrasive particle, stronger the impact and higher the material removal. Newton [1695] investigated the effect of particle size and finish. He concluded that the finish is directly dependent on the particle size, as he observed smaller particles created smaller scratches and hence, better surface finish.

However, Beilby [1903, 1921] believed that the surface of an article flowed during polishing. Certain chemical reactions were found to occur during the polishing process that gave rise to Preston's chemical theory [1930]. In the 1980s, Izumitani [1986] presented an extensive research study that involved polishing of optical glass. It was found that both mechanical and chemical actions are predominant in the polishing action, and hence, the chemo-mechanical theory started to develop. Cook [1990] investigated chemical processes in the polishing of glass. He found that silica reacts with water at a slow rate to form silicic acid.

4.2.1 Wear Theory

Thompson [1922] suggested that the surface asperities were removed by planing action of the polishing medium and the tool. A pitch was used as polishing pad, and he believed that the abrasive particles of different diameters get embedded into the polishing lap, with the larger particles getting embedded deeper. This occurs till the polishing load is evenly taken by all the particles and they protrude out of the pad to offer a uniform polishing action. He noted that the scratches produced on the glass surface, so polished, had smooth sides contrary to fractured faces seen in grinding.

Koehler [1953] determined the rate of glass removal from the surface in polishing of barnesite, by measuring the change in depth of a surface pit, and it was found that the rate initially rose to a maximum and then dropped to remain constant. It was believed that the constant cutting rate was due to the polishing particles embedded in the polisher, and the maximum rate was due to the loose particles that worked themselves to the center of the lap and to the lap grooves. Koehler concluded that the polishing particles get embedded into the polisher and plane the surface in a random manner to a uniform depth, as in the planing process.

Izumitani and Harada [1973] tested 18 different glasses with different hardness, composition, and chemical durability. According to the wear theory, the polishing rate should be dependent on the hardness of the glass. It was observed that there did not exist a correlation between the polishing rate and hardness for all types of glass. It was believed that indentation caused by the particles during the lapping process produces micro-cracks. The micro-cracks get accumulated and material is removed. In their studies, water as well as oil polishing media were used in normal atmospheres and dry nitrogen atmospheres. It was observed that the removal rates were higher when water was used than oil, and that the lapping hardness was found to be dependent on the indentation hardness and mechanical strength of the glass. This showed that there existed another mechanism of material removal in addition to the wear theory. This was believed to be the chemical theory.

4.2.2 Chemical Theory

The chemical theory was developed to explain the variations in removal rates under identical polishing conditions but different pH of the abrasive slurry. It was observed by many researchers that the removal rates were significantly affected by controlling the pH values and the presence of water in the polishing medium. Water reacts with silica forming silicic acid, thereby changing the pH of the solution. Izumitani and Harada [1986] investigated the reaction of water with glass. They found that water dissociates into hydrogen and hydroxy ions as given by:

$$H_2O \leftrightarrow H^+(H_3O^+) + OH^-$$

and the ions react with the glass and break the glass network by selective leaching of the modifier ions. Figure 4.1 shows an example of breaking of the glass network.

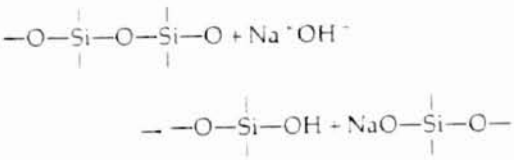


Figure 4.1 Breaking of the Glass Network [Izumitani, 1986]

As shown in Figure 4.1, Na^+ ions are formed and small molecules such as Na_2SiO_3, etc., in the solution, and these dissociate in the solution. An exchange reaction between the dissociated H^+ and H_30^+ ions in the water and the modifier ions takes place. These ions enter the interstitial spaces in the network to form a hydrated layer or silica-gel-like layer with a low index of refraction as shown by Figure 4.2 (a). Cations in the glass are leached into the solution. Figure 4.2 (b) illustrates the mechanism.

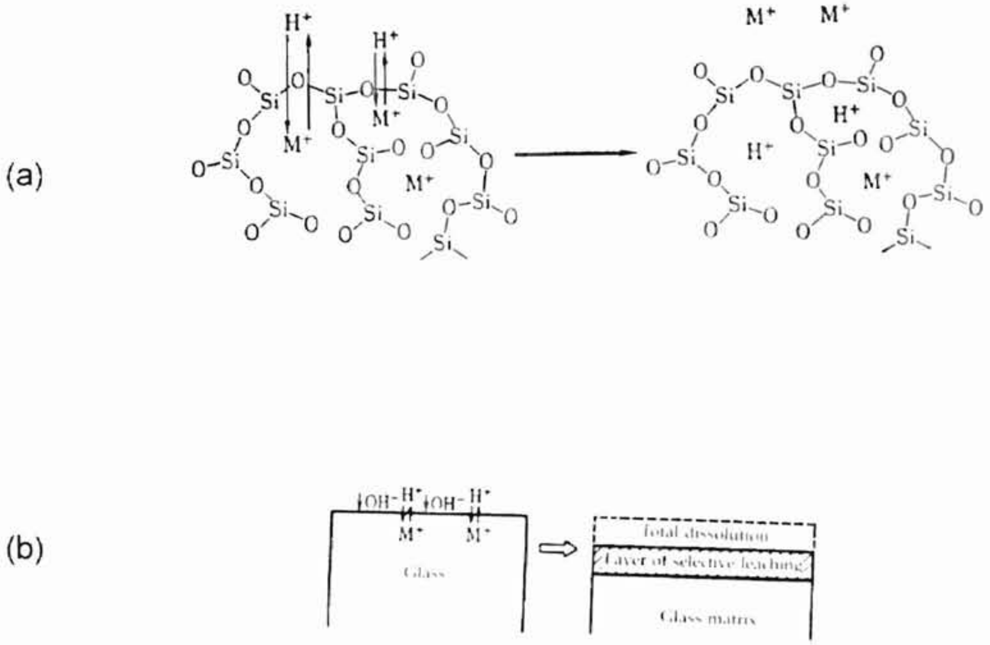


Figure 4.2 (a) and (b) Reaction between Glass and Water [Izumitani, 1986]

El-Shamy et al. [1976] conducted experiments to study the effect of pH on the decomposition of glasses in aqueous solutions. They found that a weak acid (silicic acid) forms when water reacts with silica. The pH of the solution changes as the polishing proceeds and the removal rates are noted to increase significantly for pH > 9, but remain constant with respect to time for any given pH.

4.2.3 Flow Theory

Beilby [1903] believed that there was glass flow during the polishing process. This was due to melting of the glass surface from the heat generated by friction between the surface and the abrasives. French [1917, 1921] analyzed the polishing process and divided the polishing process into the following sequential events:

1. Heat is generated due to friction between the glass surface and the abrasives, which causes glass flow
2. Grooves are produced in the flowed layer
3. The particles get embedded into the lap, which then causes the polishing action
4. Irregularities are removed, the peaks and protrusions flow to fill up the pits and valleys.

Bowden and Hughes [1937] state that glass flow occurs when the polisher has a higher melting point than glass. Schulz [1953] observed that larger the difference in the melting points, the better is the efficiency of the polishing process. Brueche and Poppa [1956a, 1957a] state that the polishing process in glass involves finishing of the surface to the bottom of the scratches produced from the previous processing, and that surface flow occurred only in the final stages of polishing.

4.2.4 Chemo-Mechanical Theory

The theories discussed so far relate to the material removal from the surface of the glass by various mechanisms. However, none of these mention re-deposition of silica on the glass surface during the polishing process. Brown [1989] found experimental evidence of the re-deposition of silica during the polishing of silica glass with cerium oxide laps. He observed that weight gain was at a faster rate than weight loss of the glass workpiece during the polishing process. This phenomenon of re-deposition during the polishing process is supported by studies of polishing accelerants done by many other researchers.

Kaller [1959] investigated the effect of different polishing materials and polishing load levels on the polishing of glass. He found that cerium oxide gave the best results in producing a smooth and polished surface. Material removal rate was found to be higher with better finish as compared to the results of polishing using chromium oxide. The best materials for polishing glass are CeO_2, ZrO_2, ThO_2, TiO_2, and Fe_2O_3 in descending order.

Cook [1990] investigated the chemical processes during glass polishing. It was found that the polishing particles, the glass, and the water from the polishing fluid react with each other. The polishing process can be summarized as a sequence of operations, as given by Figure 4.3. The particles get embedded in the polishing lap and hence, the polishing action is considered as a two-body wear mechanism. The size of the particles does not affect the polishing action as they

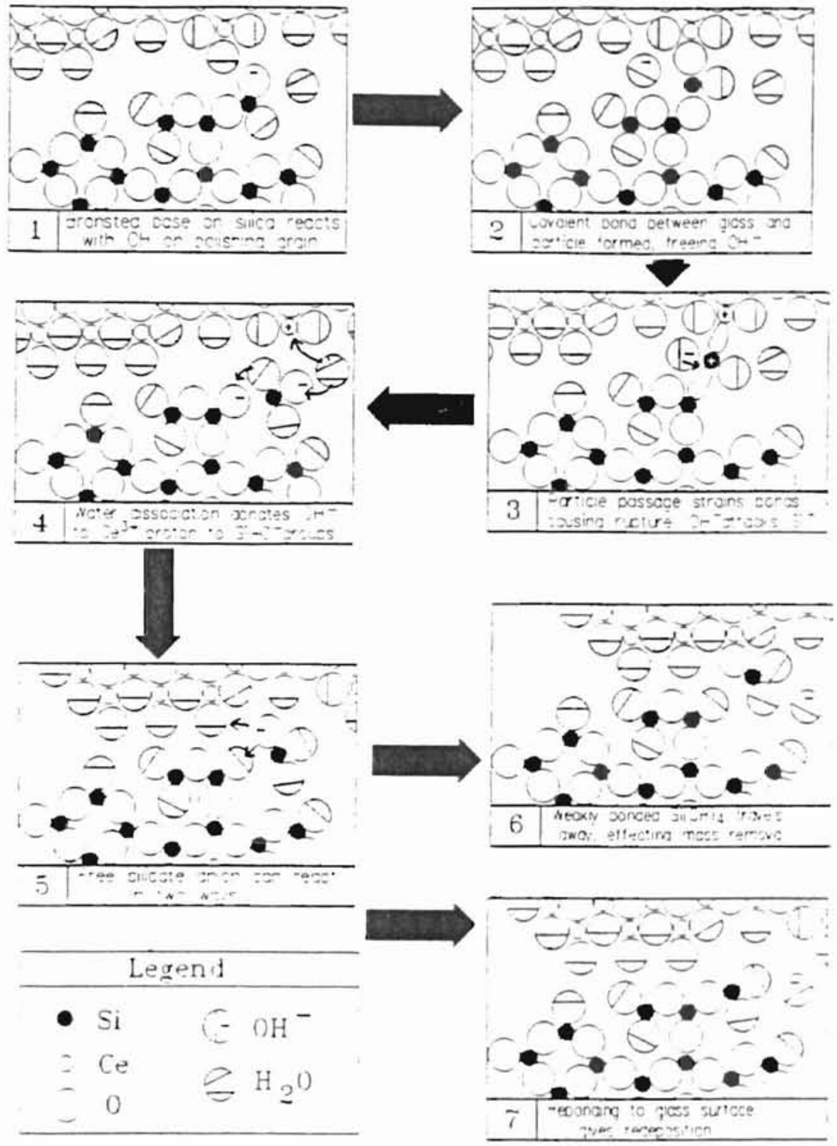


Figure 4.3 Proposed Polishing Reaction Sequence [Cook, 1990]

get embedded in the lap such that all the particles become load bearing. This is due to larger particles sinking deeper into the pad and smaller particles protruding in a manner such that all the particles come in contact with the glass surface, applying equal pressure. A hydrated layer is formed on the glass surface due to the reaction between glass and water. This layer is effectively removed by the soft abrasive. Cerium oxide is a chemically active polishing agent for polishing glass. Cook states that removal rate of polishing can be determined by the relative rates of the following five processes:

1. the rate of molecular water diffusion into the glass surface
2. the subsequent glass dissolution under the load imposed by the polishing particle
3. the adsorption rate of dissolution products onto the surface of the polishing grain
4. the rate of silica re-deposition back onto the glass surface
5. the aqueous corrosion rate between particle impacts

The major factors that influence these processes are the load and velocity of the polishing particles, the elastic properties of the glass surface and the polishing particle and the chemical durability of the glass.

Chapter 5

Approach

5.1 Introduction

The experimental and analytical work involve design modification and development of the existing polishing apparatus, investigation of effective abrasives for reasonable material removal rates and selection of the appropriate abrasives, application of Taguchi method for optimization of MFP process parameters (discussed in Chapter 7), development and setting up of various stages, such as initial stage of high material removal, semi-finishing, and final finishing for the polishing process, implementation of CMP during final finishing stage to achieve desired end results. Thus a methodology and process for finishing glass balls from the as-received condition to the best final finished condition is developed. A thorough process control is maintained at every stage.

Glass is opaque or semi-transparent when its surface is rough and unpolished. The as-received glass balls are opaque due to its rough surface. This characteristic of the workmaterial is a powerful tool in the initial stages. However, glass attains a high level of transparency if its surface is planarized or polished smooth with roughness in the order of a few nanometers. When this stage is reached for the glass balls, other tools like optical microscope and surface roughness measuring instruments can be employed to analyze the results. The sphericity, surface finish, material removal rate (both diametrical and weight reduction) are evaluated using a micrometer, precision balance, optical microscope, TalyRond, and TalySurf.

5.2 MFP Apparatus:

The MFP technique works on the principle of magneto-hydrodynamic behavior of magnetic fluid under the influence of a strong magnetic field imparting buoyant forces on non-magnetic materials suspended in the fluid. Figure 5.1 shows the schematic of the MFP apparatus. The polishing apparatus mainly consists of a cylindrical polishing chamber made of aluminum. The dimensions of the chamber with respect to its geometry are discussed in detail in the subsequent chapters. The inner side is lined with a rubber sheet for minimizing wear of the chamber. The bottom of the chamber has a thin plate below which lies a bank of permanent magnets (Nd-Fe-B, residual magnetization: 10500G) with alternate N and S poles. The magnetic fluid used for the abrasive slurry is a colloidal dispersion of extremely fine (100 to 150 Å) subdomain ferromagnetic particles (Fe_3O_4) in a carrier fluid, such as water or kerosene. A water based magnetic fluid was used in this study. The magnetic fluid is made stable against particle agglomeration by coating the surface of the fine particles with appropriate surfactant. The water based magnetic fluid (W 40) used in this study has a saturation magnetization of 400 Gauss at 25° C, and viscosity of 25 Cp at 35°.

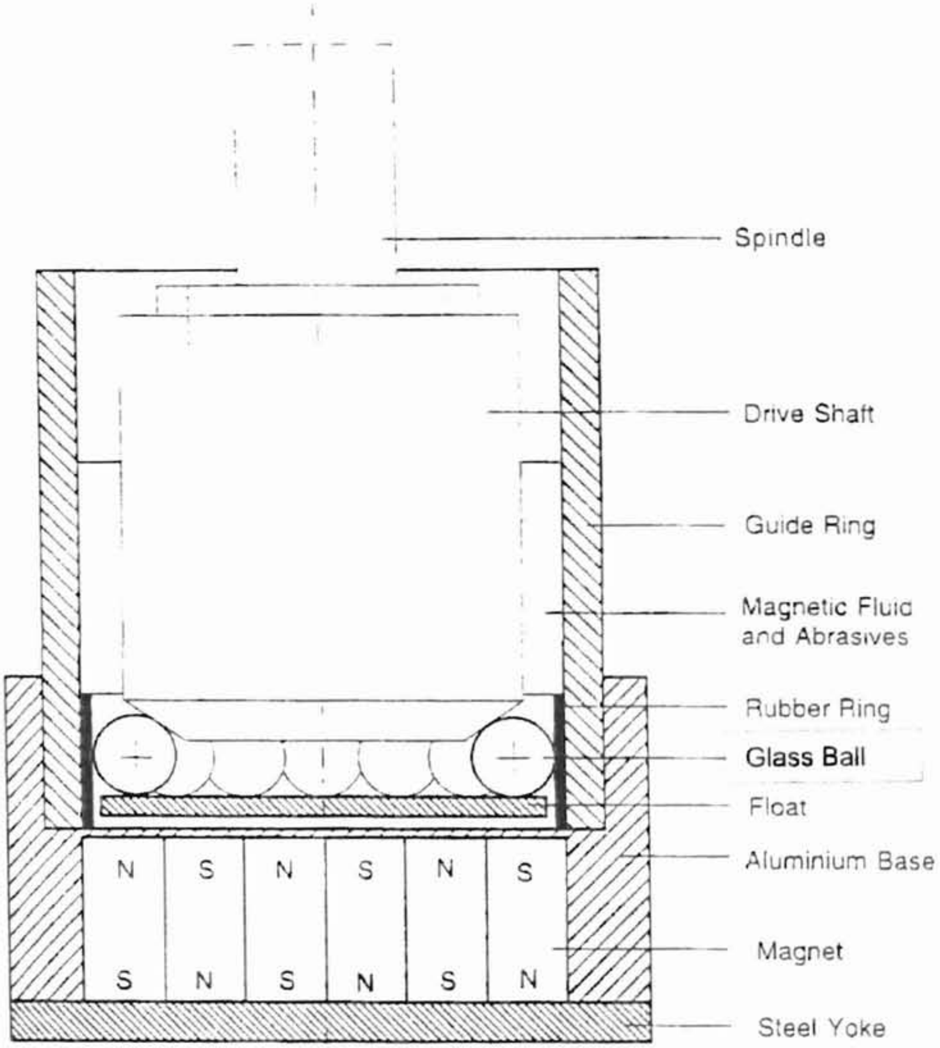


Figure 5.1 Schematic of the MFP Apparatus Used for Finishing Glass Balls

The MFP technique utilizes a mixture of magnetic fluid and abrasives to form the abrasive slurry. An acrylic float is used to support the workmaterial. The abrasive slurry, the float, and the work material are held in the polishing chamber that contains strong magnets at it's base. Due to the magnetic force, the magnetic fluid is pulled downwards to an area of high magnetic field pushing the non-magnetic float, abrasives, and workpiece upwards to an area of low magnetic field. Thus, buoyant forces act upon the workpiece and abrasives. These forces are low in magnitude (0.25 to 2.0 N per ball) and highly controllable. The main function of the float, apart from supporting the work material, is to produce more uniform and larger polishing pressure by transmitting the buoyant force in the area of high magnetic field intensity to the polishing area.

The drive of the polishing apparatus is called a polishing shaft and is made of non-magnetic austenitic stainless steel. It is attached to an air-bearing spindle (PI) and lowered into the polishing chamber in which the balls are arranged along the periphery. The design of the polishing shaft is predominantly dependent on the diameter of the balls to be polished (discussed in Chapter 6). The polishing shaft applies the polishing load on the balls. This force is lesser than the buoyant force and acts in the opposite direction. The polishing shaft pushes the workmaterial, abrasive slurry, and the float downward with a predetermined force that is monitored by a piezo-electric dynamometer mounted underneath the chamber. This force is highly controllable. On the other hand the buoyant force pushes the workmaterial, abrasive slurry, and the float upward against the polishing shaft as the spindle rotates. This phenomenon enhances the polishing action and increases effectiveness of the slurry over the workmaterial. This is one of the salient features of the MFP process. The magnetic fluid that is pulled to the area of higher magnetic field intensity remains confined to that area and supports the float. The support is flexible and acts like a cushion and allows the float to have controlled freedom of motion. This enables the MFP process to finish brittle workmaterials without much surface or sub-surface damage. Hence, this process is also called as a "gentle" finishing process.

The variable process parameters such as load, abrasive type, abrasive percentage in the slurry, polishing speed and polishing time, and type of polishing pad directly affect the results of the process. In the initial stage, the main aim is to achieve high material removal rates without abusing the workmaterial. In the semi-finishing stage, material removal rate should be reasonable and at the same time a good control over geometrical form of the workpiece is important. In the final finishing stage, though material removal rates are very low or negligible, the polishing action is important to give the workpiece a high level of surface finish and also improve the sphericity. The choice of parameters (type, level) has to be precise for optimization (cost, time, effectiveness, finish)

5.3 Salient Features of MFP Technology:

The characteristics of MFP technology are as follows:

1. High material removal rate
2. Excellent finish and accuracy
3. Good sphericity
4. Minimal or no surface and/or subsurface damage, such as microcracks, is imparted to the work material
5. Faster finishing times as compared to the conventional techniques.
6. Polishing process is "gentle" and "flexible" and forces applied are small.
7. Easier and more convenient set-up requiring a single machine throughout the process from roughing to finishing
8. Process capabilities can be expanded with respect to various parameters.

In addition to the above, the apparatus for MFP can produce small batches of finished balls. This is particularly useful when only a small number of balls need to be polished as per customer's need or during the materials development program where the material available for evaluation is limited. The process is economical, not only due to the faster polishing time but also due to the use of cheaper abrasives, as diamond abrasives are not used at any stage. Some of the salient features listed will be discussed elaborately in the following.

5.3.1 High Material Removal Rate:

The material removal by polishing or lapping is due to sliding at the contact region between the workpiece and the abrasives embedded in the tool or polishing pad. The material removal rate during MFP of glass balls is high because there is more sliding in this process than in conventional lapping due to the following two reasons: (i) The polishing load in MFP is orders of magnitude (up to 100 times) lower than in conventional lapping. Hence, the frictional force at the contact region is significantly reduced. Consequently, there is more sliding than rolling. (ii) The drive shaft in MFP rotates at higher speed (up to 10 times) than in the conventional lapping. Thus, there is more sliding in the polishing region due to increased relative speed. The experimental results show that material removal rates in polishing of glass balls by MFP are much higher (up to 10 times) than in conventional lapping method. Moreover, the polishing time required is considerably reduced, due to the existing good surface integrity and roughness as compared to the conventional methods.

5.3.2 Excellent Surface Finish and Accuracy:

The use of polishing pad highly enhances the surface finish and also offers many other advantages to the process. The chemical reaction is produced by the interaction between the selected abrasive, the work material - glass, and the water from the water-based magnetic fluid. The resulting surface of the glass balls is thus extremely smooth (9~13 nm) and damage free. The process is highly accurate due to precise control of the polishing load and use of effective abrasives. The material removal rates offer a wide range enabling precise material removal in the final stages to achieve high finish and form.

5.3.3 Good Sphericity:

During material removal from a spherical surface, the load acting on the work material increases when the larger diameter portion enters the contact area. This phenomenon leads to higher material removal from that portion. This process of material removal continues, that results in decreasing the sphericity of the balls, also called out-of-roundness. The process is carried out till the desired sphericity is obtained when the abrading tracks are uniformly distributed over the whole ball surface. MFP gives reasonable values of sphericity even during the initial stage when sphericity is not critical. During the semi-finishing stage, good sphericity values are accomplished and controlled. The sphericity is further improved in the final finishing stage, though the main emphasis at this stage is achieving good surface finish.

In the conventional lapping for balls, the material is removed by the V-groove lapping. Recycling of the balls (i.e., from the output of the container to the input of the groove plate and from the output of the groove plate to the input of the container) is not only for automatic feeds but also for changing the lapping contact position. The ball is re-input into the groove randomly, therefore the lapping track over the whole ball surface is random and thus over a very large number of lapping runs. it is uniform. Thus, the sphericity is improved after lapping.

In MFP, there are three contact-points to each ball to bring two main motions: rotation around the axis parallel to the contact area and spinning around the axis vertical to the contact area. The analogy of this polishing mechanism with the fundamentals of machining would be: the rotation of the ball is the motion for polishing and the spinning motion is the feed for polishing. The polishing track all around the ball is uniform due to its spinning motion during polishing. Thus a good sphericity can be obtained by MFP

5.4 Abrasives:

The abrasives used in the final stage of MFP are often softer than the workmaterial, still they are very effective in achieving good material removal rates as well as good finish and form. Table 5.1 gives a list of the abrasives used in this study with their hardness. These abrasives offer two different mechanisms of material removal and hence, can be classified into two groups, one predominantly for mechanical polishing and the other for CMP depending on their hardness and chemical reactivity with respect to the work material in a given environment

Diamond paste is also used in the experiments to study its effect and compare it with other abrasive slurries. Diamond abrasives can be used in MFP, however, its use is not recommended as other abrasives are equally or more effective in spite of their low hardness values than the work material itself. Also these abrasives give the same or better results as by diamond paste.

Table 5.1 Abrasives used in MFP for this study.

Abrasive	Hardness	
	Mohs	Knoop (kg/mm^2)
Cerium Oxide (CeO_2)	6	-
Aluminum Oxide (Al_2O_3)	9	2150
Silicon Carbide (SiC)	9.2	2500
Boron Carbide (B_4C)	9.3	3200
Diamond	10	7000

Fine grain size boron carbide (B_4C), silicon carbide (SiC), aluminum oxide (Al_2O_3), and diamond gel which are harder than the work material are used for mechanical polishing to achieve high material removal rates and reach desired diameter and geometry rapidly. The material removal in this case is considered by mechanical microfracture

5.5 Polishing Pad:

The polishing pads used in this study are made by Buehler Ltd. and sold under the trade names 'Chemomet', 'Microcloth', and Nylon. Amongst these pads, Chemomet is extensively used and explored in this study. It is also found to give the best surface finish for the glass balls. More on these pads is given in Table

5.2 (as provided by the manufacturer). A sample of each of these is also provided in Appendix C.

Table 5.2 Types of Polishing Pads Used and Their General Properties

Pad Type	General Properties	Recommended Use
Chemomet	Soft, porous, chemical-resistant, synthetic pad	Final polishing stage for glass, semi-conductors.
Microcloth	Soft, versatile, long-napped, synthetic rayon cloth	Final finishing stage of most materials.
Nylon	Soft, woven cloth	Medium hard materials in the sample integrity stage and final polishing stage.

The pad is mounted directly to the drive unit using the pressure sensitive adhesive backing on its other side. In some trial runs it is not fixed (stuck) to the drive unit, but is placed in between the drive unit and the surface to be polished. In the latter case, the pad does not take 100% of the feed of the driving unit. The pad also allows for some allowance in polishing zone and load by providing a cushioning effect. However, it makes it difficult sometimes to determine the exact load that the drive unit should have over the pad which in turn is exerted on the glass balls.

5.6 Experimental Work:

The experimental and test procedure are described below:

- The polishing shaft is driven by a high-speed, high-precision air bearing spindle (PI spindle) with a step-less speed regulation of up to 10,000 rpm.
- The magnetic field is measured using a Gauss / Tesla meter.
- The polishing load is set and monitored by measuring the normal force with a Kistler's piezo-electric dynamometer connected to a charge amplifier and a display (resolution 0.02N).
- The weight of the abrasive used along with the magnetic fluid is measured using a precision balance [Brinkman Instruments - resolution: 0.1mg]. It is the weight of the selected abrasive that corresponds to 1~10% (which ever is selected) of the volume of magnetic fluid used.
- The ball diameter is measured using a digital micrometer [Mitutoyo - resolution: 1µm].
- Full characterization of the balls is required, which includes the size (specific diameter), size variation, sphericity, and surface finish. In this investigation, three to four balls are randomly selected from each batch and each ball is traced 3 times in approximately three orthogonal planes. The out-of-roundness or sphericity is measured using TalyRond 250 and surface roughness using Form TalySurf 120L. According to AFBMA, the sphericity of each ball is defined from the maximum value of the roundness measured on three orthogonal planes of the ball. Similarly, the surface finish of each ball is

taken as the maximum value of three traces along three orthogonal planes of the ball (refer Appendix B for AFBMA ball grades).

- The roundness of the balls is measured at several stages using TalyRond 250 (cut off: 50upr, filter: 2CR). The out-of-roundness trace measures the maximum departure (maximum peak-to-valley height) from a true circle and as such it denotes roundness.
- The surface finish of the balls is measured and analyzed at several stages using:
    - Form TalySurf 120L (cut off: 0.25mm, evaluation length: 6 cut off, filter: ISO_2CR).
    - ZYGO laser interference microscope,
    - Atomic Force Microscope (AFM)

5.7 Evaluation of Surface Integrity

In the present study, the surface roughness and the out-of-roundness of the glass balls are measured and analyzed at several stages for evaluating surface integrity. If material removal rates are very low but the surface finish is reasonably good, then this indicates that a particular set-up could be used for the final finishing stage. The surface roughness values thus are important for the investigation of various stages in MFP – initial high removal stage, semi-finishing, and final finishing. In case of an undesired set-up, the polishing shaft is eccentric (with respect to the polishing chamber) as a result of which the sphericity i.e. out-of-roundness values of the balls go higher.

Chapter 6

Design of Polishing Shaft

Polishing of glass balls using the MFP technology used for the finishing of silicon nitride ceramic balls illustrates MFP's wide capabilities. MFP is being used to finish ceramic (silicon nitride and alumina) balls to give superior surface finish and sphericity. The MFP technology allows changes in regard to parameters like work material, finish, quality, and quantity. In this study, the work material is glass. With minor design changes, the MFP technique could be readily used to finish glass balls.

6.1 Polishing Apparatus

The polishing apparatus that includes the polishing chamber, an air bearing spindle, acrylic float, and magnetic fluid is essentially as that used for finishing silicon nitride balls [Jiang and Komanduri, 1997]. The polishing shaft however is re-designed. The free end of the spindle is 1.9" in diameter and has four screw holes at a PCD of 1.5", 90° apart. The polishing shaft is attached to the spindle with set screws.

The dimensions of the polishing chamber and the diameter of the glass balls [5.012mm (0.1973inch)] are important considerations and these act as constraints. The polishing chamber is of the form of a hollow cylinder. The inner diameter of the chamber is 2.9" and the outer diameter is 3.45". The depth of the chamber is 4.15". It has a solid base, which houses a bank of permanent magnets (Nd-Fe-B, residual magnetization 10500 gauss), with alternate N and S magnets. A strong magnetic field acts on the inside of the chamber concentrated at the bottom, where polishing takes place. The inside wall of the chamber is covered with an iso-propylene rubber sheet. Hence, the actual polishing chamber diameter is reduced slightly by twice the thickness of the rubber sheet. The polishing zone between the shaft, the float on the bottom, and the rubber lining. A strong buoyant force in this zone acts upon the non-magnetic balls.

6.2 Design Considerations

The following are some important design considerations for the polishing shaft:

6.2.1 Diameter Constraints

The polishing shaft should have an outer diameter such that lowering the shaft into the polishing chamber is easy and the balls make contact approximately at the center of the thickness of the shaft. To facilitate this, the dimensions of the polishing chamber as well as the shaft diameter have to be considered carefully. The gap between the rubber sheet and the shaft should not be too wide and this is particularly critical when polishing balls of very small diameters ≤ 9/32". If the gap is wider there is a chance that the balls slip out of the polishing zone and get trapped between the rubber sheet and the polishing shaft. Also, the balls can roll out as polishing proceeds and remain unprocessed. At the end of the polishing run, when the chamber is cleaned, the balls that remain unprocessed (due to slipping or rolling out) can again get mixed with the processed balls. It can sometimes be difficult to notice this, in which case the polishing that follows such runs does not yield the desired results.

6.2.2 Wear

Though not desired, the shaft wears with every polishing run. The wear is more during the initial stage, when coarser abrasives are used for high material removal. The wear on the shaft follows the geometry of the balls by forming a groove. Hence, smaller balls form a smaller groove and larger balls would make a bigger groove. The groove depth increases with each polishing run. After a certain number of polishing runs and a specific groove depth, the polishing shaft has to be re-machined. The wear on the polishing shaft has to be considered during the designing stage, as it effects life. Though the shaft can be re-machined and re-used, the life of the polishing shaft is limited by its length, i.e. till it reaches the screws with which it is attached to the spindle. Therefore, the length should be properly taken into account, such that the shaft can be used several times.

6.2.3 Three-point Contact

The polishing process gives best results when there is a three-point contact of the balls to the wall of the chamber i.e. the rubber, the float on the bottom and the shaft. The balls should be retained along the periphery throughout the polishing run and should not be allowed to scatter or roll to the center where there is no polishing action. For this purpose the shaft end that actually makes contact with the balls is machined with a certain taper/angle, such that the balls stay in the actual polishing zone.

Also, at the time of setting-up of each run, it is convenient to lower the shaft into the chamber. Any balls that are slightly off the rubber lining are automatically pushed towards the periphery and aligned properly as desired. Other researchers have reported that a 30° taper/angle between the outer and inner diameters of the polishing shaft gives best results with respect to sphericity and material removal. The arrangement should be such that approximately the center of the ball matches with the center of the inclination of the polishing shaft.

However, for a particular batch as the diameter of the balls reduces due to polishing, the point of contact of the balls with the shaft continuously shifts and moves away from the center. If the as-received diameter of the balls is taken into account in the design of the shaft, there are chances that during the final stages the balls may not contact the polishing shaft on the inclined surface at all. Therefore, the design of the polishing shaft should be done taking into consideration the final finish diameter of the balls having point of contact in the final finishing runs approximately at the center of the taper.

6.3 Final Design

Figure 6.1 shows the final design of the polishing shaft. The outer diameter of the polishing shaft is 2.770" with a gap of < 0.15". Thus, the balls can be restrained to the polishing zone within the groove and kept from rolling out through the gap. The thickness of hollow polishing shaft is 0.1725" such that the inner diameter becomes 2.425". In this way, the center of the ball approximately makes contact at the center of the shaft thickness.

The inner diameter of the shaft is greater than the pitch circle diameter, PCD, of the bolt circle on the spindle. Thus, it leaves comfortable allowance for reaching through the shaft to the screws with which the shaft is attached to the spindle. Also, cleaning the shaft after every run becomes easy, as there is no need of a recess to be made to reach the screws. The need of a recess however would arise for balls of larger diameters i.e. 0.5" and more. The upper surface of the shaft should precisely mate with the free end of the spindle. Therefore, another design requirement is that the upper surface be perpendicular to the axis of the spindle and the outer surface of the polishing shaft be parallel to the axis. Hence, the tolerance for parallelism and perpendicularity is set to 0.001". With this design, vibrations of the polishing shaft can be minimized. An inward taper of 30° from the OD to the ID is necessary as per the discussion above for best results of polish. The total height of the shaft is fixed at 3.0". The shaft should not be too heavy, which would cause to balancing problems. Austenitic stainless steel is used as the material for the shaft as it is non-magnetic and also resistant to corrosion. In this design, the shaft can be used only to a certain diameter range of balls to be polished. When balls of different diameter range have to be polished it is recommended that a different shaft be used as per the design considerations and ball diameter.

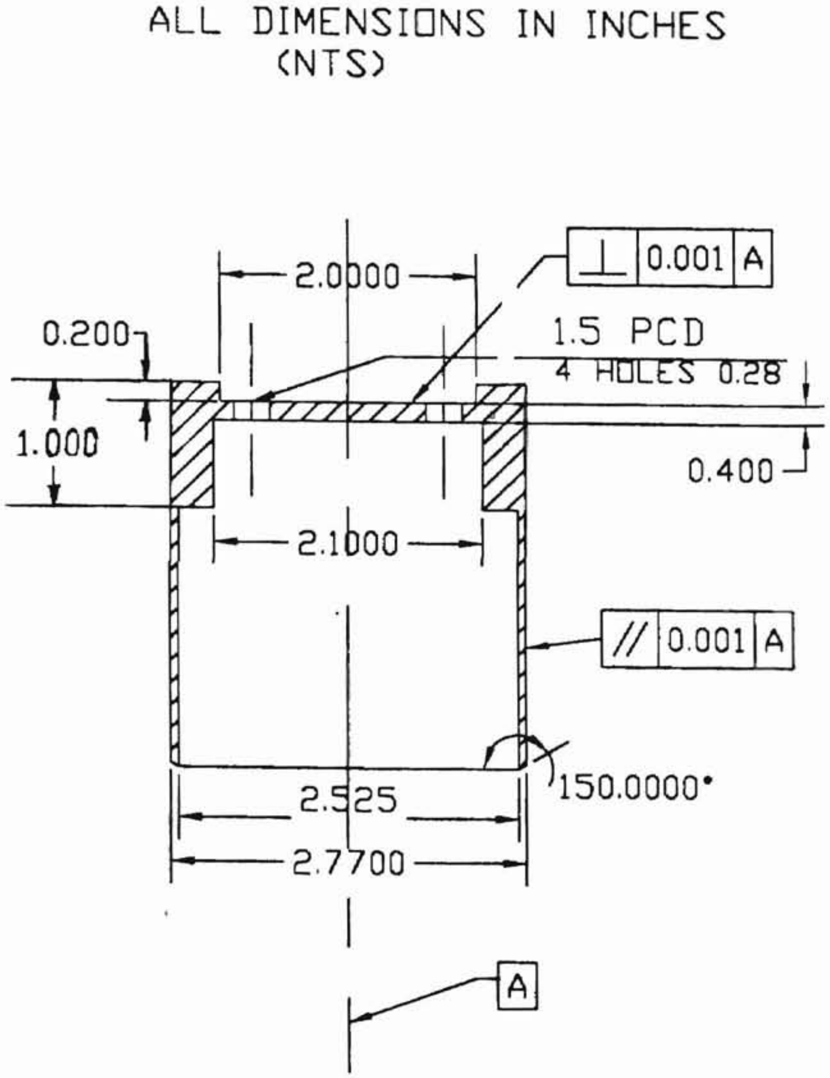


Figure 6.1 Final Design of the Polishing Shaft

Chapter 7

Application of the Taguchi Method to Determine Optimum Process Parameters

7.1 Introduction

Since the late 1940s, Dr. Taguchi introduced several statistical concepts for quality improvement. The Taguchi method was developed after the Second World War by Dr. Taguchi, who was in charge of improving R&D productivity and enhancing product quality at the Electrical Communication Laboratories (ECL), Japan [Dr. Genichi Taguchi, 1990; Roy, 1990].

Jiang and Komanduri [1997] investigated the optimum polishing conditions in MFP using the Taguchi method to achieve superior finish in the polishing of ceramic (Si_3N_4) balls with boron carbide abrasive (grit size 1500). It is a classic example of a successful application of the Taguchi method to MFP, where finishing capabilities of MFP can be investigated very efficiently. The present investigation follows this methodology in considerable detail and extends it to the finishing of glass balls for determining the optimum polishing conditions by MFP. The optimal polishing conditions derived from the Taguchi Experimental Design are further used in polishing of the glass balls with cerium oxide and a synthetic pad.

7.2 Test Conditions and Parameters:

The main objective is to determine the effect of the variable parameters on the surface finish during CMP by CeO_2 abrasive. Table 7.1 shows the test conditions used for the Taguchi Experimental Design. Parameters which affect the quality of the glass balls finished by the MFP process, include the workmaterial, the abrasive used (type, grit size, and percent volume), the rotational speed of the shaft.

Table 7.1 Test Conditions Used

Work Material	Leaded Glass Balls As-received: 1. Diameter: 5.012 mm (0.1973inch) 2. Surface roughness: Ra: 475~665 nm Rt: 4585~6263 nm 3.Sphericity: 2.05~2.55 μm
Abrasive	Type: CeO_2 Size: 5 μm Concentration: 1%, 3%, 5%
Load per Ball (N)	0.1, 0.25, 0.5
Speed (rpm)	500, 750, 1000, 1500
Run Time (min)	30, 60, 90
Magnetic Fluid	Water-based (W-40) Saturation magnetization at 25°C: 400 Gauss Viscosity at 27°C: 25 Cp

For a given abrasive-workmaterial combination, three polishing parameters, namely, (i) the polishing force, (ii) the abrasive concentration, and (iii) the polishing speed are considered to have major influence on the surface quality by MFP. Each factor is investigated at three levels to determine the optimum settings for the polishing process in this study. The smallest standard 3-level OA (orthogonal array) L_9 (3^4) which has four 3-level columns (for a maximum of four parameters that can be tested) available is chosen for this case. The factors and their levels are given in Table 7.2.

Table 7.2 Test Parameters and Their Levels

Level	Parameters			
	A: Load	B: Abr.Vol.%	C: Speed	D: Time
1	0.1N	1%	500	30
2	0.25N	3%	750	60
3	0.5N	5%	1000	90

7.3 Experimental Design:

The Taguchi Experimental Design 1 as shown by Table 7.3 involves only three parameters and the fourth parameter, time, is introduced in Design 2 shown by Table 7.4. The variable parameters, namely, load (N), abrasive concentration (vol.%), speed (rpm), and time (min) are placed in the four columns (A, B, C, and D) of the OA L_9 (3^4). The outputs, namely, the surface finish (Ra and Rt) values are the test results measured using a Form TalySurf 120L (cut-off: 0.25mm, evaluation length: 6 consecutive cut-off, Filter: ISO_2CR). The vertical columns show the levels of polishing parameters specified in the study and each row represents a trial condition. The performance characteristic value from each trial run are then used to compute the statistical performance characteristic (discussed in Chapter 8), which is affected by any one parameter but independent of others.

Table 7.3 Taguchi Experimental Design 1

Trial	Factors Investigated			Test Results	
No.	Load (N)	Speed (rpm)	Abr. Vol.%	Ra (nm)	Rt (nm)
1	0.1	500	1		
2	0.1	750	3		
3	0.1	1000	5		
4	0.25	500	3		
5	0.25	750	5		
6	0.25	1000	1		
7	0.5	500	5		
8	0.5	750	1		
9	0.5	1000	3		

Table 7.4 Taguchi Experimental Design 2

Trial	Factors Investigated				Test Results	
No.	Load (N)	Speed (rpm)	Abr. Vol.%	Time (min)	Ra (nm)	Rt (nm)
1	0.1	500	1	30		
2	0.1	1000	3	60		
3	0.1	1500	5	90		
4	0.25	500	3	90		
5	0.25	1000	5	30		
6	0.25	1500	1	60		
7	0.5	500	5	60		
8	0.5	1000	1	90		
9	0.5	1500	3	30		

7.4 Evaluation of Taguchi Experimental Design Results

The experiments (batch 1 to batch 62) were jointly conducted with N. Chandrasekaran, while the measurement of the surface roughness values as well as the analysis of the results of the Taguchi experimental design was done individually for comparison.

The Taguchi experimental design results are analyzed to determine the optimum polishing conditions, and to estimate contribution of individual parameters. This is done according to the level of variable process parameters at different stages of polishing. Typically a batch of 40 balls is used in a run (though fewer balls are used in some cases). Taguchi experimental design is employed for two batches, numbered 2 through 10, and 11 through 19 (Taguchi Experimental Design 1), and batch numbers 51 through 59 (Taguchi Experimental Design 2).

The surface roughness readings are taken at random in several areas for different balls of the same run. The surface quality of the polished balls is evaluated in terms of surface roughness values – both Ra and Rt. The average of these readings is used in the analysis.

7.5 Averaging surface roughness values:

The average value of surface roughness (Ra or Rt) is given by:

$$\overline{Ri} = \sum_{j=1}^{r} \frac{R_{ij}}{r} = \frac{1}{3}\left(R_{i1} + R_{i2} + R_{i3}\right)$$

where i is the run number, r is the number of region for which surface roughness values are taken for that particular run. E.g., refer to Table 8.1, for Test No.1.

Average Ra is given by: $\overline{Ra_1} = \frac{1}{3}(96 + 65 + 60) = 74$ nm

Average Rt is given by: $\overline{Rt_1} = \frac{1}{3}(1501 + 1054 + 964) = 1173$ nm

The average values of Ra and Rt are considered as an average deviation from the target value. The target value has to be as minimum as possible, and hence can be considered as zero (i.e. Ra and Rt $\rightarrow 0$).

7.6 Signal-to-Noise Ratio (S/N):

The signal-to-noise (S/N) ratio is defined by the logarithmic function of the mean square deviation (MSD) around the target. It is expressed in decibel units (dB). In the present study, smaller S/N ratio indicates better results of the polishing conditions. The S/N ratio is given by the equation:

$$S/N = -10 \log_{10} \text{MSD}$$

The constant 10 in the above equation magnifies the S/N ratio for easier analysis. The negative sign sets the signal-to-noise ratio of larger-the-better relative to the square deviation of the smaller-the-better. In other words, the equation is set to give larger signal with a smaller noise. The mean square deviation (MSD) is calculated from the sum of the squares of roughness values of all data points. Since the target value tends to zero for all random samples of roughness (Ra and Rt $\rightarrow 0$), the MSD only utilizes sum of the squares of the roughness values $(R_{ij} - 0)^2$. The MSD value reflects the average R_i as well as the variance ΔR_{iij} of each trial run data series. MSD is given by the following equation:

$$MSDi = \sigma_{ij}^2 = \frac{1}{r}\sum_{j=1}^{r}(R_{ij})^2 = \frac{1}{r}\sum_{j=1}^{r}(\overline{R_i} + \Delta R_{ij})^2$$

$$= \frac{1}{r}\left(\sum_{j=1}^{r}(\overline{R_i})^2 + 2\sum_{j=1}^{r}\overline{R_i}\Delta R_{ij} + \sum_{j=1}^{r}(\Delta R_{ij})^2\right)$$

$$= \frac{1}{r}\left(\sum_{j=1}^{r}(\overline{R_i})^2 + \sum_{j=1}^{r}(\Delta R_{ij})^2\right)$$

(since ΔR_{ij} are normally distributed, $2\sum_{j=1}^{r}\overline{R_i}\Delta R_{ij} = 0$)

The MSD_i reflects the deviation of the trial run result from the target value of zero. The above equation when substituted for MSD_i in the equation for S/N yields:

$$S/N = -10 \log10 \, MSDi = -10 \log \frac{1}{r}\sum_{j=1}^{r}(R_{ij})^2$$

where i is the trial run number, σ_i is the standard deviation in a trial, and r is the number of surface roughness values for that trial.

For example, from Table 8.1, Test No.1 we get:

MSD for Ra

$$MSD_i = \frac{1}{3}(R_{i1}^2 + R_{i2}^2 + R_{i3}^2)$$

$$MSD_{Ra1} = \frac{1}{3}(96^2 + 65^2 + 60^2)$$

Therefore,

$$S/N \text{ for } Ra_1 = -10 \log MSD_{Ra1} = -37.54 \text{ dB}$$

Similarly, MSD for Rt:

$$\mathrm{MSD}_{\mathrm{Rt1}} = \frac{1}{3}\,(1501^2 + 1054^2 + 964^2)$$

Therefore,

$$\mathrm{S/N\ for\ Rt_1} = -10 \log \mathrm{MSD}_{\mathrm{Rt1}} = -61.56\ \mathrm{dB}$$

7.7 Level Average Response Analysis Using Average Values of Each Run

The orthogonal array (OA) of experiments also enables analysis based on the average response of each parameter over the polishing process. The polishing conditions with one parameter kept constant give different results showing the pronounced effect of the other variable parameters. But in the design of experiments, two process parameters are kept as variables for any trial run. The level average response analysis is based on combining and averaging the response associated with each level for each factor that appears once in every three trial runs. The level average analysis is very important and gives valuable comparison of the process parameters and their comparative effectiveness.

For example, referring to Table 7.3, it can be seen that the first level of factor A occurs in experiment numbers 1, 2, and 3. Where as, all three levels of the other factors B and C appear once in these experiments. The second level of A occurs in the next set of experiments, i.e. 4, 5, and 6, and all three levels of factors B and C also occur in these three experiments. Similarly, the third level of factor A occurs in the next set of experiments, numbers 7, 8, and 9, and all three levels of factors B and C also appear in these experiments. This means that the level conditions of factors B and C are the same with different levels of factor A. Thus, the response of factor A is counteracted by the effects of factors B and C. The optimum level of factor A can be determined from the average data of the three experiments wherein one level of factor A occurs. Similarly the level average analysis for other factors B and C can be done.

For example referring to Table 8.1 the average performance of factor A at level 1 (i.e. load = 0.1N) can be determined by adding the roughness values for tests including that load level and then dividing by the number of such tests. A load level of 0.1N occurs in the tests numbered 1, 2, and 3. The average effect of this load level is therefore calculated by adding the results for these tests and then dividing by 3. Average effect of this load level can be analyzed by taking into consideration Ra and Rt values separately. Sample calculations are shown below:

$$R_{a(A1)} = \frac{1}{3}\,(74^2 + 47^2 + 306^2) = 142\text{nm}$$

$$R_{t(A1)} = \frac{1}{3}\,(1173^2 + 947^2 + 3479^2) = 1866\text{nm}$$

In a similar manner the average effects for the other two parameters – B and C, i.e. abrasive and speed are calculated in the Taguchi Experimental Design 1. The pair-wise balancing property of the orthogonal design used in this analysis enables only one parameter to be effective for a given set of experiments. The surface quality remains independent of the other parameters and thus the average effect of the chosen parameter can be analyzed with ease. The S/N values provide a better understanding of the analysis as they are more objective, while the average values of Ra and Rt are more a perception. Smaller values for Ra and Rt indicate good surface finish and quality.

7.8 Level Average Response Analysis Using S/N values:

The level average response analysis using S/N values is more objective, though it is abstract and has no physical meaning of the quality or parameter response. It is similar to the analysis using Ra and Rt values, the only difference being this method uses the S/N values. The purpose of this is to obtain S/N ratio as large as possible relative to the mean (that is the target Ra and Rt → 0) and variation as small as possible. To analyze the results of experiments involving multiple runs, use of the S/N ratio is preferred over the average of results. Tables 8.3 (a) and 8.3 (b) show the level average analysis using S/N ratio for Ra and Rt, respectively. The analysis using S/N ratio offers 2 main advantages:

1. Provides guidance to the selection of the optimum level based on least variation around the target and also on the average value closest to the target.
2. Offers objective comparison of two sets of experimental data with respect to variation around the target and the deviation of the average from the target.

7.9 Analysis of Variance (ANOVA)

Different levels of the variable process parameters and different combination of these levels are used during the analysis. The optimum polishing conditions give the best suitable level of each variable process parameter and the best combination of these levels. However, the analysis is incomplete if one doesn't know how strong is the influence of each one of these parameters on the polishing process. Does polishing load play any role in achieving the best surface finish? Is abrasive concentration the dominant factor? Apart from this, there remains some unknown factor in the process, which also directly affects the results of the polishing process and has to be taken into account.

Taguchi design of experiments replaces the full factorial experiment with a lean, less expensive, faster, partial factorial experiment. Since the partial experiment is only a sample of the full experiment, the analysis of the partial experiment must include analysis of the confidence that can be placed in the results. A standard statistical technique, Analysis of Variance (ANOVA) is used to provide a measure of confidence. The technique does not directly analyze the data, but rather determines the variability (variance) of the data. Analysis of variance (ANOVA) is used to study and evaluate the influence of individual parameter on the process i.e. the response magnitude (%). It can be used to identify and quantify the sources of different trial run results from different trial runs.

The experiments are designed in a way so as to extract useful information from the results of the trial runs that vary due to change in the polishing conditions. These are also the variations from controlled parameter level conditions. However, the results vary due to some variations produced by unknown parameters, called random interference (noise factors). These are the variations form uncontrolled parameter conditions.

In ANOVA, the sum of the squares of the standard deviation is used as it is additive (the standard deviation not being additive). The standard deviation given by, $\sigma_T^2 = \sigma_A^2 + \sigma_B^2 + \sigma_C^2$ is used for the calculation and analysis of the variation or variability from each and every factor or parameter. The sum of the squares of the standard deviation (taking into consideration all the condition parameters, e.g. SS_A, SS_B, SS_C) and the square of the error function (SS_e) is the total variation SS_T. Thus,

$$SS_T = SS_A + SS_B + SS_C + SS_e$$

1. Total Variation (SS_T):

In this study, results are analyzed from nine trial runs (hence, n=9). The variations in the results are caused by the controlled parameter settings (i.e. different polishing conditions) and the uncontrolled parameters which are also called the unknown parameters. The sum of the squares of the deviation (SS) of the resulting data from the trial runs represents the total variation. This is given by:

$$SS_T = \sum_{i=1}^{n} (y_i - \overline{y})^2$$

$$= \sum_{i=1}^{n} y^2_i - \sum_{i=1}^{n} 2y_i\overline{y} + \sum_{i=1}^{n} \overline{y^2}$$

$$= \sum_{i=1}^{n} y^2_i - 2n\overline{y^2} + n\overline{y^2}$$

$$\therefore\ SS_T = \sum_{i=1}^{n} y^2_i - \frac{G^2}{n}$$

where G is the sum of the resulting data of all the trial runs ($=\Sigma y_i$). The values of the sum levels (Σy_i) and the squares of the sum (Σy_i^2) are calculated from the signal-to-noise (S/N) ratios and are shown in Table 8.7, and n (=9) is the total number of trial runs.

Degrees of Freedom (DOF): This is an important and useful concept that is difficult to define. Degree of Freedom is the measure of the amount of information that can be uniquely determined from a given set of data. For data concerning a factor, DOF equals one less than the number of levels. In this study, the design of experiments uses a 3 level factor and therefore, has 2 DOF. The concept of DOF can be extended to the experiment with *n* trial runs and *r* repetitions of each trial i.e. *(n* x *r)* trial runs. In this case, the number of trial runs equals (3 x 3) = 9. The total DOF is denoted by F_T and equals the number of trial runs minus one. Therefore, $F_T = 9 - 1 = 8$.

Referring to Table 8.7 the total variation SS_T is calculated as:

$$\text{For Ra:} \quad SS_T = 17446.18 - \frac{(-386.46)^2}{9} = 851.31$$

$$\text{For Rt:} \quad SS_T = 41699.53 - \frac{(-608.82)^2}{9} = 514.26$$

2. Trial Variation of Variable Parameters (SS_K):

The results from the variable parameters are used to determine the trial variation caused by each parameter. The sums of the squares of the deviation are tabulated as per different levels involving that parameter. The trial variation of parameters (SS_K) is given by the following equation:

$$SS_K = \sum_{j=1}^{t} t \times (\bar{y}_j - \bar{y})^2 = \sum_{j=1}^{t} \left(\frac{Sy_j^{\,2}}{t}\right) - \frac{G^2}{n}$$

where K represents the chosen tested parameter; j is the level number of the chosen parameter K; $\overline{y_i}$ is the average of the level for the parameter K; t is the repetition of each level of the parameter K; Sy_i is the sum of all the trial results involving this parameter K for level j; n is the number of trial runs which equals 9 in this study. Tables 8.3 (a), 8.3 (b), 8.6 (a), 8.6 (b), 8.6 (c), and 8.6 (d) give the values for Sy_l Ra and Rt. Thus, the trial variation for each parameter can be calculated as shown below.

For e.g. referring to Tables 8.3 (a) and 8.7, for Ra

$$SS_{load} = \frac{(-120.72)^2 + (-136.08)^2 + (-129.67)^2}{3} - \frac{(-386.46)^2}{9} = 39.88$$

$$SS_{abr.vol\%} = \frac{(-137.12)^2 + (-123.65)^2 + (-125.71)^2}{3} - \frac{(-386.46)^2}{9} = 36.81$$

$$SS_{speed} = \frac{(-102.34)^2 + (-118.36)^2 + (-165.78)^2}{3} - \frac{(-386.46)^2}{9} = 727.27$$

Similarly, referring to Tables 8.3 (b) and 8.7, for Rt

$$SS_{load} = \frac{(-192.38)^2 + (-209.62)^2 + (-206.82)^2}{3} - \frac{(-608.82)^2}{9} = 57.66$$

$$SS_{abr.vol\%} = \frac{(-206.35)^2 + (-202.16)^2 + (-200.31)^2}{3} - \frac{(-608.82)^2}{9} = 6.38$$

$$SS_{speed} = \frac{(-183.72)^2 + (-193.90)^2 + (-231.20)^2}{3} - \frac{(-608.82)^2}{9} = 416.59$$

The sum of the square (SS) deviation of each parameter is also used to calculate the variance (V_K). This is given by SS_K/F_K, where F_K is the degree of freedom. F_K is the number of levels for each parameter minus one. Thus, F_K equals 3-1=2.

3. Trial Variation of Unknown Parameters or Random Variations (SS_e):

The influence of random variations or unknown parameters, if present, is calculated from the following:

$$SS_e = SS_T - SS_{load} - SS_{abr.vol.\%} - SS_{speed}$$

For e.g., referring to Table 8.8, for Ra

$$SS_e = 851.31 - 39.88 - 36.81 - 727.27 = 47.35$$

Similarly, from Table 8.9, for Rt

$$SS_e = 514.26 - 57.66 - 6.38 - 416.59 = 33.63$$

The variance of the unknown parameters $V_e = SS_e/F_e$, where $F_e = 3-1=2$. The percentage influence is then calculated from these values as shown in Tables 8.8, 8.9, 8.11, and 8.12.

Chapter 8

Results and Discussion

8.1 Taguchi Experimental Design Results and Evaluation

Table 8.1 gives the average Ra and Rt values and signal-to-noise ratio for both Ra and Rt for other trial runs. Smaller average values and larger signal-to-noise ratios indicates better results with respect to surface finish. The surface integrity of the polished balls is better when both the variability (MSD) and average values are smaller. This means uneven amount of surface damage is worse than an even amount of surface damage. Hence, the optimum conditions are those that correspond to the lowest values of Ra and Rt.

Referring to Table 8.2 (a), the only parameter that directly affects the surface quality is the load (at different levels) and the other two parameters, namely, speed and abrasive volume (%) do not affect the surface quality. Similarly, the pair-wise balancing property applies for analysis of other parameters also when chosen individually, as shown in Tables 8.2 (b), and 8.2 (c). This is also shown graphically in Figure 8.1 (a) for Ra and Figure 8.1 (b) for Rt. The optimum conditions for the analysis of runs 11 through 19 (test numbers 1 through 9), therefore, are determined as:

For both Ra and Rt: Load: 0.1N; Abrasive volume: 5%; Speed: 500rpm.

Table 8.1 Taguchi Experimental Design 1

Batch No.	Test No.	Surface Finish: Ra (nm)			Average Ra (nm)	MSD (Ra)	S/N ratio (dB)
		R1	R2	R3			
11	1	96	65	60	74	5680	-37.54
12	2	47	45	49	47	2212	-33.45
13	3	315	302	302	306	93878	-49.73
14	4	156	169	70	132	19266	-42.85
15	5	317	1342	814	824	854683	-59.32
16	6	57	46	45	49	2463	-33.92
17	7	655	734	667	685	470890	-56.73
18	8	25	37	41	34	1225	-30.88
19	9	118	73	170	120	16051	-42.06

Batch No.	Test No.	Surface Finish: Rt (nm)			Average Rt (nm)	MSD (Rt)	S/N ratio (dB)
		R1	R2	R3			
11	1	1501	1054	964	1173	1431071	-61.56
12	2	955	552	1333	947	997873	-59.99
13	3	3663	3312	3463	3479	12126427	-70.84
14	4	2681	1578	1649	1969	4132349	-66.16
15	5	5690	17729	10030	11150	149098147	-81.73
16	6	1279	1445	858	1194	1486677	-61.72
17	7	8175	7381	9878	8478	72961557	-78.63
18	8	924	884	1298	1035	1106679	-60.44
19	9	3101	1014	2688	2268	5956580	-67.75

Table 8.2(a) Average Effect of Load Level (Design 1)

Load Level (N)	Analysis				Average Response	
	Batch No.	Test No.	Ra(nm)	Rt(nm)	Ra(nm)	Rt(nm)
0.10	11	1	74	1173	**142**	**1866**
	12	2	47	947		
	13	3	306	3479		
0.25	14	4	132	1969	335	4771
	15	5	824	11150		
	16	6	49	1194		
0.50	17	7	685	8478	280	3927
	18	8	34	1035		
	19	9	120	2268		

Table 8.2(b) Average Effect of Abrasive Concentration Level (Design 1)

Abrasive Level (vol %)	Analysis				Average Response	
	Batch No.	Test No.	Ra(nm)	Rt(nm)	Ra(nm)	Rt(nm)
1	11	1	74	1173	297	3873
	14	4	132	1969		
	17	7	685	8478		
3	12	2	47	947	302	4377
	15	5	824	11150		
	18	8	34	1035		
5	13	3	306	3479	**158**	**2314**
	16	6	49	1194		
	19	9	120	2268		

Table 8.2(c) Average Effect of Speed Level (Design 1)

Speed Level (rpm)	Analysis				Average Response	
	Batch No.	Test No.	Ra(nm)	Rt(nm)	Ra(nm)	Rt(nm)
500	11	1	74	1173	**52**	1134
	16	6	49	1194		
	18	8	34	1035		
750	12	2	47	947	100	1728
	14	4	132	1969		
	19	9	120	2268		
1000	13	3	306	3479	605	7702
	15	5	824	11150		
	17	7	685	8478		

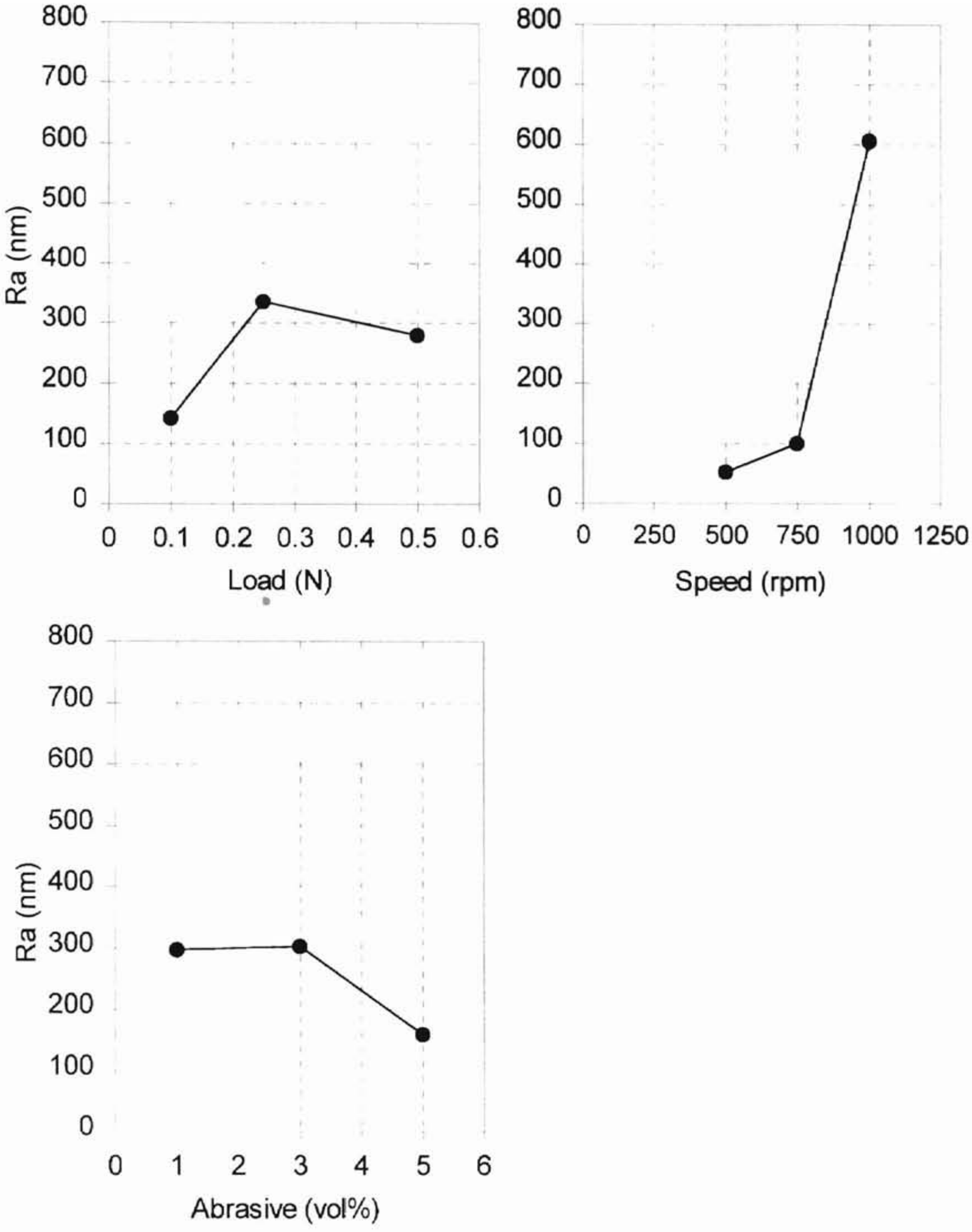


Figure 8.1(a) Response of Each Parameter Level on Surface Finish - Ra (Design 1)

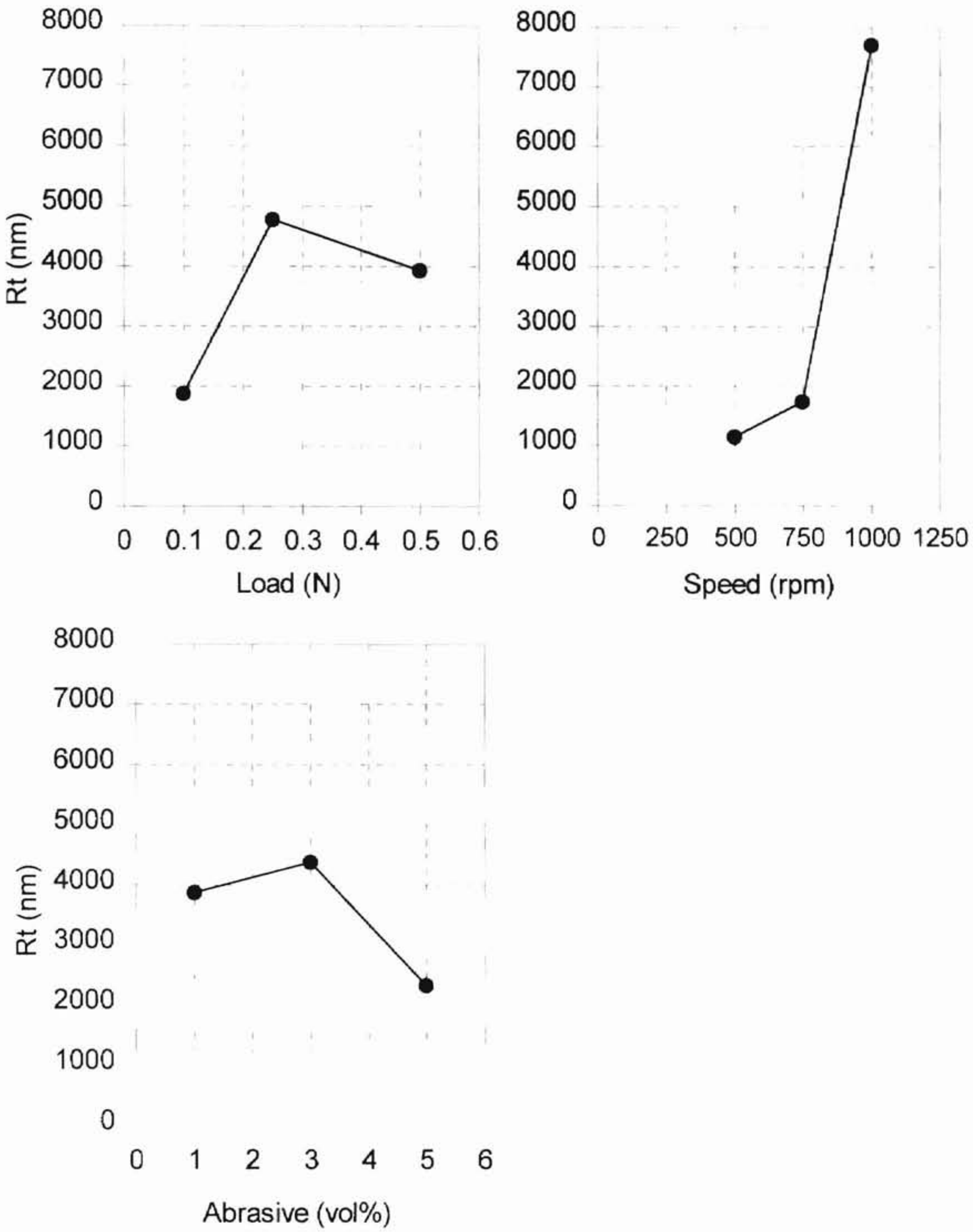


Figure 8.1(b) Response of Each Parameter Level on Surface Finish - Rt (Design 1)

Tables 8.3 (a) and 8.3 (b) show the level average analysis using S/N ratio for Ra and Rt, respectively. It can be noted that the variation in the average values is quite small. In this method, the values are obtained from the equation that sets the signal-to-noise ratio of larger-the-better relative to the square deviation of the smaller-the-better. Hence, larger values of S/N ratio indicate better results. The optimum polishing conditions are determined based on this and are shown in the tables. Therefore, the optimum conditions are as follows:

For Ra: Load: 0.1N; Abrasive volume (%): 3; and Speed: 500rpm.
For Rt: Load: 0.1N; Abrasive volume (%): 5; and Speed: 500rpm.

In this method, however, the variation is smaller and also the values are calculated using the sum of the squares of roughness values. The graphical representation of the level average response analysis using the S/N values is shown in Figures 8.2 (a) and 8.2 (b). Both the mean and the variation are the smallest for the highest S/N value. The condition that gives the best surface finish and quality, therefore, is indicated by the highest S/N value.

Table 8.3(a) Level average analysis using S/N ratio for Ra

(Design 1)

Load Level (N)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy$_i$	Average
0.10	11	1	-37.54	-120.72	**- 40.24**
	12	2	-33.45		
	13	3	-49.73		
0.25	14	4	-42.85	-136.08	-45.36
	15	5	-59.32		
	16	6	-33.92		
0.50	17	7	-56.73	-129.67	-43.22
	18	8	-30.88		
	19	9	-42.06		
Abrasive Level (vol%)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy$_i$	Average
1	11	1	-37.54	-137.12	-45.71
	14	4	-42.85		
	17	7	-56.73		
3	12	2	-33.45	-123.65	**-41.22**
	15	5	-59.32		
	18	8	-30.88		
5	13	3	-49.73	-125.71	-41.90
	16	6	-33.92		
	19	9	-42.06		
Speed Level (rpm)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy$_i$	Average
500	11	1	-37.54	-102.34	**-34.11**
	16	6	-33.92		
	18	8	-30.88		
1000	12	2	-33.45	-118.36	-39.45
	14	4	-42.85		
	19	9	-42.06		
1500	13	3	-49.73	-165.78	-55.26
	15	5	-59.32		
	17	7	-56.73		

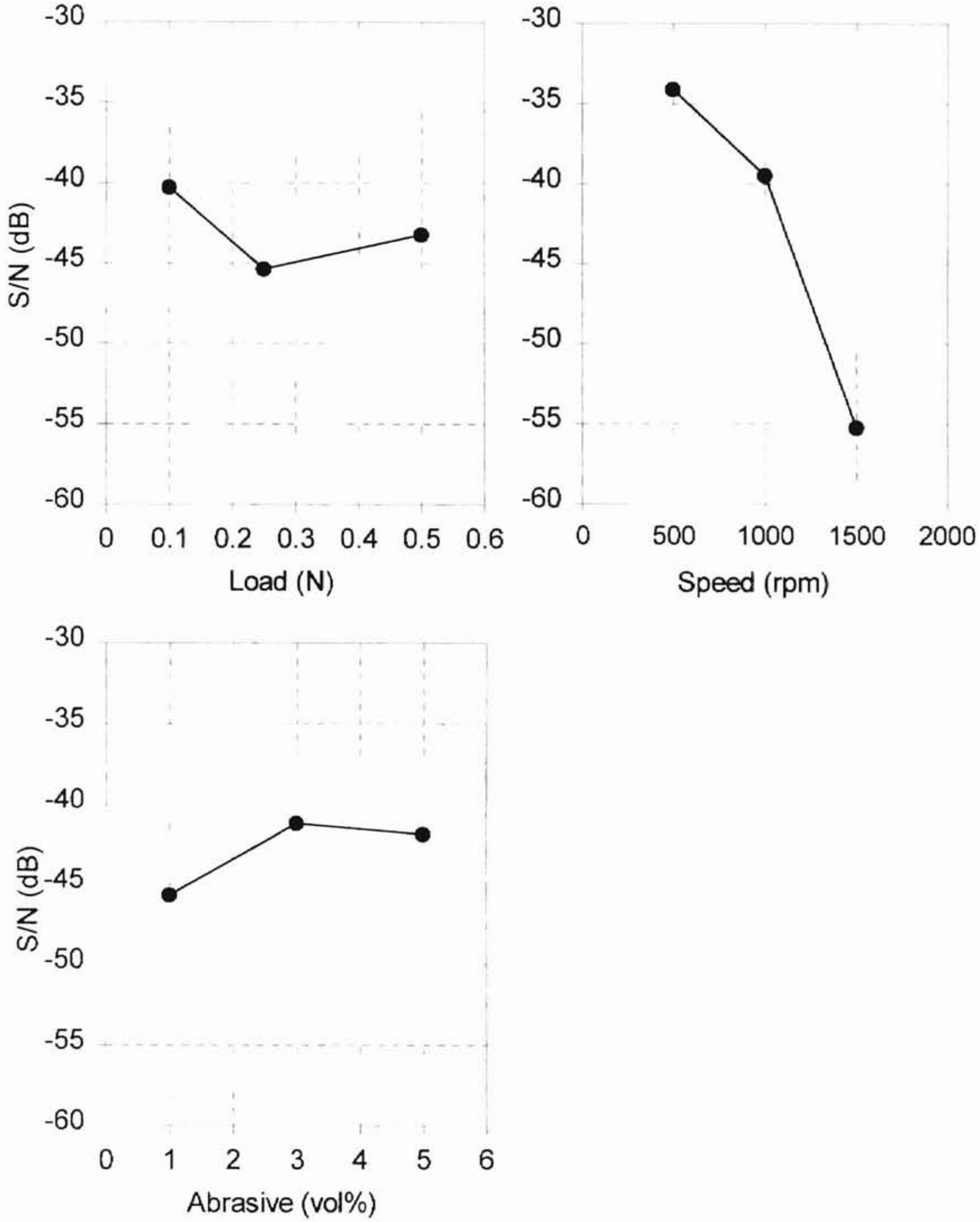


Figure 8.2(a) Response of Each Parameter Level on Surface Finish - Ra using S/N ratios (Design 1)

Table8.3 (b) Level Average Analysis using S/N ratio for Rt (Design1)

Load Level (N)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy_i	Average
0.10	11	1	-61.56	-192.38	**-64.13**
	12	2	-59.99		
	13	3	-70.84		
0.25	14	4	-66.16	-209.62	-69.87
	15	5	-81.73		
	16	6	-61.72		
0.50	17	7	-78.63	-206.82	-68.94
	18	8	-60.44		
	19	9	-67.75		

Abrasive Level (vol%)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy_i	Average
1	11	1	-61.56	-206.35	-68.78
	14	4	-66.16		
	17	7	-78.63		
3	12	2	-59.99	-202.16	-67.39
	15	5	-81.73		
	18	8	-60.44		
5	13	3	-70.84	-200.31	**-66.77**
	16	6	-61.72		
	19	9	-67.75		

Speed Level (rpm)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy_i	Average
500	11	1	-61.56	-183.72	**-61.24**
	16	6	-61.72		
	18	8	-60.44		
1000	12	2	-59.99	-193.90	-64.63
	14	4	-66.16		
	19	9	-67.75		
1500	13	3	-70.84	-231.20	-77.07
	15	5	-81.73		
	17	7	-78.63		

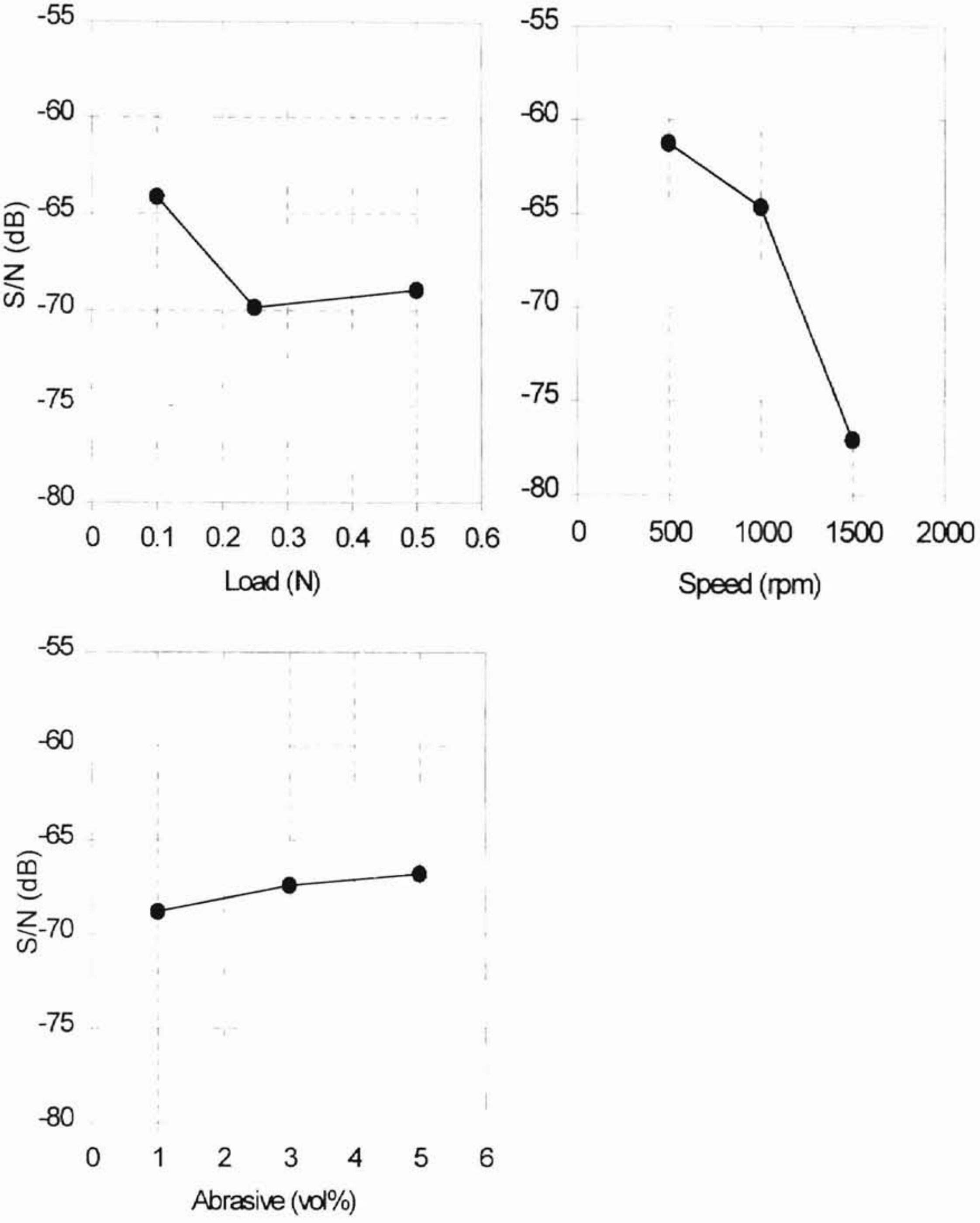


Figure 8.2 (b) Response of Each Parameter Level on Surface Finish - Rt using S/N ratios (Design 1)

The optimum polishing conditions for achieving the best surface finish thus derived from the above two methods of analysis (average effect using roughness values and level average using S/N ratio values) are found to be identical for optimal levels of polishing speed and polishing load but different for the abrasive volume percent for Ra. As discussed before, the roughness values are more a perception while the S/N values are more objective. The difference in the results can be attributed to this fact. Also, it will be shown later that the influence of the abrasive volume percent on the polishing process is low and hence, either 3% or 5% of abrasive volume can be used to achieve best results.

Table 8.4 shows Taguchi Experimental Design 2, where average response of four parameters, namely load, abrasive %, speed, and time is analyzed. The calculation of the average effects of these parameters is done similar to the previous method used in Taguchi Experimental Design 1 (for three parameters). Tables 8.5 (a), 8.5 (b), 8.5 (c), and 8.5 (d) show the average effects of each parameter on the surface finish (Ra and Rt). These are also graphically shown in Figures 8.3 (a) and 8.3 (b). The optimum polishing conditions from the analysis based on the average effect are determined as:

For Ra: Load: 0.1N; Abrasive vol.(%): 5; Speed: 500rpm; Time: 60 min.

For Rt: Load: 0.25N; Abrasive vol.(%): 5; Speed: 500rpm; Time: 60 min.

Table 8.4 Taguchi Experimental Design 2

Batch No.	Test No.	Surface Finish: Ra (nm)			Average Ra (nm)	MSD (Ra)	S/N ratio (dB)
		R1	R2	R3			
51	1	100	90	105	98	9708	-39.87
52	2	191	225	187	201	40692	-46.10
53	3	520	500	606	542	295879	-54.71
54	4	224	193	207	208	43425	-46.38
55	5	190	193	250	211	45283	-46.56
56	6	482	460	601	514	268375	-54.29
57	7	39	34	44	39	1538	-31.87
58	8	266	151	286	234	58451	-47.67
59	9	2158	661	3891	2237	6744589	-68.29

Batch No.	Test No.	Surface Finish: Rt (nm)			Average Rt (nm)	MSD (Rt)	S/N ratio (dB)
		R1	R2	R3			
51	1	1171	1185	1947	1434	2188758	-63.40
52	2	1508	1692	1902	1701	2918177	-64.65
53	3	4536	5832	5244	5204	27362352	-74.37
54	4	1628	1716	1586	1643	2703479	-64.32
55	5	1519	1635	3143	2099	4953012	-66.95
56	6	4347	4174	4800	4440	19786228	-72.96
57	7	521	593	765	626	402772	-56.05
58	8	3337	2306	3792	3145	10277490	-70.12
59	9	29290	7554	27420	21421	555607805	-87.45

Table 8.5(a) Average Effect of Load Level (Design 2)

Load Level (N)	Analysis				Average Response	
	Batch No.	Test No.	Ra(nm)	Rt(nm)	Ra(nm)	Rt(nm)
0.10	51	1	98	1434	**280**	2780
	52	2	201	1701		
	53	3	542	5204		
0.25	54	4	208	1643	311	**2727**
	55	5	211	2099		
	56	6	514	4440		
0.50	57	7	39	626	837	8397
	58	8	234	3145		
	59	9	2237	21421		

Table 8.5(b) Average Effect of Abrasive Concentration Level (Design 2)

Abrasive Level (vol %)	Analysis				Average Response	
	Batch No.	Test No.	Ra(nm)	Rt(nm)	Ra(nm)	Rt(nm)
1	51	1	98	1434	282	3006
	56	6	514	4440		
	58	8	234	3145		
3	52	2	201	1701	882	8255
	54	4	208	1643		
	59	9	2237	21421		
5	53	3	542	5204	**264**	**2643**
	55	5	211	2099		
	57	7	39	626		

Table 8.5(c) Average Effect of Speed Level (Design 2)

Speed Level (rpm)	Analysis				Average Response	
	Batch No.	Test No.	Ra(nm)	Rt(nm)	Ra(nm)	Rt(nm)
500	51	1	98	1434	**115**	**1234**
	54	4	208	1643		
	57	7	39	626		
1000	52	2	201	1701	215	2315
	55	5	211	2099		
	58	8	234	3145		
1500	53	3	542	5204	1098	10355
	56	6	514	4440		
	59	9	2237	21421		

Table 8.5(d) Average Effect of Time Level (Design 2)

Time Level (min)	Analysis				Average Response	
	Batch No.	Test No.	Ra(nm)	Rt(nm)	Ra(nm)	Rt(nm)
30	51	1	98	1434	849	8318
	55	5	211	2099		
	59	9	2237	21421		
60	52	2	201	1701	**251**	**2256**
	56	6	514	4440		
	57	7	39	626		
90	53	3	542	5204	328	3331
	54	4	208	1643		
	58	8	234	3145		

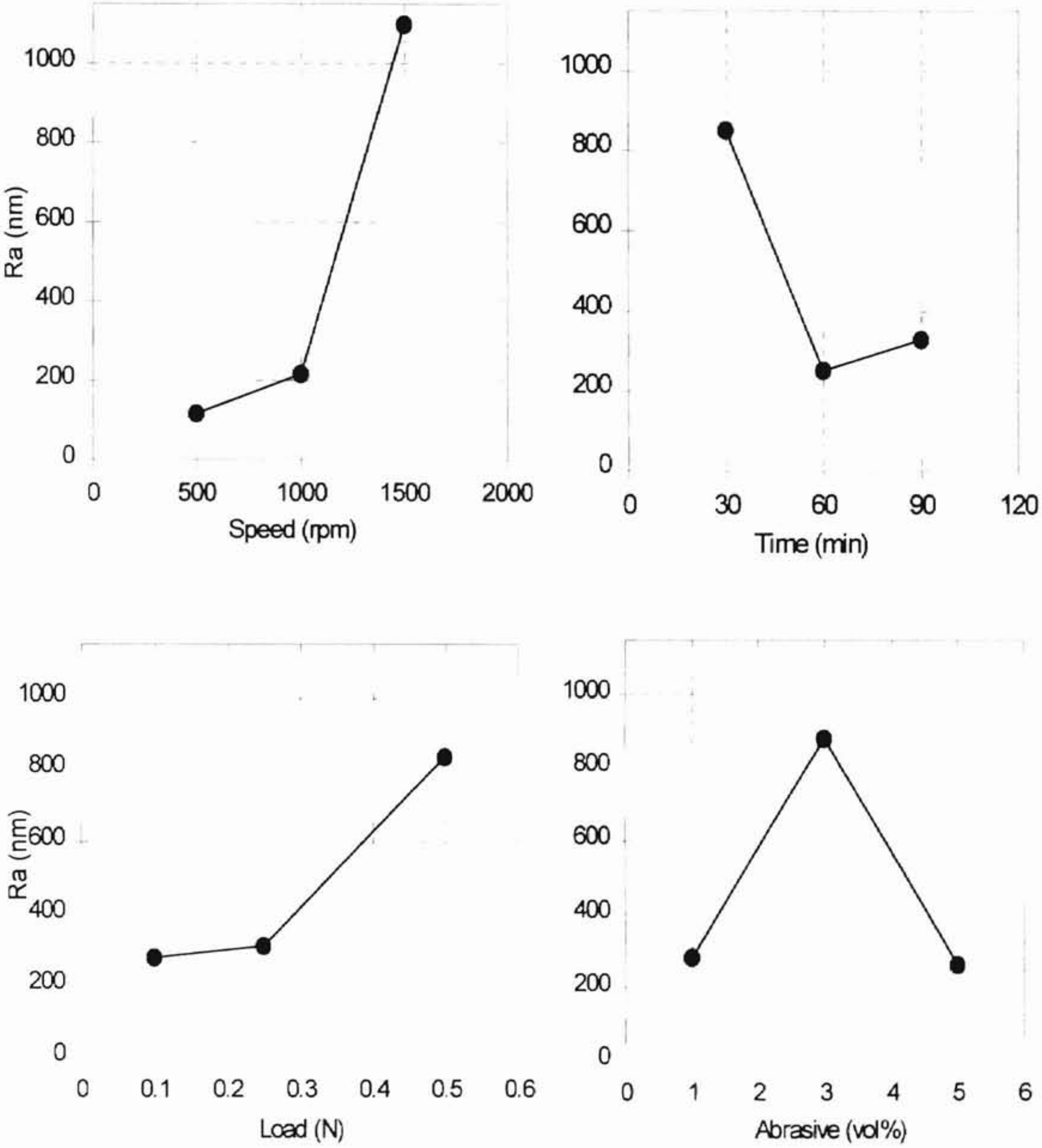


Figure 8.3 (a) Response of Each Parameter Level on Surface Finish - Ra
(Design 2)

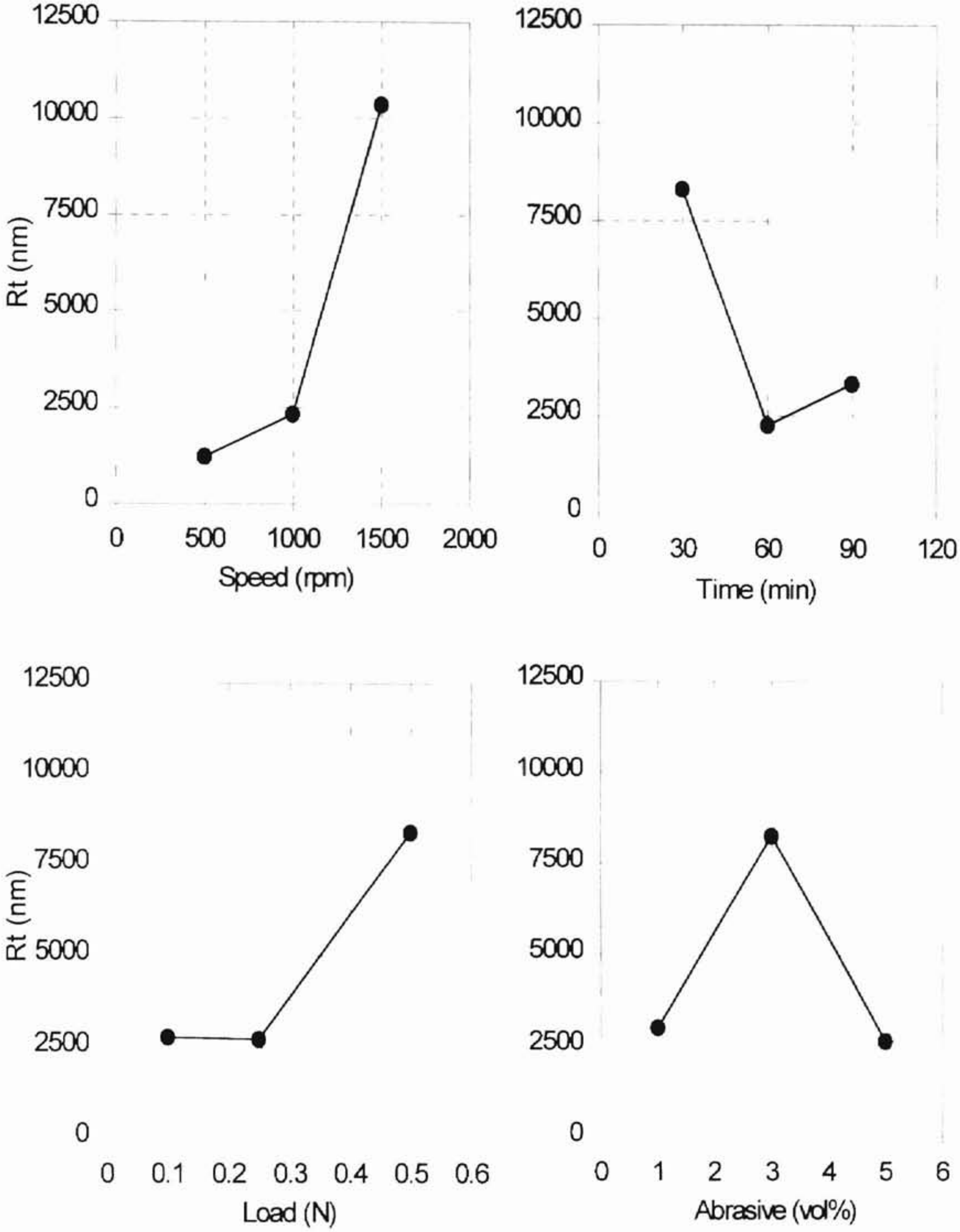


Figure 8.3 (b) Response of Each Parameter Level on Surface Finish - Rt
(Design 2)

Tables 8.6 (a) and 8.6 (b) show the level average analysis using the S/N ratio for Ra, and Tables 8.6 (c) and 8.6 (d) show level average analysis using S/N ratio for Rt. Figures 8.4 (a) and 8.4 (b) are the graphical representation of these results. The optimum levels of load, abrasive %, speed, and time are determined from the above. The calculation of the level average analysis of these four parameters is done similar to the previous method used in Taguchi Experimental Design 1 (for three parameters).

The optimum conditions from the analysis based on the level average of the parameters are identified as:

For Ra and Rt: Load: 0.1N; Abrasive Vol.(%): 5; Speed: 500rpm;
Time: 60 min.

Table 8.6 (a) Level average analysis using S/N ratio for Ra (Design 2)

Load Level (N)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy_i	Average
0.10	51	1	-39.87	-140.68	**-46.89**
	52	2	-46.10		
	53	3	-54.71		
0.25	54	4	-46.38	-147.22	-49.07
	55	5	-46.56		
	56	6	-54.29		
0.50	57	7	-31.87	-147.83	-49.28
	58	8	-47.67		
	59	9	-68.29		

Abrasive Level (vol%)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy_i	Average
1	51	1	-39.87	-141.83	-47.28
	56	6	-54.29		
	58	8	-47.67		
3	52	2	-46.10	-160.77	-53.59
	54	4	-46.38		
	59	9	-68.29		
5	53	3	-54.71	-133.14	**-44.38**
	55	5	-46.56		
	57	7	-31.87		

Table 8.6 (b) Level average analysis using S/N ratio for Ra (Design 2)

Speed Level (rpm)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy_i	Average
500	51	1	-39.87	-118.12	**-39.37**
	54	4	-46.38		
	57	7	-31.87		
1000	52	2	-46.10	-140.33	-46.78
	55	5	-46.56		
	58	8	-47.67		
1500	53	3	-54.71	-177.29	-59.10
	56	6	-54.29		
	59	9	-68.29		
Time Level (min)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy_i	Average
30	51	1	-39.87	-154.72	-51.57
	55	5	-46.56		
	59	9	-68.29		
60	52	2	-46.10	-132.26	**-44.09**
	56	6	-54.29		
	57	7	-31.87		
90	53	3	-54.71	-148.76	-49.59
	54	4	-46.38		
	58	8	-47.67		

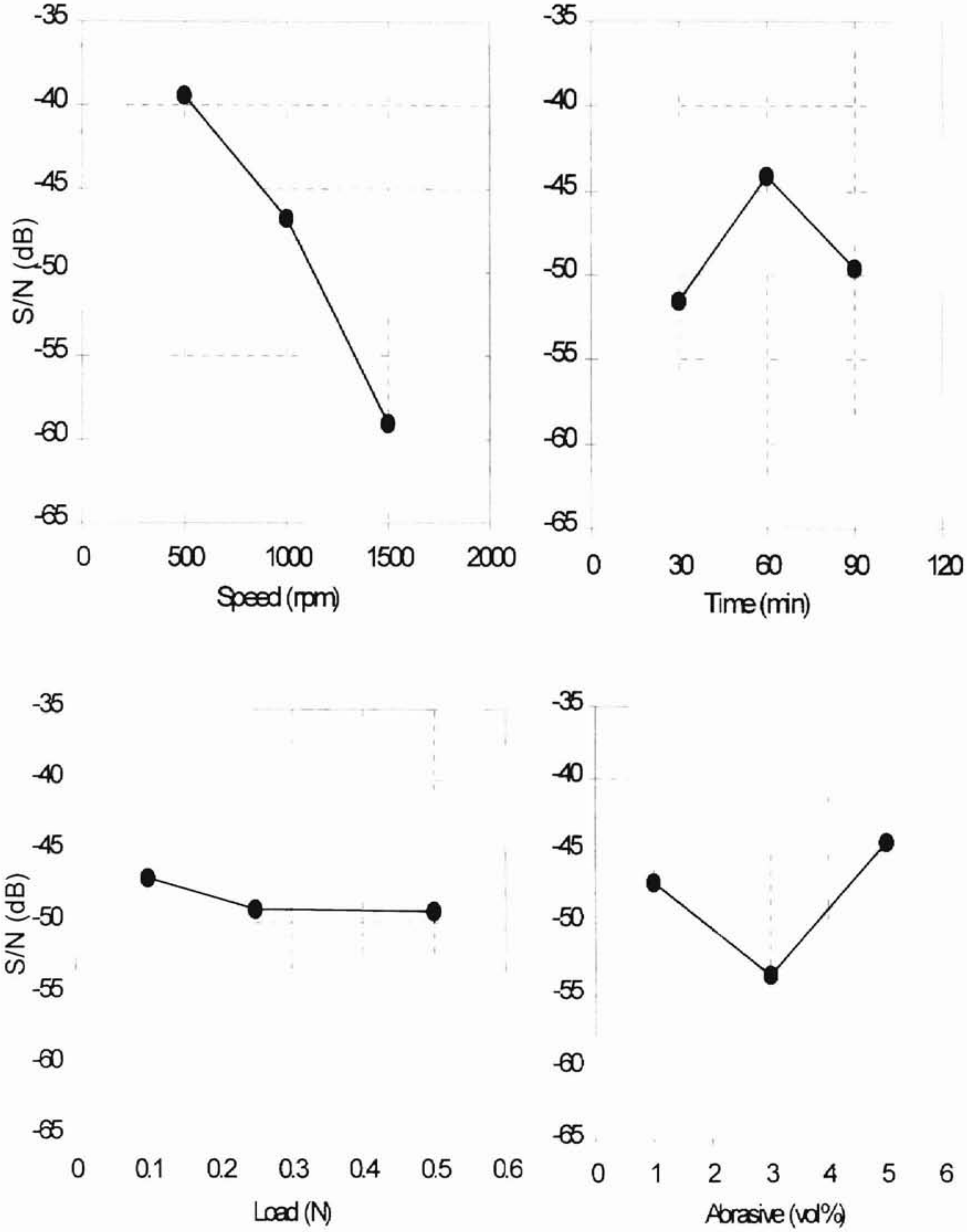


Figure 8.4 (a) Response of Each Parameter Level on Surface Finish - Ra using S/N ratios (Design 2)

Table 8.6 (c) Level average analysis using S/N ratio for Rt (Design 2)

Speed Level (rpm)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy_i	Average
500	51	1	-63.40	-183.77	**-61.26**
	54	4	-64.32		
	57	7	-56.05		
1000	52	2	-64.65	-201.72	-67.24
	55	5	-66.95		
	58	8	-70.12		
1500	53	3	-74.37	-234.78	-78.26
	56	6	-72.96		
	59	9	-87.45		

Time Level (min)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy_i	Average
30	51	1	-63.40	-217.80	-72.60
	55	5	-66.95		
	59	9	-87.45		
60	52	2	-64.65	-193.66	**-64.55**
	56	6	-72.96		
	57	7	-56.05		
90	53	3	-74.37	-208.81	-69.60
	54	4	-64.32		
	58	8	-70.12		

Table 8.6 (d) Level average analysis using S/N ratio for Rt (Design 2)

Load Level (N)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy_i	Average
0.10	51	1	-63.40	-202.42	**-67.47**
	52	2	-64.65		
	53	3	-74.37		
0.25	54	4	-64.32	-204.23	-68.08
	55	5	-66.95		
	56	6	-72.96		
0.50	57	7	-56.05	-213.62	-71.21
	58	8	-70.12		
	59	9	-87.45		

Abrasive Level (vol%)	Batch No.	Test No.	S/N (dB)	S/N of Level (dB)	
				Sum Sy_i	Average
1	51	1	-63.40	-206.48	-68.83
	56	6	-72.96		
	58	8	-70.12		
3	52	2	-64.65	-216.42	-72.14
	54	4	-64.32		
	59	9	-87.45		
5	53	3	-74.37	-197.37	**-65.79**
	55	5	-66.95		
	57	7	-56.05		

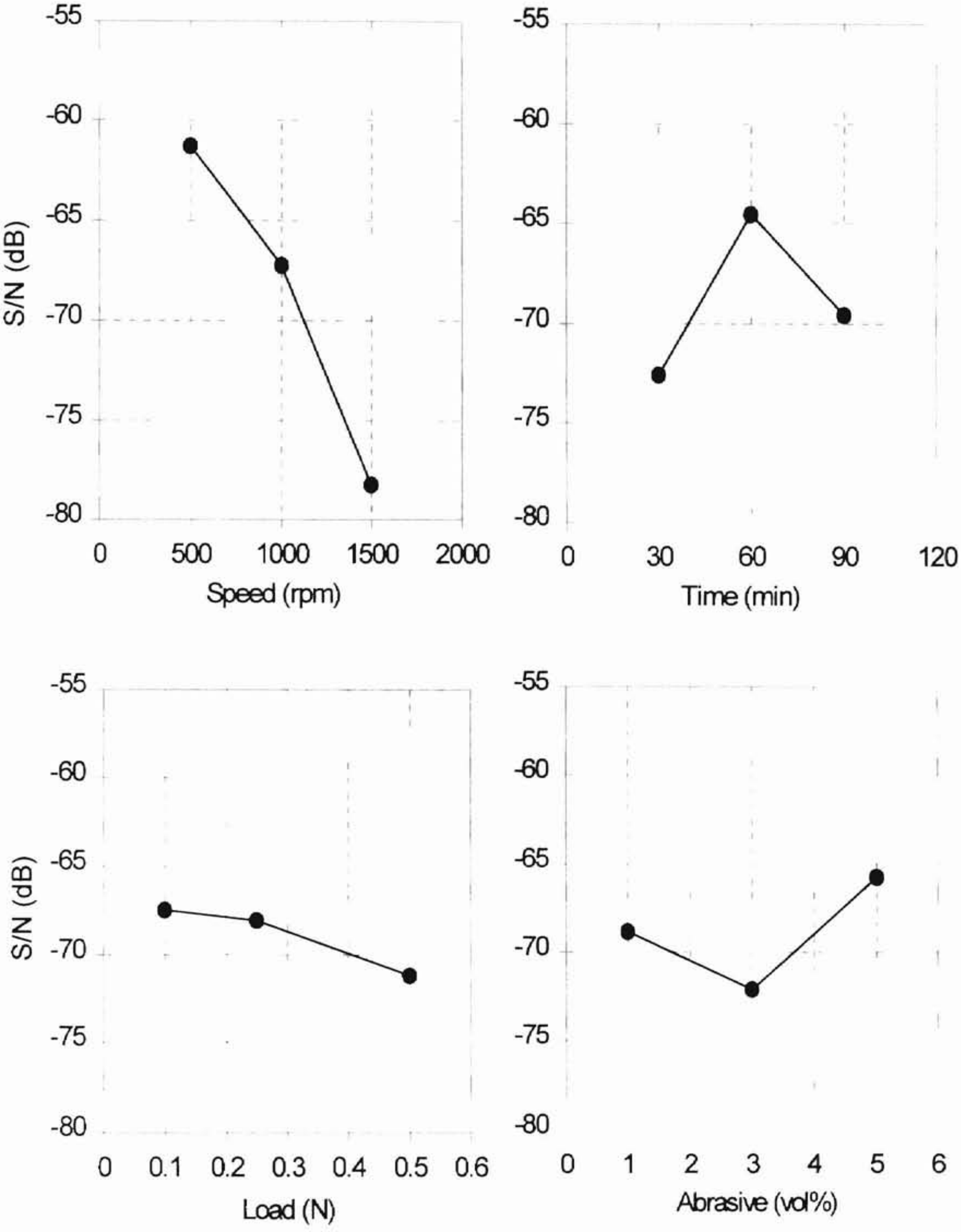


Figure 8.4 (b) Response of Each Parameter Level on Surface Finish - Rt using S/N ratios (Design 2)

From the results obtained so far, the percentage influence is calculated as shown in Tables 8.8, 8.9, 8.11, and 8.12. It is observed that polishing speed is the dominant factor amongst all the four parameters analyzed. It strongly affects the experimental results with respect to the surface roughness values Ra and Rt.

In both the Taguchi experimental designs (1 and 2), a high level of polishing speed (1000 and 1500 rpm) has either damaged the surface or has not produced good surface finish. These results (at higher speeds) can be considered as the worst. On the other hand, low speeds of 500 rpm have produced exceptionally good surface finish and these results can be considered as the best, (even the range is among the best results).

The influence of speed is 71.8% for Ra and 70.8% for Rt in the case of experimental design 1. For experimental design 2, the influence of polishing speed is much higher: 85.4% for Ra and 81% for Rt. This can be attributed to the fact that the speed range chosen for that particular experimental design includes much higher speeds – 1500rpm - at the higher end of the range, and hence produces surfaces with higher Ra and Rt values. This further lets the polishing speed to be more influential and dominant over the other variable parameters.

Table 8.7 Values of S/N and $(S/N)^2$ for Ra and Rt
(Taguchi 1)

Batch No.	Test No.	For Ra		For Rt	
		S/N or y_i	$(S/N)^2$ or y_i^2	S/N or y_i	$(S/N)^2$ or y_i^2
51	1	-37.54	1409.53	-61.56	3789.22
52	2	-33.45	1118.71	-59.99	3598.89
53	3	-49.73	2472.64	-70.84	5017.93
54	4	-42.85	1835.94	-66.16	4377.41
55	5	-59.32	3518.63	-81.73	6680.56
56	6	-33.92	1150.24	-61.72	3809.63
57	7	-56.73	3218.20	-78.63	6182.82
58	8	-30.88	953.66	-60.44	3653.02
59	9	-42.06	1768.62	-67.75	4590.06
Sum		-386.46	17446.18	-608.82	41699.53

Table 8.8 Analysis of Variance for Ra

Factor	DOF	SS	SS%
A: Polishing Speed	2	727.27	85.4
B: Polishing Load	2	39.88	4.7
C: Abrasive Vol. %	2	36.81	4.3
D: Unknown	2	47.35	5.6
Total	8	851.31	100

Table 8.9 Analysis of Variance for Rt

Factor	DOF	SS	SS%
A: Polishing Speed	2	416.59	81.0
B: Polishing Load	2	57.66	11.2
C: Abrasive Vol. %	2	6.38	1.2
D: Unknown	2	33.63	6.5
Total	8	514.26	100

Figure 8.5(a): Percent Influence of Variable Parameters - Ra
(Taguchi 1)

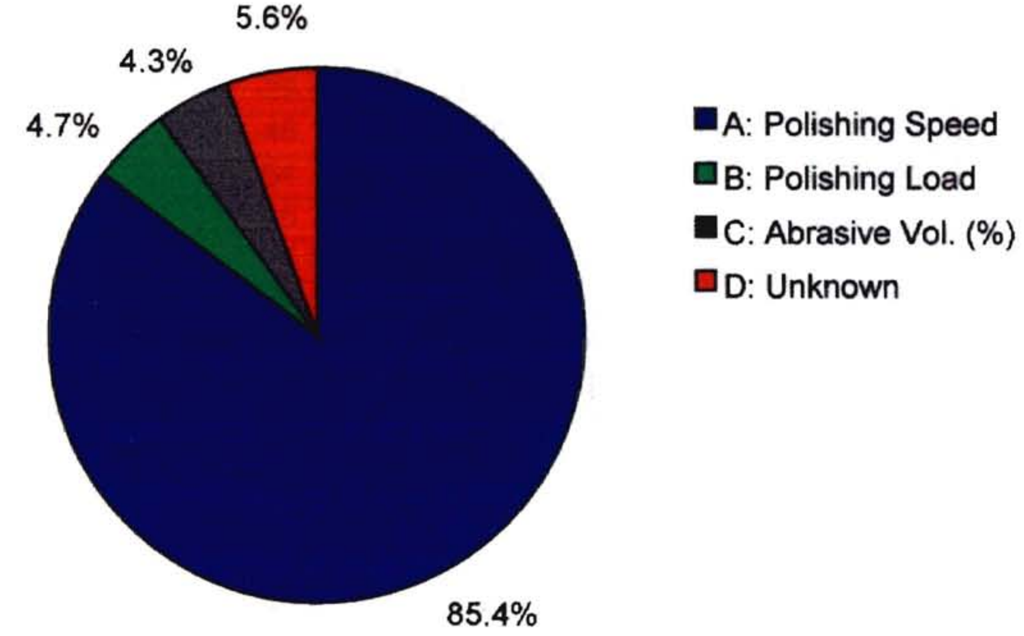


Figure 8.5(b): Percent Influence of Variable Parameters - Rt
(Taguchi 1)

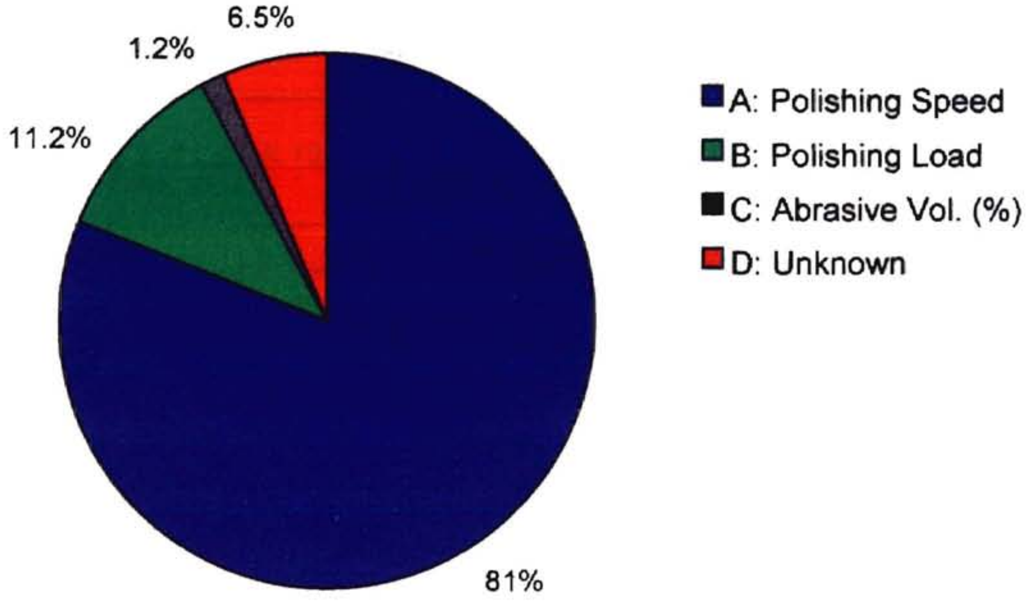


Table 8.10 Values of S/N and $(S/N)^2$ for Ra and Rt (Taguchi 2)

Batch No.	Test No.	For Ra		For Rt	
		S/N or y_i	$(S/N)^2$ or y_i^2	S/N or y_i	$(S/N)^2$ or y_i^2
51	1	-39.87	1589.62	-63.40	4019.56
52	2	-46.10	2125.21	-64.65	4179.62
53	3	-54.71	2993.18	-74.37	5530.90
54	4	-46.38	2151.10	-64.32	4137.06
55	5	-46.56	2167.83	-66.95	4482.30
56	6	-54.29	2947.40	-72.96	5323.16
57	7	-31.87	1015.70	-56.05	3141.60
58	8	-47.67	2272.43	-70.12	4916.81
59	9	-68.29	4663.52	-87.45	7647.50
Sum		-435.74	21926.00	-620.27	43378.53

Table 8.11 Analysis of Variance for Ra

Factor		DOF	SS	SS%
A: Polishing Speed		2	595.60	71.8
B: Polishing Time		2	90.25	10.9
C: Polishing Load		2	9.51	1.1
D: Abrasive Vol. %		2	133.07	16.0
E: Unknown		2	0.98	0.1
Total		10	829.41	100

Table 8.12 Analysis of Variance for Rt

Factor		DOF	SS	SS%
A: Polishing Speed		2	446.35	70.8
B: Polishing Time		2	99.23	15.7
C: Polishing Load		2	24.10	3.8
D: Abrasive Vol. %		2	60.52	9.6
E: Unknown		2	0.01	0.0
Total		10	630.21	100

Figure 8.6(a): Percent Influence of Variable Parameters - Ra (Taguchi 2)

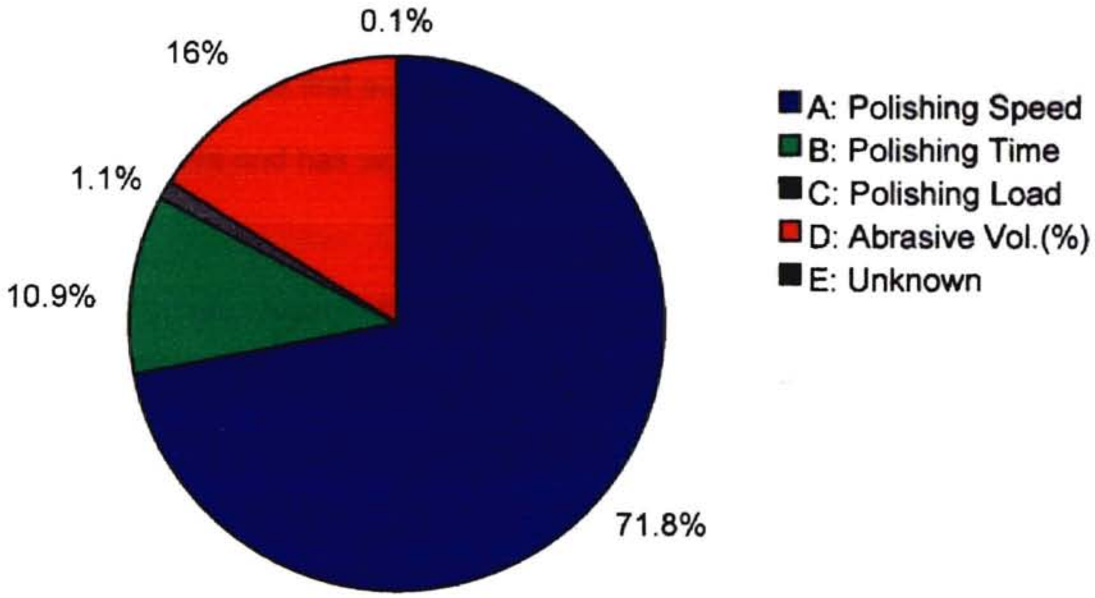
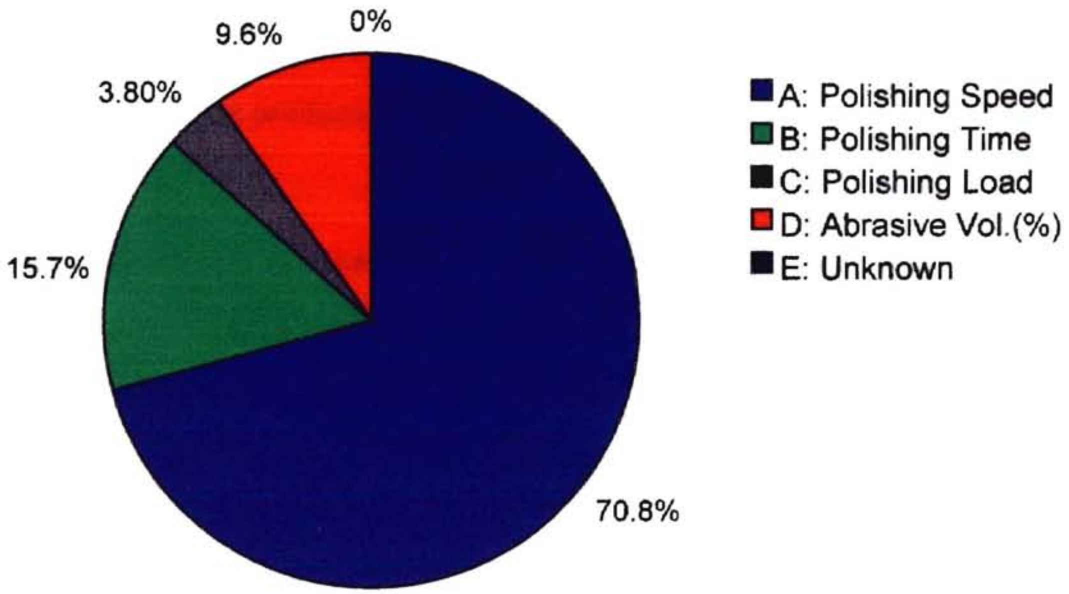


Figure 8.6(b): Percent Influence of Variable Parameters - Rt (Taguchi 2)



The influence of polishing load is low at 4.7% for Ra but higher for Rt at 11.2% for the first set of experiments (Tables 8.8 and 8.9). It is almost negligible for the second set of experiments at 1.1% for Ra and remains low at 3.8% for Rt. The unknown factor in the first set (Taguchi 1) has a considerable influence over the polishing process and has values of 5.6% for Ra and 6.5% for Rt.

However, the unknown factor is seen to have no effect on the process with experimental design 2 where polishing time is the additional fourth parameter analyzed at three different levels of 30, 60, and 90 min. Polishing time affects the polishing process to a high level, next to the polishing speed. Polishing time of 60 min is found to give the best results in terms of surface finish, both Ra and Rt. Its influence is 10.9% for Ra and 15.7% for Rt. The polishing time however, produced good or better surface finishes. It can be characterized as a parameter that has a more than moderate influence on the process without playing any role in damaging the surface or producing undesired results having high Ra and Rt values (as the effects produced by polishing speed).

Thus, the influence of any parameter is not merely how good a surface finish it produces but how effective it is in producing highly undesired (surface finish with high values of Ra and Rt) results and at the same time its ability to offer desired results (surface finish with very low values of Ra and Rt), when proper level is chosen.

8.2 Using Polishing Pad to Improve Surface Finish:

Introducing a polishing pad in this system improves the surface finish considerably with the proper choice of polishing conditions derived from the Taguchi experiments. The inside wall of the polishing chamber does not have any deteriorating effect on the polishing process as it is covered with a soft rubber sheet. In the case of polishing without a pad, the stainless steel polishing shaft may cause damage to the glass surface due to its impact on the balls. This is because the polishing shaft applies certain specified load onto the glass balls, and hence, during its rotation imparts various forces onto the glass balls. Also, its hard surface where the balls make contact, does not offer any flexibility or cushioning effect to the brittle glass surface. In contrast, polishing pads are used to provide some flexibility and cushioning effect to the polishing system, apart from other reasons

Therefore, in the final polishing stages a polishing pad is used in the MFP system to avoid direct contact with the polishing shaft and improve the effectiveness of the CMP action. Figure 8.7 shows a schematic of the modified MFP system with polishing pads on the shaft and float.

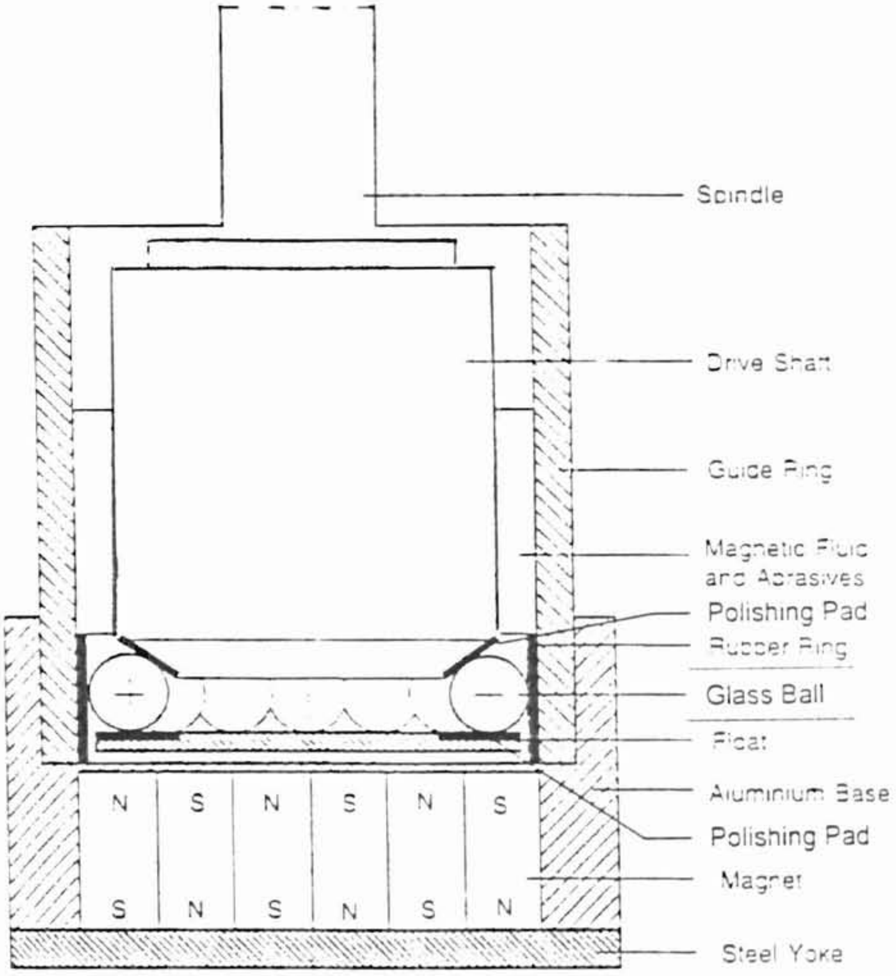


Figure 8.7 Schematic of MFP Apparatus with Polishing Pads

From the Taguchi experiments the optimal polishing conditions are low polishing speeds (500 rpm), abrasive percentage between 3~5%, and low polishing load (0.1N ~ 0.25N per ball). Results of most trial polishing runs suggest use of higher loads, i.e. 0.25N. This offers good material removal rates and more effective polishing. When polishing pads are used, a load of 0.1N is very low due to the cushioning effect of the pads. The pads take certain percentage of load applied during polishing and thus, the actual load acting upon the glass balls is low. Also the pads have to be pressed against the glass balls with sufficient pressure so that the polishing is most effective resulting in smoother surfaces. For these reasons, a higher load (0.25N) is used in the experiments to study effect of load on polishing using pads (batch numbers 28 through 33). This is also found to be the optimal polishing load level giving the best surface finish after polishing with cerium oxide abrasive slurry and polishing pad.

Higher loads (0.5N and 1N) are used in an attempt to obtain higher material removal rate and better surface finish. However, it is seen that the polishing pads restrict the motion of the balls by gripping the balls in place. This phenomenon occurs for the two load levels and produces partially finished glass balls, (i.e. balls finished only at a small portion that makes contact with the pad on the polishing shaft). These glass balls are opaque all over the surface except for the small circular portion where they are highly polished. These look like 'eyeballs' except for it's plain single coloring, and these batches (# 29, 30, and 33) were noted and named thereafter as 'eyeballs' in our study! These results are tabulated in Table 8.13.

Table 8.13 Study of Load Levels for Polishing With Pad *

Batch No.	Load (N)	Speed (rpm)	Observation	Avg. Ra (nm)	Conclusion / Action
28	**0.25**	500	Surface finish – good MRR – low	**41**	Proper loading / Trial run with high load w/ pad
29	1	500	Partially finished, no Rolling motion to balls	NA	Overloaded, hence Ball motion restricted/ Decrease load
30	0.5	500	Partially finished, no Rolling motion to balls	NA	Overloaded, hence Ball motion restricted/ Decrease load
31	0.1	500	Surface finish – good MRR - very low	47	Low load / Trial run for load = 0.5N increase speed
33	0.5	1000	Partially finished, no Rolling motion to balls	NA	Load = 0.5N too high. Pads restrict ball motion

* For all runs - Abrasive: 3%; Time: 60mins

Maintaining a high polishing load and increasing the polishing speed for proper motion of the glass balls is done in trial run 33. In this run, a load of 0.5N per ball and a speed of 1000 rpm are used. However, the results remain the same producing 'eyeballs'. This can also be attributed to the slimy surface of the polishing pad. Due to high load, the balls get pressed against the pads more likely on the bottom pad on the float. This is because, the pad on the float does not move relative to the balls.

Also, the abrasive slurry that consists of water-based magnetic fluid and cerium oxide makes the surface of polishing pad very slippery. Due to this the pad on the polishing shaft (that provides the drive) tends to slip over the surface of the glass balls (that are sunk into the bottom pad) rather than cause any rotational motion. This gives the appearance of the so called 'eyeballs'.

The polishing time (continuous for each run) plays an important role in the finishing stages especially with the use of polishing pads. This is due to the slurry consistency and the condition of polishing pad that change considerably after certain time of continuous polishing. It is difficult to study the inter-relation of the slurry consistency and the condition of polishing pad, as the pad component itself is the most poorly understood one in the polishing system. It is also difficult to exactly determine the pad life and the rate at which it deteriorates.

The best that can be predicted about the pad is the end point (also called the stop time) when the polishing should be stopped. This does not necessarily indicate the pad life as it can be used again in some cases after dressing the pad or in some cases after cleaning the polishing chamber (that involves thoroughly removing the used slurry along with the wear debris) and setting-up a new run with fresh slurry. It can be said that the wear debris plays a significant role in causing damage to the polished surface, if a large amount of it gets stuck into the pad material.

Table 8.14 Effect of Polishing Time on Surface Finish *

Bch. No.	Time (min)	Load (N)	Observation	Avg Ra (nm)	Avg Rt (nm)	Conclusion
28	60	0.25	Surface finish – good Very small scratches, No noticeable fracture	41	523	Pad not very effective Needs more run time
32	**120**	**0.25**	Surface finish – best, Minimal or no damage, No scratches / fracture	**11**	**100**	Best polishing action Pad condition - good
34	180	0.25	Surface finish – fair Fine scratches, no fracture, small indentations	34	445	Pad condition - bad deteriorates, comes off

* For all runs – Abrasive: 3%; Speed: 500rpm

The results of trial runs with a low load of 0.1N can be analyzed in the same manner. Since the condition of polishing pad stays good only for 120 min of continuous polishing time, tests with higher levels of time are not performed.

Table 8.15 Effect of Polishing Time on Surface Finish *

Bch. No.	Time (min)	Load (N)	Observation	Avg Ra (nm)	Avg Rt (nm)	Conclusion
31	60	0.1	Surface finish – fair Lot of voids No fracture	47	755	Polishing action - poor Pad not effective at all Needs more run time
35	120	0.1	Surface finish – good Very few voids No scratches / fracture	28	344	Polishing action - good Pad effectiveness -fair Pad condition - good

* For all runs – Abrasive: 3%; Speed: 500rpm

From these tests it is concluded that polishing time of 120 minutes is the optimal level to obtain the best surface finish. This combined with a load level of 0.25N per ball (as in run# 32) provides reasonable material removal rates so as to remove sufficient material (diametrically) to correct any damage from earlier runs. For example, use of coarser (as compared to cerium oxide) silicon carbide 8000 grit in the semi-finishing stage may produce fine scratches on the surface of the balls. These can be then corrected in the subsequent finishing stages that make use of polishing conditions similar to trial run number 32 with polishing pad (chemomet).

Higher levels of polishing speed with the use of polishing pad do not have as bad an effect as recorded in the Taguchi set of experiments where no pad is used. This can be due to the cushioning effect provided by the pads and mainly because the contact between polishing shaft and the glass balls is avoided. Most likely, the scratches produced in earlier experiments could be due to the absence of polishing pad. Test runs at the optimal polishing load i.e. 0.25N are conducted for 120 minutes for different levels of polishing speed – 500 and 1000rpm.

It is however seen that even at high speed of 1000rpm, there is no significant damage to the glass ball surface. The surface finish is also reasonable and of an order of magnitude better than those obtained at the same speeds and other polishing conditions but without the polishing pad. An average Ra of 34nm is obtainable even with the use of high speeds (as shown in Table 8.16 run# 36). These results are tabulated in Table 8.16.

Table 8.16 Effect of Polishing Speed on Surface Finish *

Bch. No.	Speed (rpm)	Observation	Avg Ra (nm)	Avg Rt (nm)	Conclusion
32	500	Surface finish – best, Minimal or no damage No scratches / fracture	11	100	Optimal polishing speed Pad condition - good Optimum combination
36	1000	Surface finish – good Not much damage No scratches / fracture	34	610	Polishing speed – too high, pad condn. - good Pad reduces damage

* For all runs – Load: 0.25N; Abrasive: 3%; Time: 120 min

Experiments were conducted using the conditions similar to trial run number 32 (that gave the best finish with pad) for different polishing pads. It was seen that the 'chemomet' pad that is used in number 32 gave the best results in comparison to 'Microcloth' and 'Nylon' as shown by Figures 8.10 and 8.11 and Table 8.17. The polishing with microcloth resulted in a finish with an average Ra=25nm and average Rt=188nm as compared to an average Ra=11nm and average Rt=100nm with chemomet. Nylon pad is not effective for the polishing of the glass balls as there was no significant polishing action on the balls using the same conditions as number 32 and the finish of the balls was found to be close to the as-received balls. Figures 8.8 (a) and (b) show an optical microscope image of the surface of the as-received glass balls.

Figure 8.8 (a)

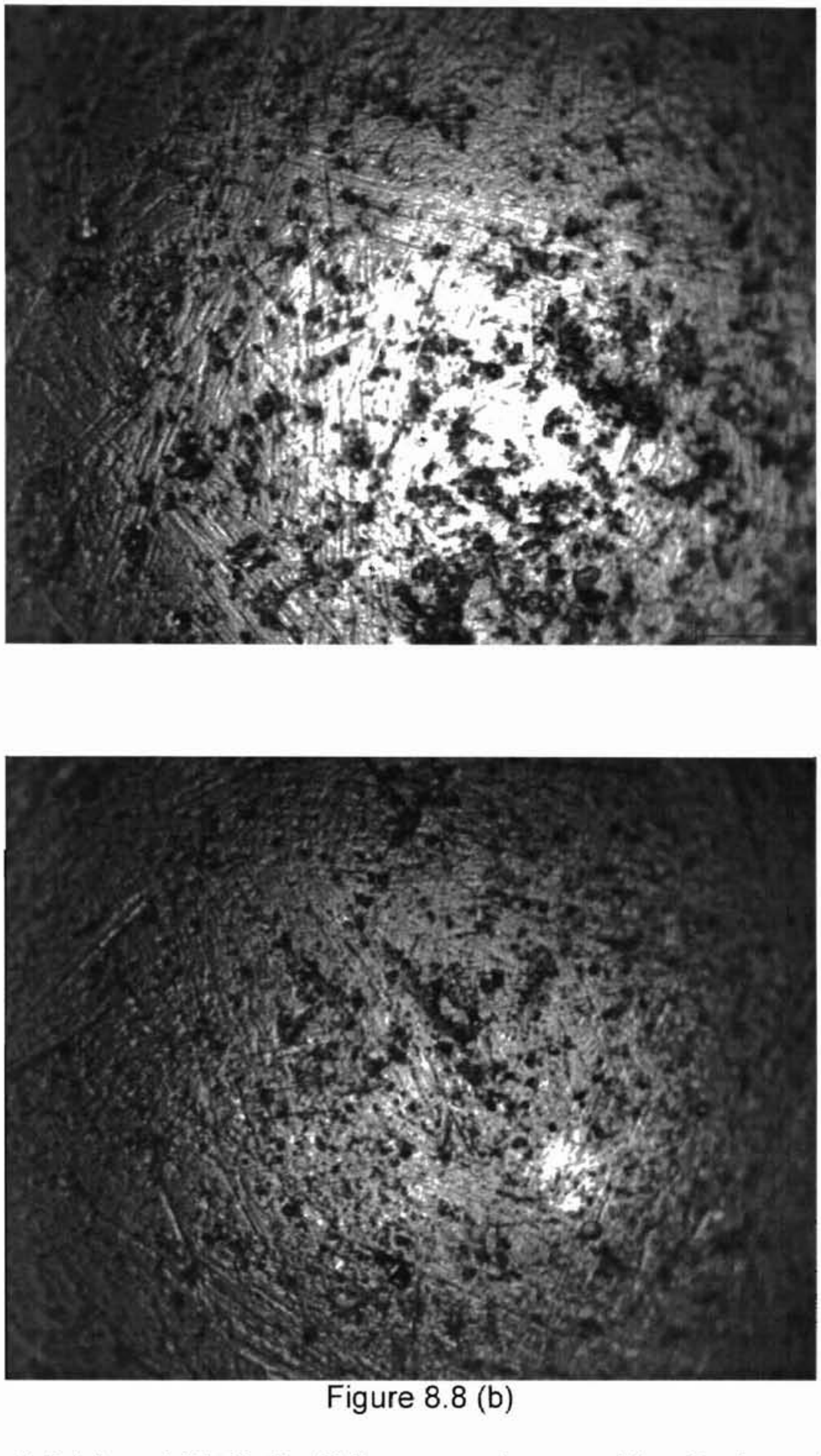


Figure 8.8 (b)

Figures 8.8 (a) and (b) Optical Microscope Image of the Surface of the As-Received Glass Balls (Magnification 10x)

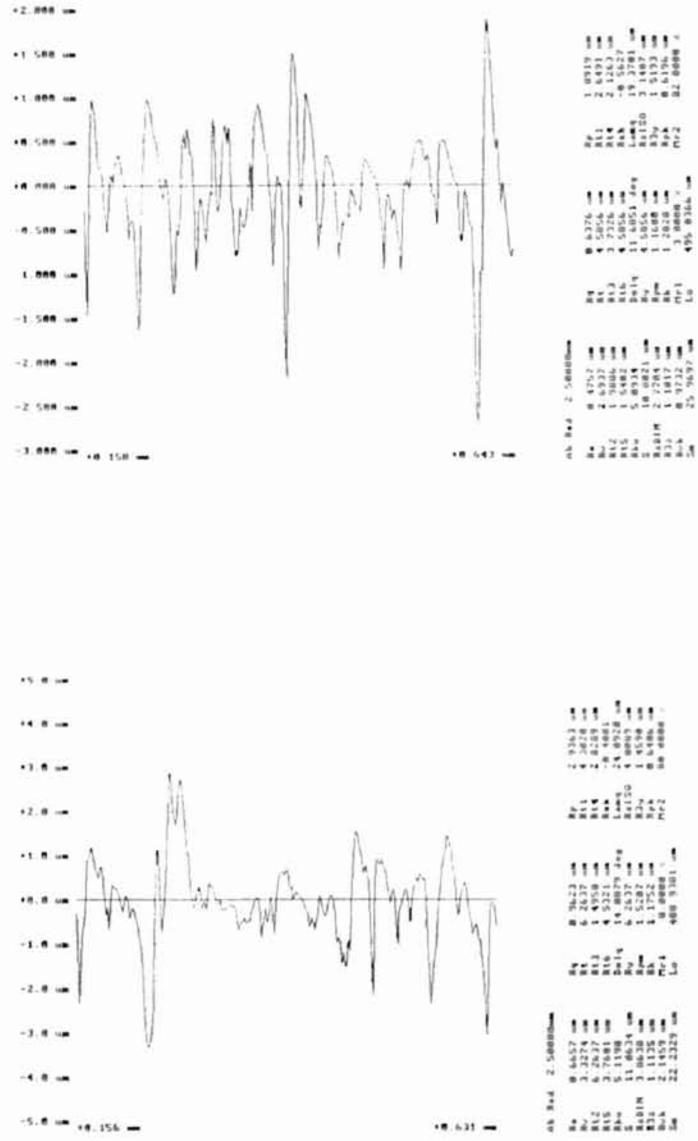


Figure 8.9 Surface Roughness - Ra and Rt of the As-Received Glass Balls

Table 8.17 Effect of Polishing Pads on Surface Finish *

Batch No.	Pad Type	Avg. Ra (nm)	Avg. Rt (nm)
22	No Pad	54	519
32	Chemomet	11	100
60	Microcloth	24	188
61	Nylon	-	-

* For all runs – Load: 0.25N; Abrasive: 3%; Time: 120 min; Speed: 500 rpm

Trial run number 22 resulted in a good polished surface without the use of polishing pad. However, the use of polishing pad improves the surface finish significantly.

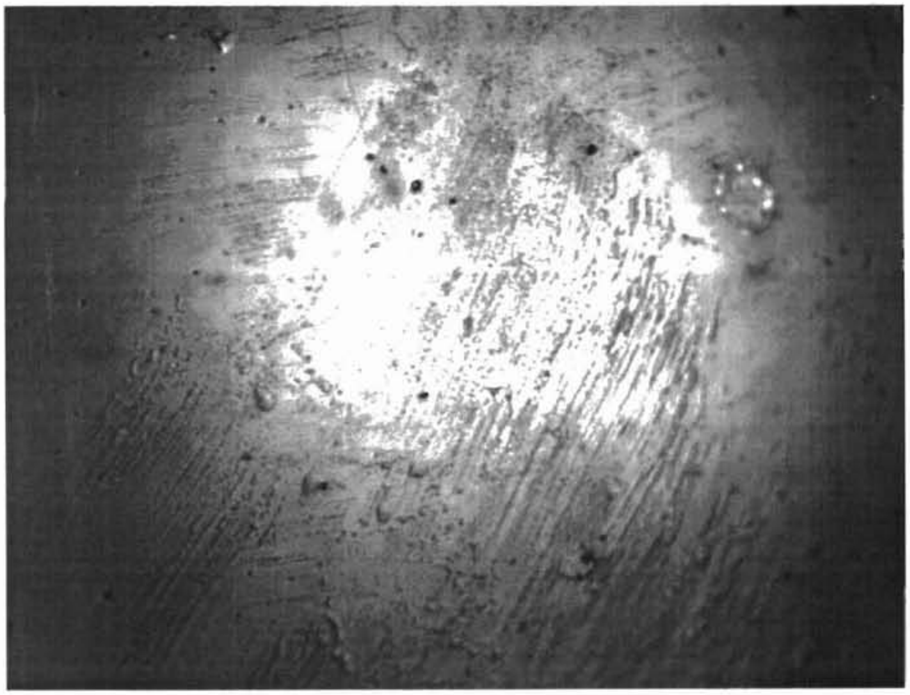


Figure 8.10 (a)

Figure 8.10 (a), (b), and (c) Optical Microscope Images of the Glass Balls Polished by Chemomet (Magnification of 10x; Batch 32)

Figure 8.10 (b)

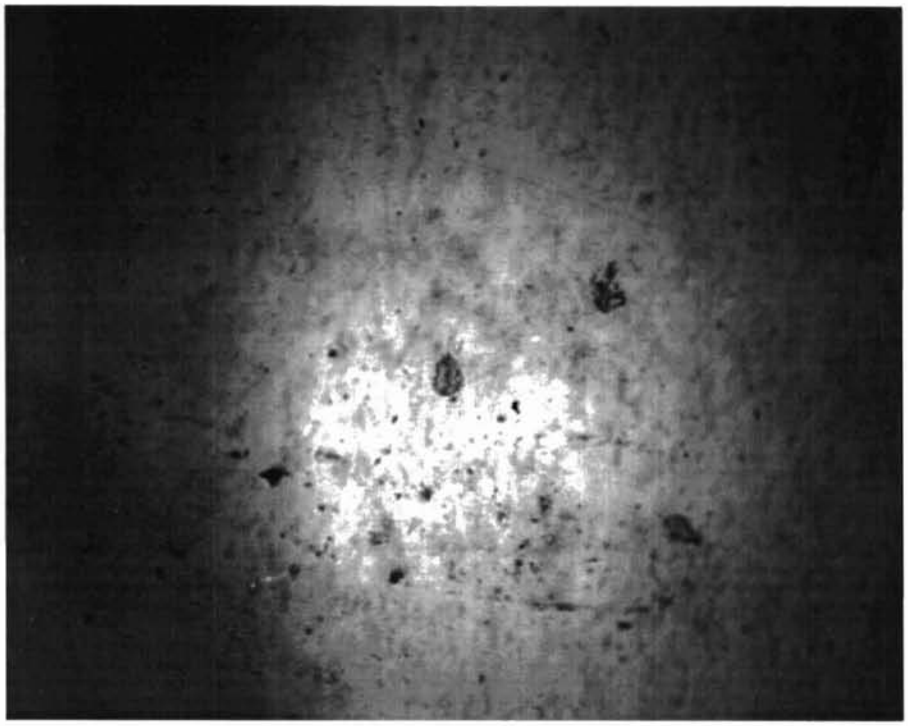
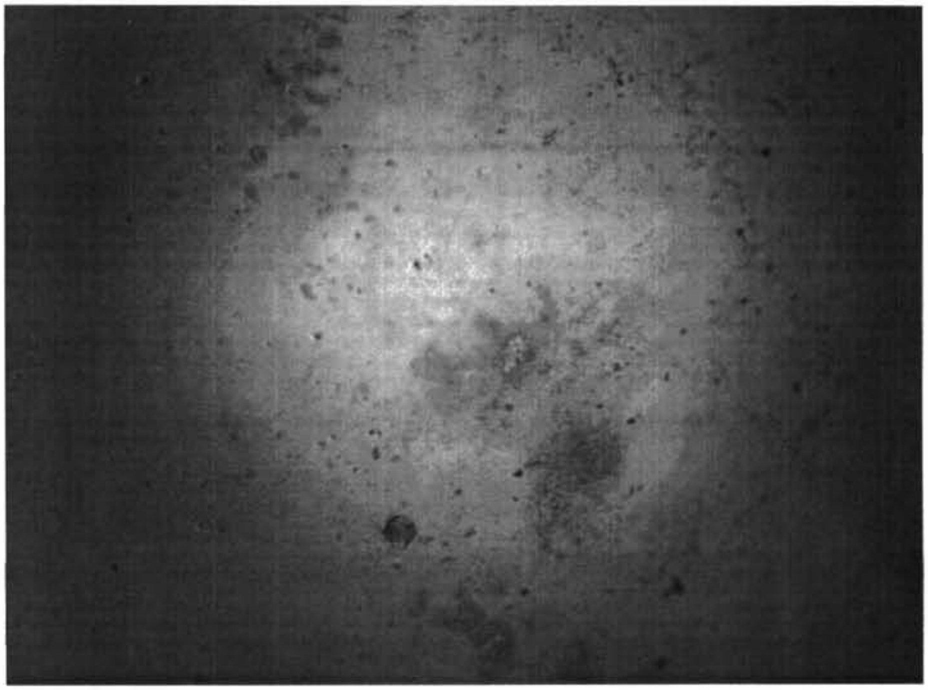


Figure 8.10 (c)



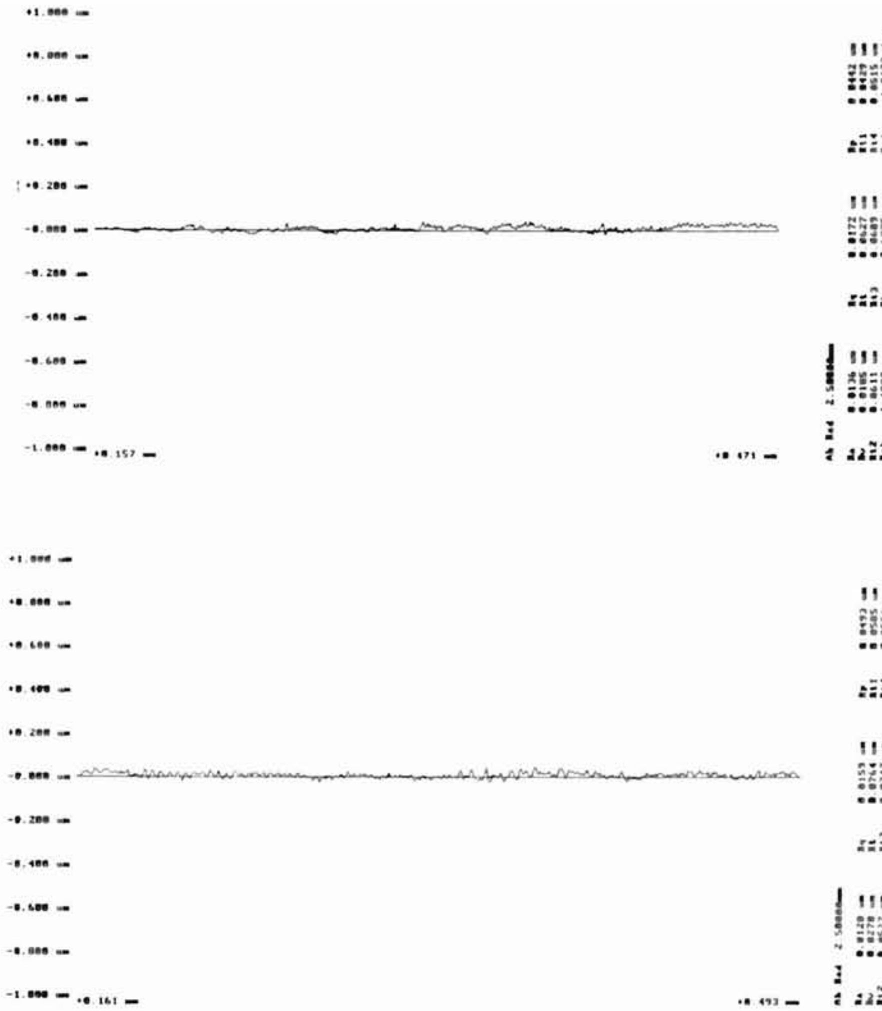


Figure 8.11 Surface Roughness - Ra and Rt of the Glass Balls Polished by Chemomet (Batch 32)

8.3 Finishing a Batch of Glass Balls that meet Specific Requirements

The optimum polishing conditions to achieve the best surface finish and quality of the glass balls are determined using Taguchi Experimental Designs 1 and 2. In these experiments cerium oxide (CeO_2) is used in various proportions (1 to 5 % by volume) with the magnetic fluid to form the abrasive slurry. It is known that cerium oxide is a good finishing abrasive for glass and gives a smooth damage-free surface due to the CMP action. However, in the present study, the finishing process once optimized, is employed after initial roughing and semi-finishing stages. Material removal rates during these stages are very high (as compared to those in CMP) and the surface roughness values may also be higher (than the as-received balls used for the optimization process). It is quite possible that surface roughness values are higher for a batch of balls set to be finished to a certain diameter with specified surface finish and sphericity. A target of finishing a batch of 40 glass balls that meet certain specifications is set. As per the target the final finished balls should have:

- Good sphericity value (improved significantly over as-received balls: 2.05 to 2.40μm sphericity),
- Good surface roughness value (close to the best obtained in the optimization process: 10 to 13nm Ra – as-received balls: 465 to 665nm - Ra), and
- Specific diameter (obtainable only after significant material removal from the as-received balls – to study process capability and process control).

The material removal rates obtainable at different stages in the polishing process are tabulated in table 8.18 (the rates are determined from material removed on the diameter)

Table 8.18 Material Removal Rate (MRR) for Different Abrasive Types and Grit Sizes (Batch 42)

Sr. No.	Abrasive Type / Grit	MRR (μm/hr)
1	SiC 400	238
2	SiC 1000	57
3	SiC 1200	44
4	SiC 8000	18
5	CeO_2	4

The polishing results are tabulated in Tables 8.19 and 8.20. Three distinct stages are developed offering a wide range of material removal rates and at the same time achieving good surface finish and sphericity values. These are as follows:

- The initial roughing stage offers high material removal rates with low damage (referring to Tables 8.19 and 8.20, trial Runs 1 to 4; Batch 42).
- The semi-finishing stage with minimum damage with the capability to correct any excessive damage from previous roughing stage; control over sphericity and surface roughness at this stage (Trial Runs 5 to 10; Batch 42).
- The final finishing stage with minimum or no damage. The optimized polishing conditions are used during this stage for final finishing of the balls (Trial Run 11; Batch 42).

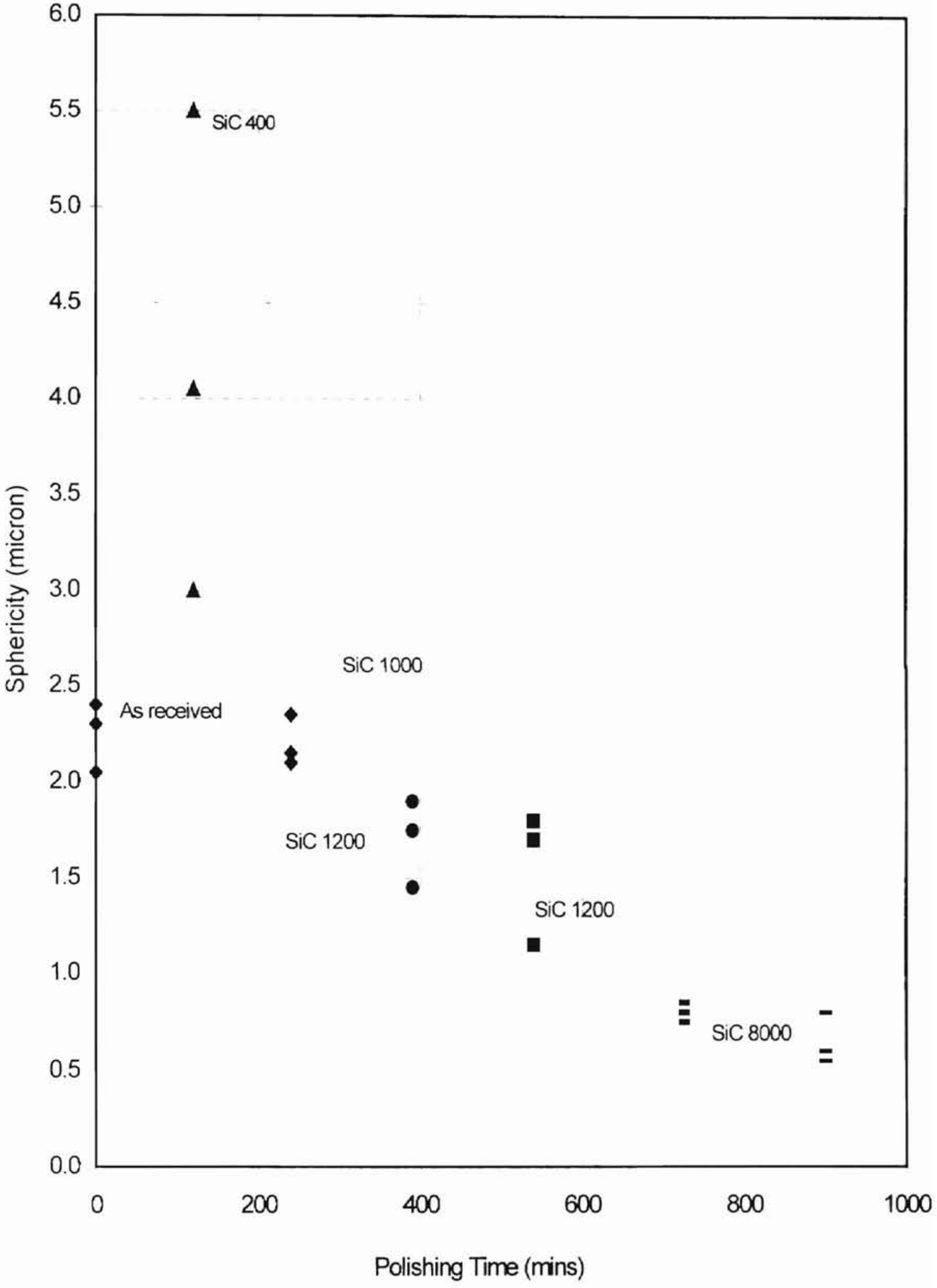
Table 8.19 Effect of Abrasive Size and Polishing Time on Diameter and Spericity

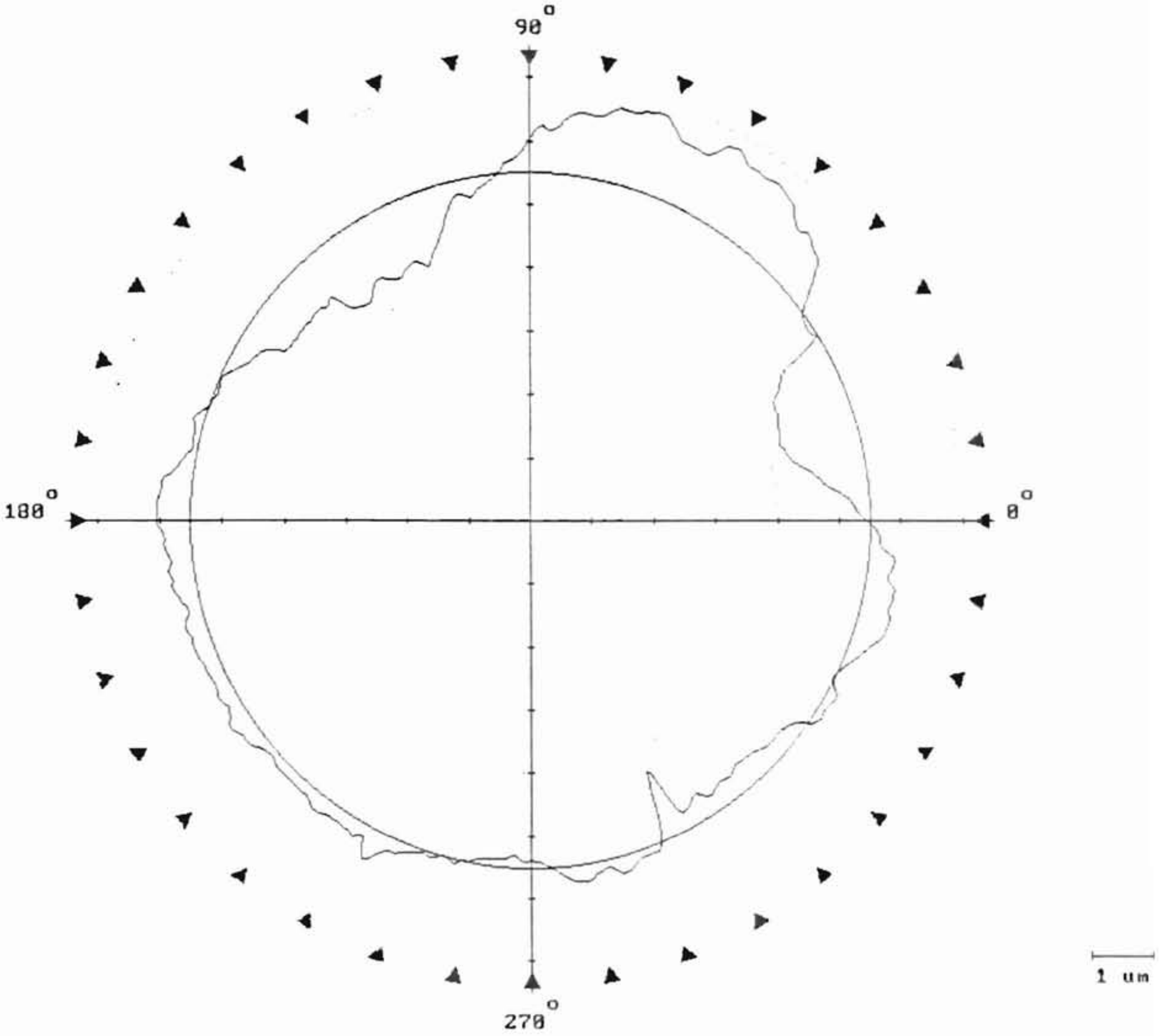
(Batch 42 *)

Test Run#	Abrasive (Vol 3%)	Polishing Time (mins)	Sphericity (μm)	Avg. Dia. (mm)	Mat. Rem. (μm)
As Received	-	0	2.05 2.40 2.30	5.012	0
1, 2	SiC 400	120	4.05 3.00 5.50	4.536	476
3, 4	SiC 1000	240	2.35 2.10 2.15	4.442	114
5	SiC 1200	390	1.75 1.45 1.90	4.318	110
6	SiC 1200	540	1.80 1.70 1.15	4.200	112
7, 8, 9	SiC 8000	720	0.85 0.80 0.75	4.140	60
10	SiC 8000	900	0.80 0.55 0.60	4.087	53
11	CeO_2	1050	0.80 0.55 0.60	4.076	11

* Polishing Load = 0.25N; Speed = 500rpm

Figure 8.12 Effect of Abrasive size and Polishing time on Sphericity



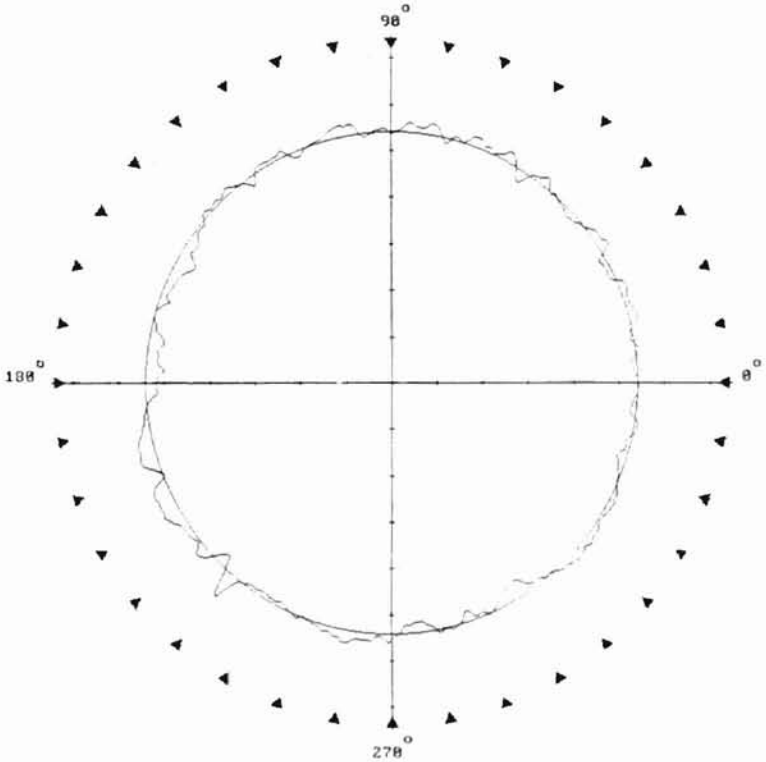


LS ROUNDNESS RESULTS

○	2.55 um	Meas. mode	External
E	25.40 um	Z Height	150.4 mm
∠	102.1 deg	Filter	50 upr 2CR
↗	51.30 um	Profile	100.0 %

Datum : SPINDLE

Figure 8.13 Sphericity of the As-received Glass Balls



LS ROUNDNESS RESULTS

○	0.55 um	Meas. mode	External
E	1.05 um	Z Height	150.3 mm
∠	153.0 deg	Filter	50 upr 2CR
↗	3.75 um	Profile	100.0 %

Datum : SPINDLE

Figure 8.14 Sphericity of the Glass Balls Polished by MFP (Batch 42)

Figure 8.15 Effect of Abrasive Type, Size and Polishing Time on Diameter of Glass Balls

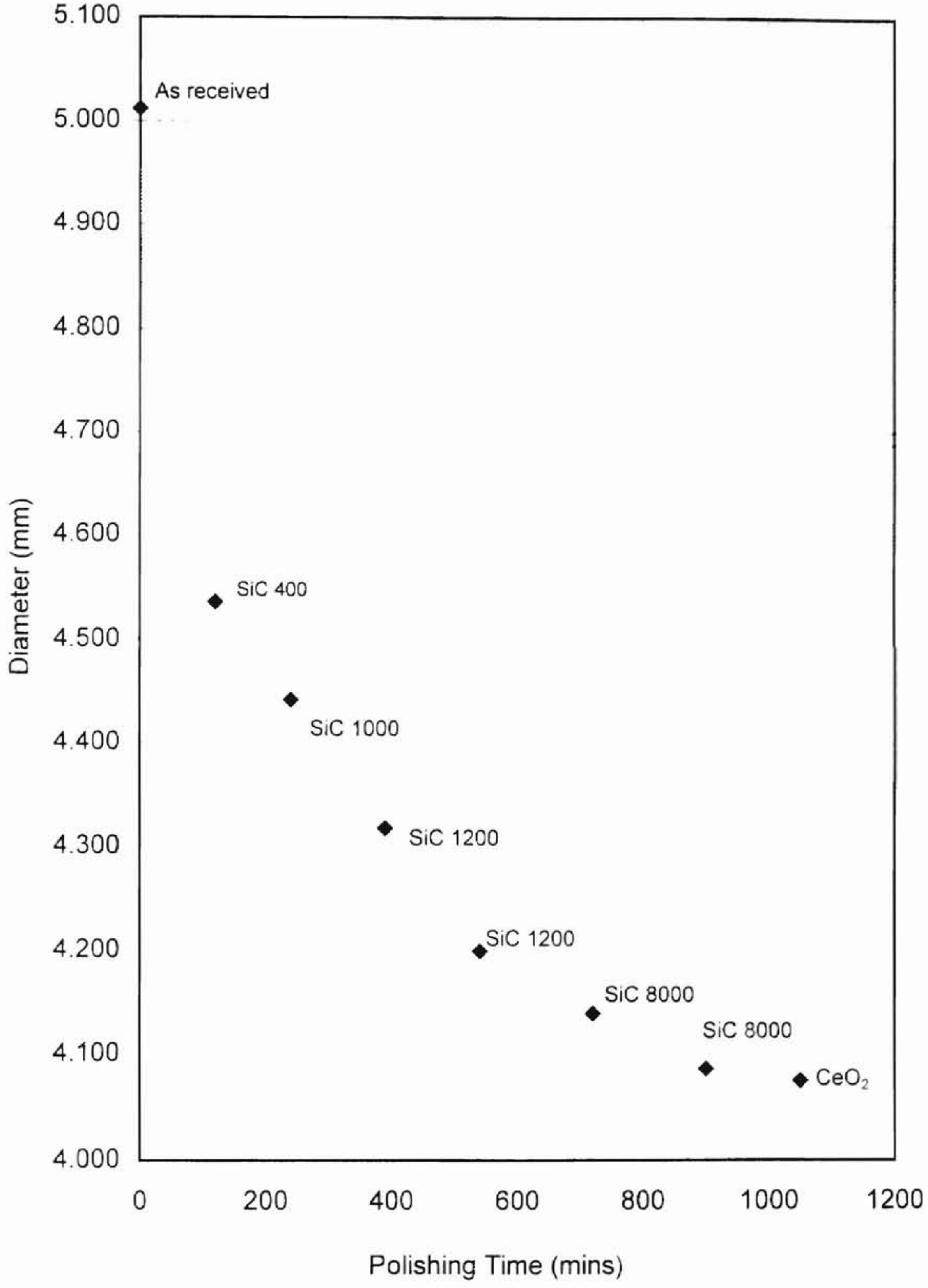


Figure 8.16 Effect of Abrasive Type, Size and Polishing Time on Material Removal in Polishing of Glass Balls

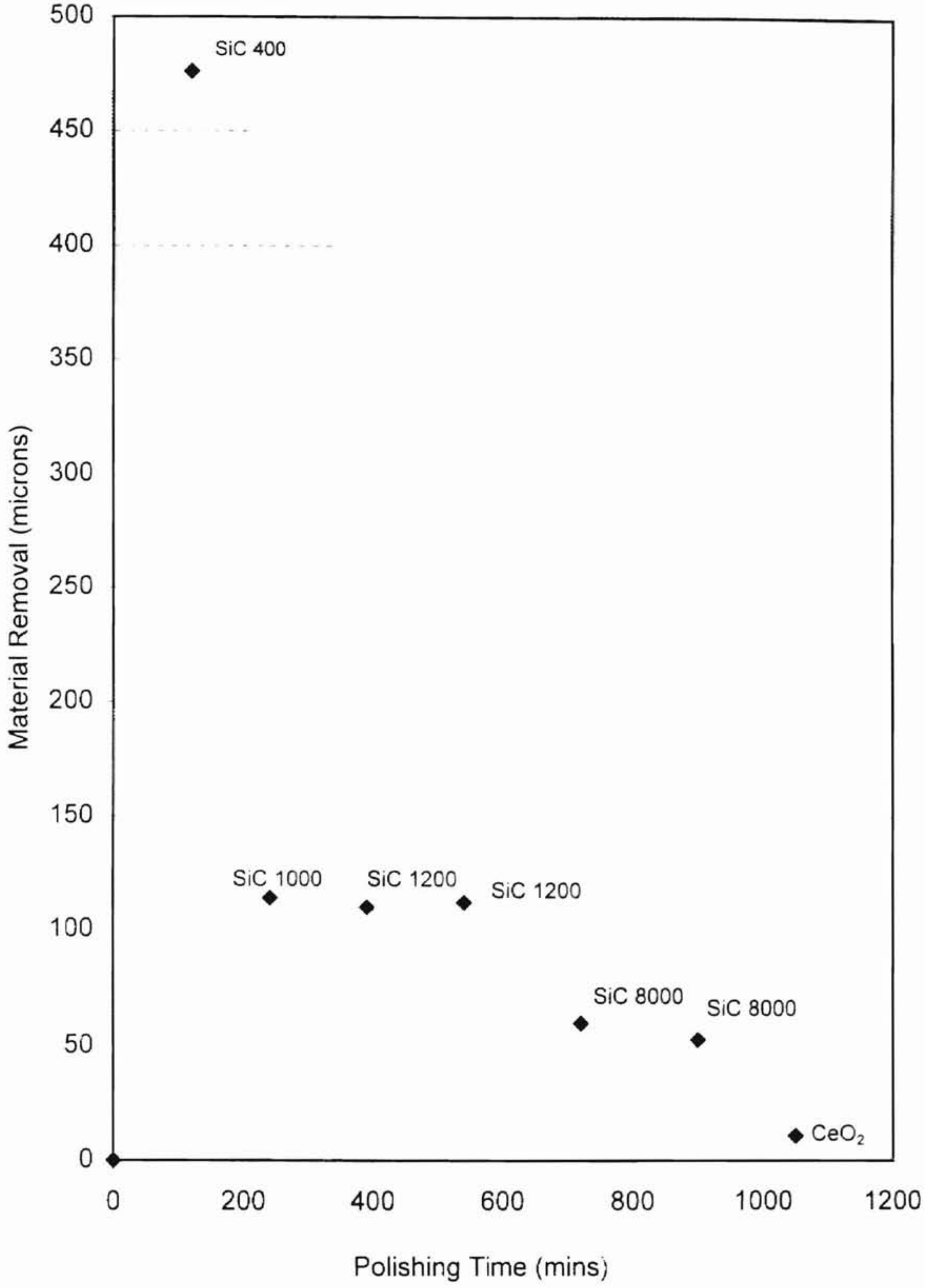


Table 8.20 Effect of Abrasive Size and Polishing Time on Surface Finish (Batch 42 *)

Test Run#	Abrasive (Vol 3%)	Polishing Time (mins)	Ra (nm)	Rt (nm)
As Received	-	0	475 665 534	4585 6263 4798
1, 2	SiC 400	120	989 865 817	6448 5246 6102
3, 4	SiC 1000	240	433 428 479	3189 4128 3792
5	SiC 1200	390	292 302 305	2414 3312 2638
6	SiC 1200	540	274 195 215	2126 2059 1975
7,8,9	SiC 8000	720	53 57 86	646 687 1042
10	SiC 8000	900	38 31 41	362 314 397
11	CeO2	1050	18 17 21	145 126 106

* Polishing Load = 0.25N; Speed = 500rpm

Figure 8.17 Effect of Abrasive and Polishing Time on Surface Finish - Ra

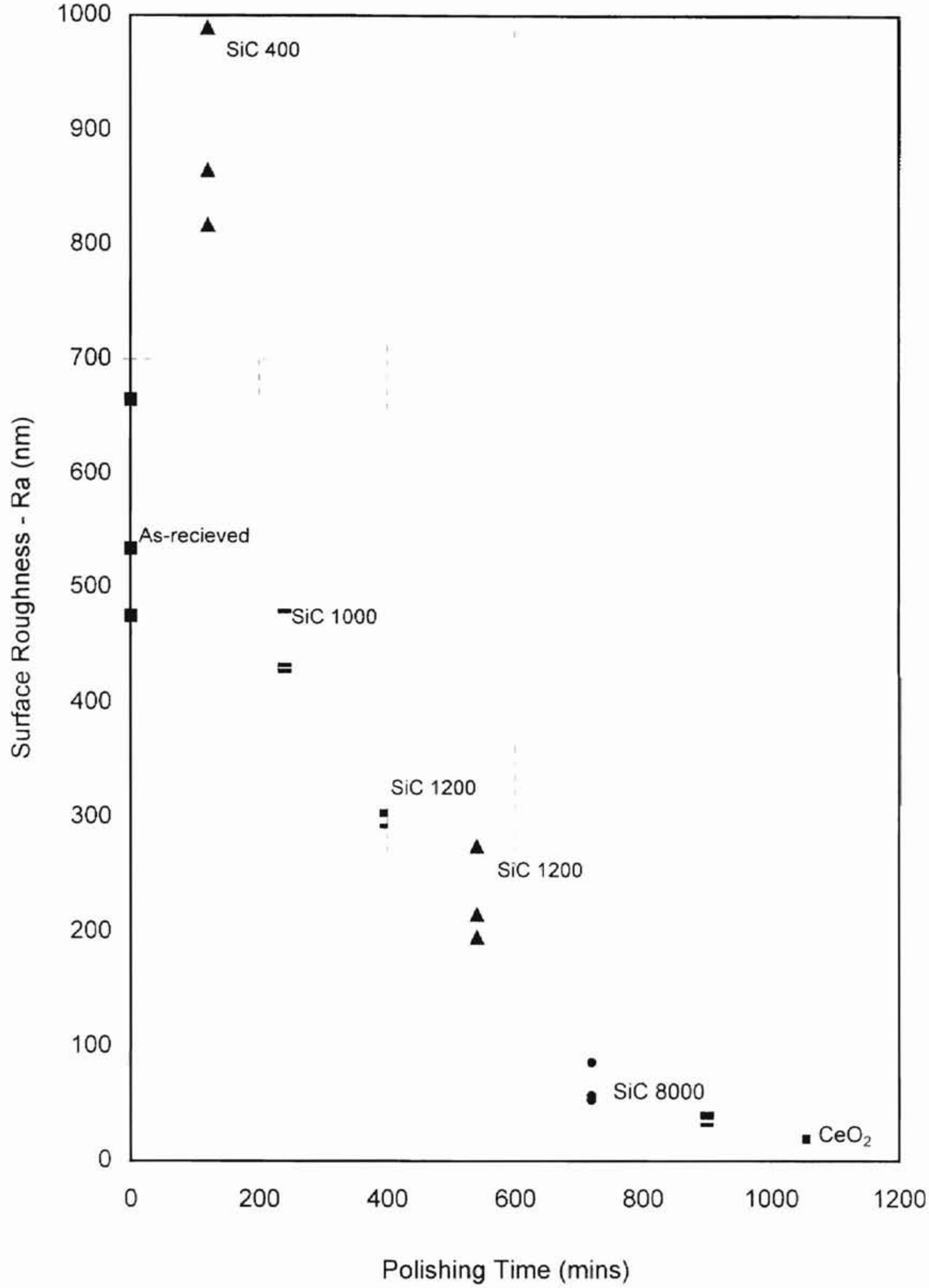


Figure 8.18 Effect of Abrasive Size and Polishing Time on Surface Finish - Rt

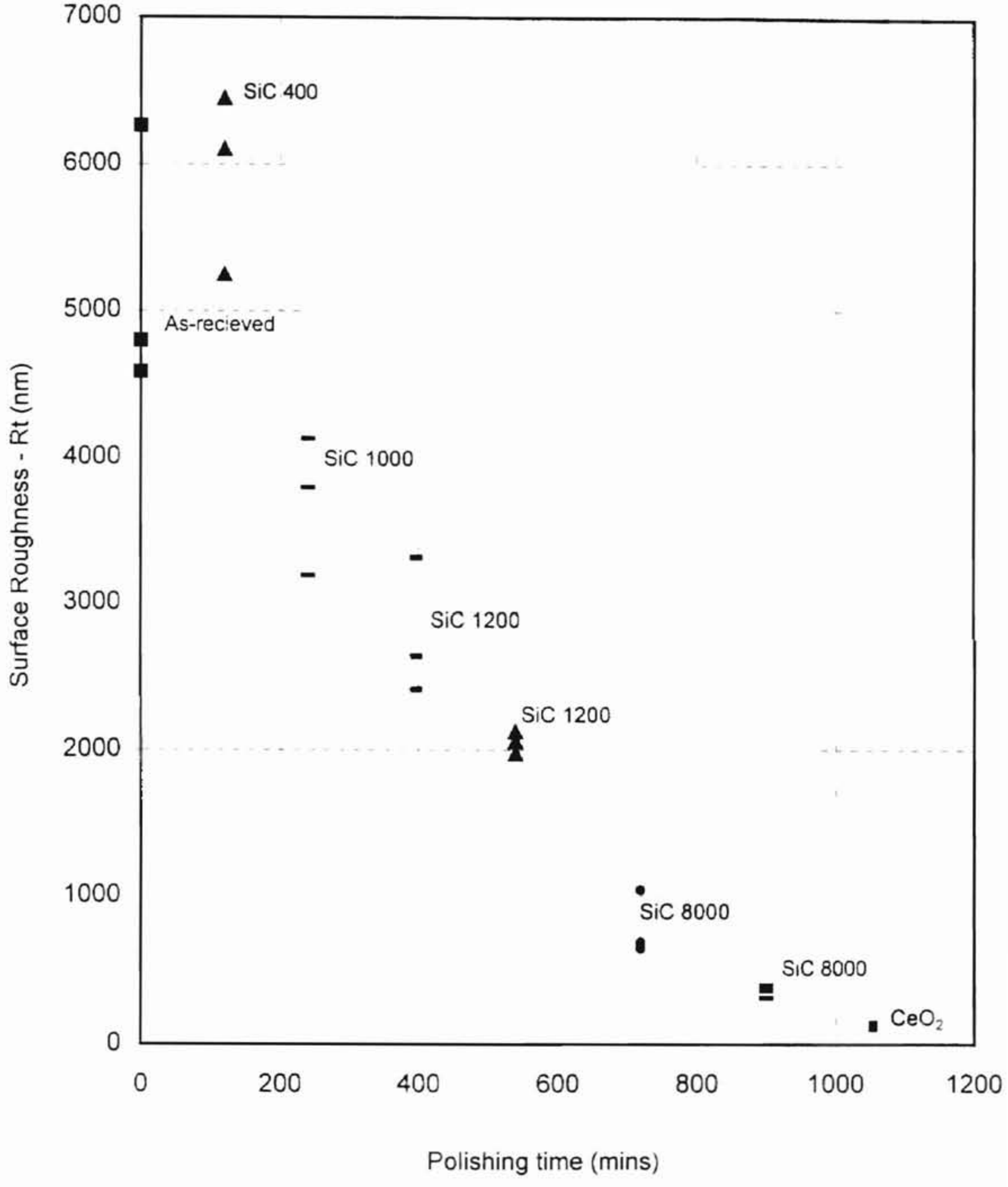
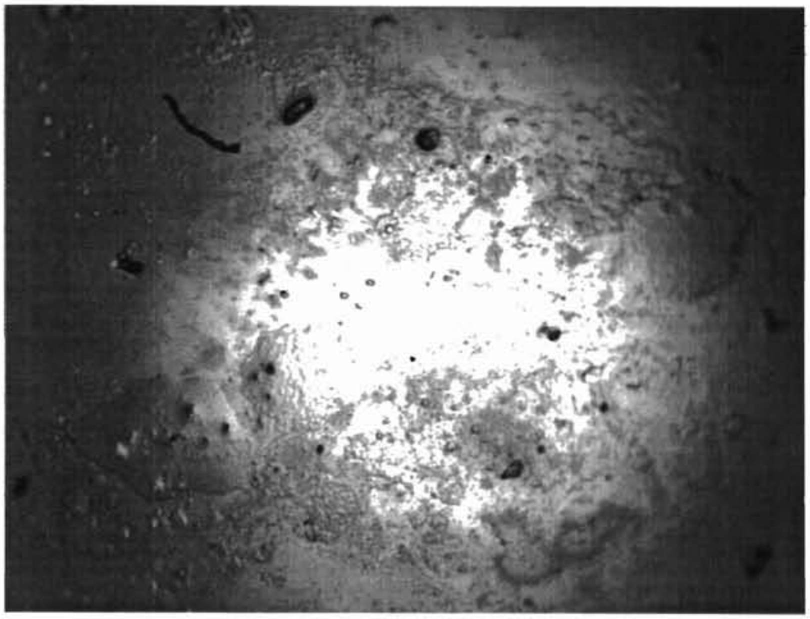


Figure 8.8 (a) and (b) show surface of the as-received glass balls as it appears under an optical microscope (magnification 10x). The surface has several defects - significant number of pits and voids that have to be removed during the polishing process by MFP. Figure 8.9 shows the as-received glass balls having a surface roughness in the range of Ra: 475 to 665 nm and Rt: 4.585 to 6.263 μm. The sphericity of the balls is from 2.05 to 2.40 μm as shown by Figure 8.13.

The final stage of polishing using cerium oxide and polishing pad (chemomet) results in a surface finish with an average Ra of 18nm and an average Rt of 125nm (after run#11, batch 42). The polished surface of the balls is smooth with relatively less number of pits and voids and comparable to the finish as in trial run number 32. The surface has minimal damage, however, some scratches and pits can be traced. Figures 8.19 (a) and (b) show the optical microscope images of the glass balls finished to a given diameter (batch 42). Figures 8.20 shows the surface roughness of these balls. The sphericity of these balls is in the range of 0.55 to 0.80 μm as shown by Figure 8.14.

Figure 8.19 (a)



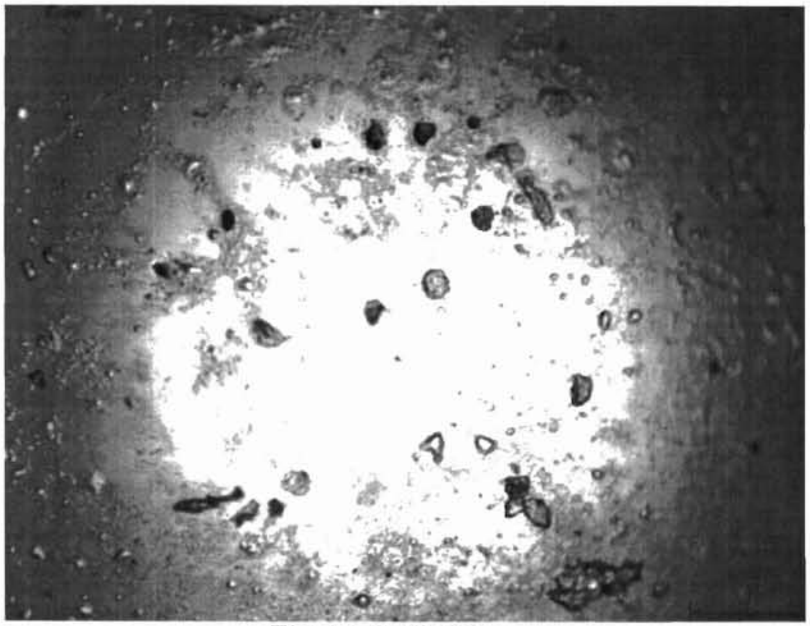
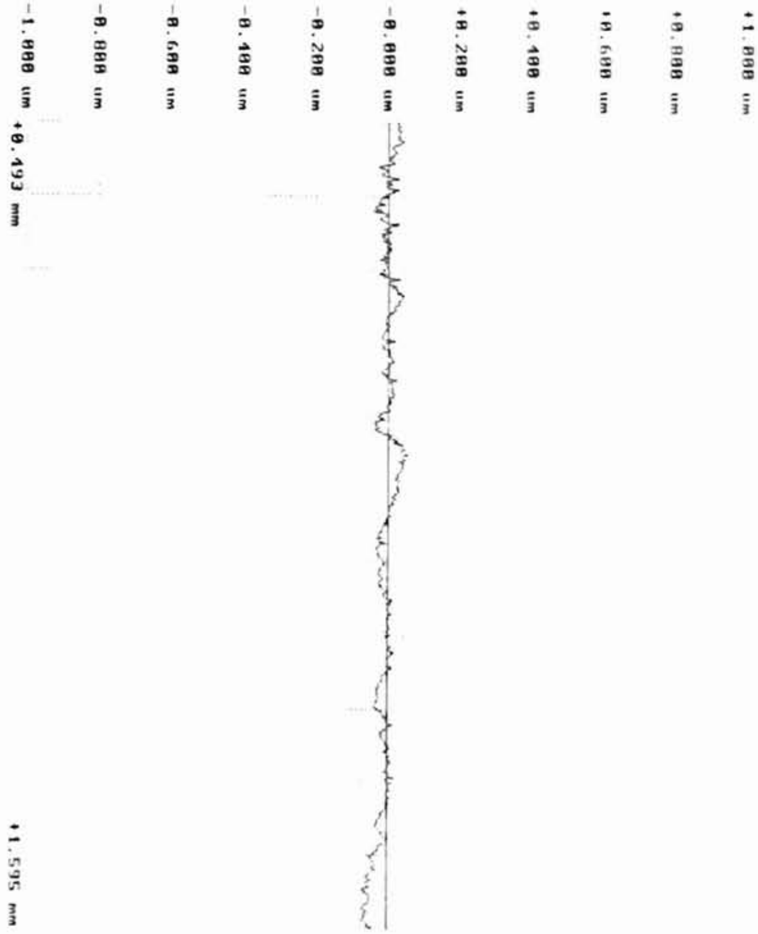


Figure 8.19 (b)

Figure 8.19 (a), and (b) Optical Microscope Images of the Glass Balls Polished by Cerium Oxide with Chemomet after Using SiC (Magnification: 10x, Batch 42)

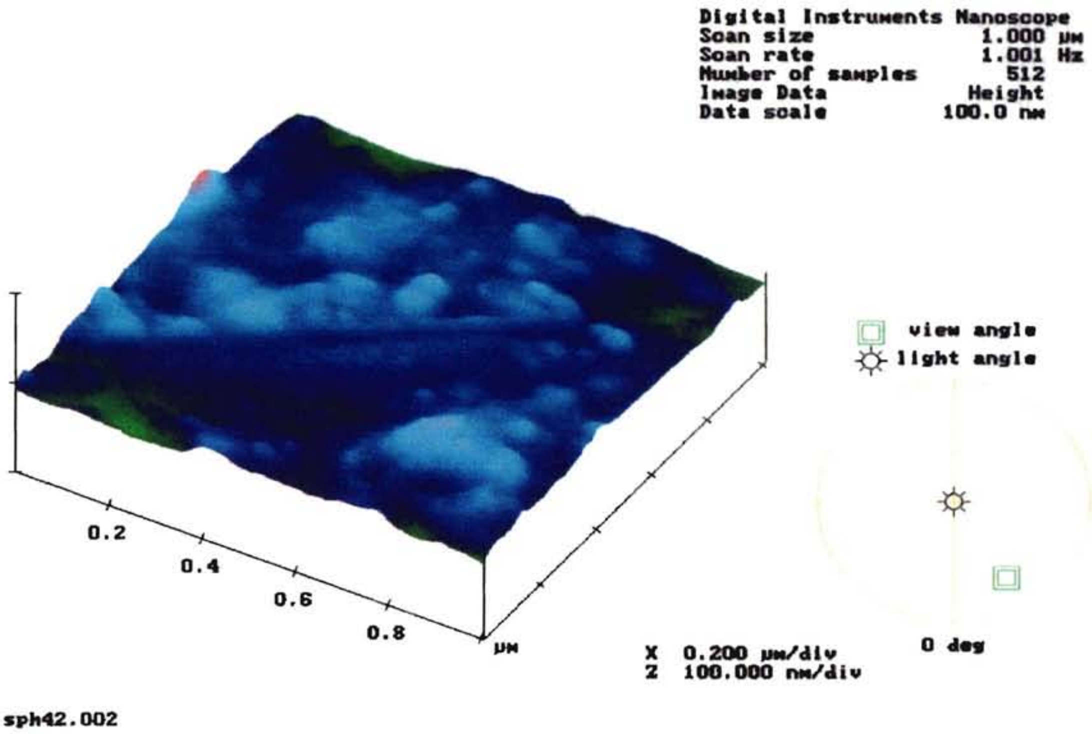


```
LS Rad  2.16971mm

Ra      0.0179 um      Rq      0.0235 um      Rp      0.0557 um
Rv      0.0789 um      Rt      0.1266 um      Rt1     0.0000 um
Rt2     0.0949 um      Rt3     0.0587 um      Rt4     0.0950 um
Rsk     -0.7676        Rku     3.3284         Delq     0.3660 deg
Lamq    23.1569 um     S       4.4328 um      Ry      0.0950 um
RzISO   0.0790 um      RzDIN   0.0842 um      Rpm     0.0361 um
R3y     0.0842 um      R3z     0.0717 um      Rk      0.2097 um
Rpk     0.3024 um      Rvk     0.0990 um      Mr1     33.0000 %
Mr2     98.0000 %      Sm      15.7053 um     Lo      1.1026 mm
```

Figure 8.20 Surface Roughness - Ra and Rt of the Glass Balls Polished by Cerium Oxide with Chemomet after Using Different Grit Sizes of SiC (Batch 42)

Analysis from the AFM images indicates that the finish on the surface of the glass balls (Batch 42) is superior with significantly less damage. The surface roughness analysis shows a Ra in the range of 4.3 nm to 27 nm (Figures 8.21 and 8.22). However, some scratches can be traced on the surface of the polished glass balls. The scratch depth produced on the glass ball is analyzed by AFM for its dimensions - depth and width. The scratch shown by Figure 8.23 (a) has a depth of 4.7 nm and width of 839 nm. Also, small pits are produced on the surface as shown by Figure 8.24 (a). Analysis of the image for the dimensions of the pits shows that the width of the pit is 505 nm and the depth is 257 nm (vertical distance from the bottom of the pit along with the material build-up around the pit periphery).


Digital Instruments Nanoscope
Scan size 1.000 μm
Scan rate 1.001 Hz
Number of samples 512
Image Data Height
Data scale 100.0 nm

X 0.200 μm/div
Z 100.000 nm/div

sph42.002

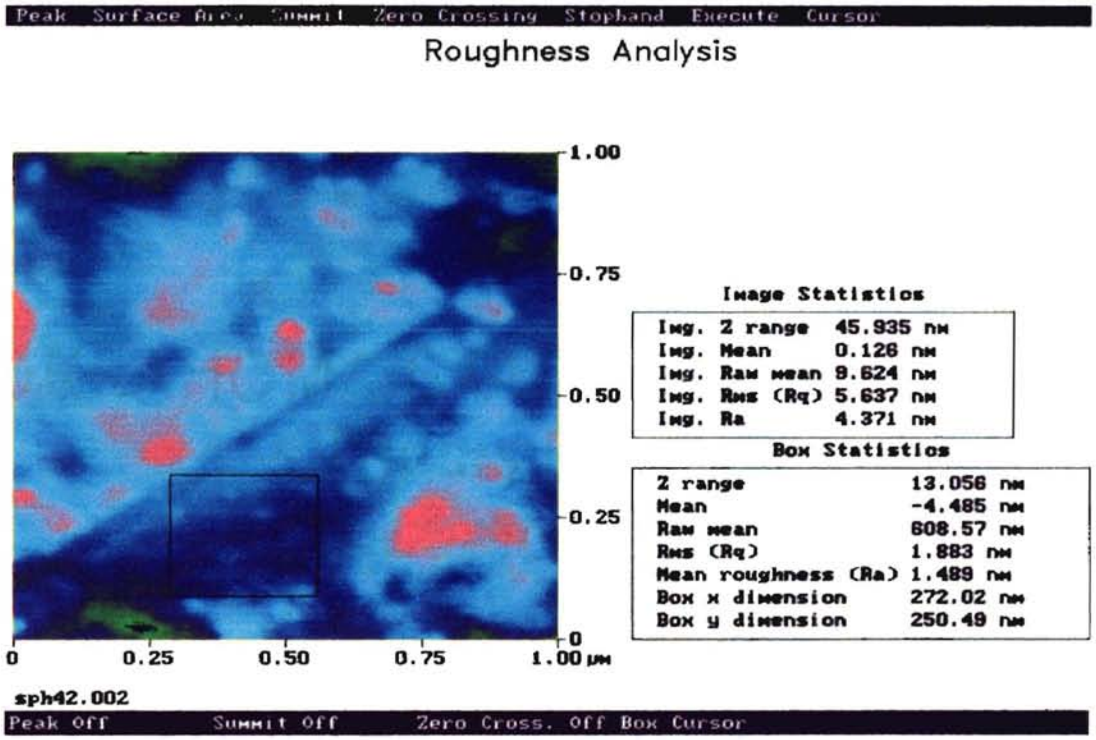

Roughness Analysis

Image Statistics

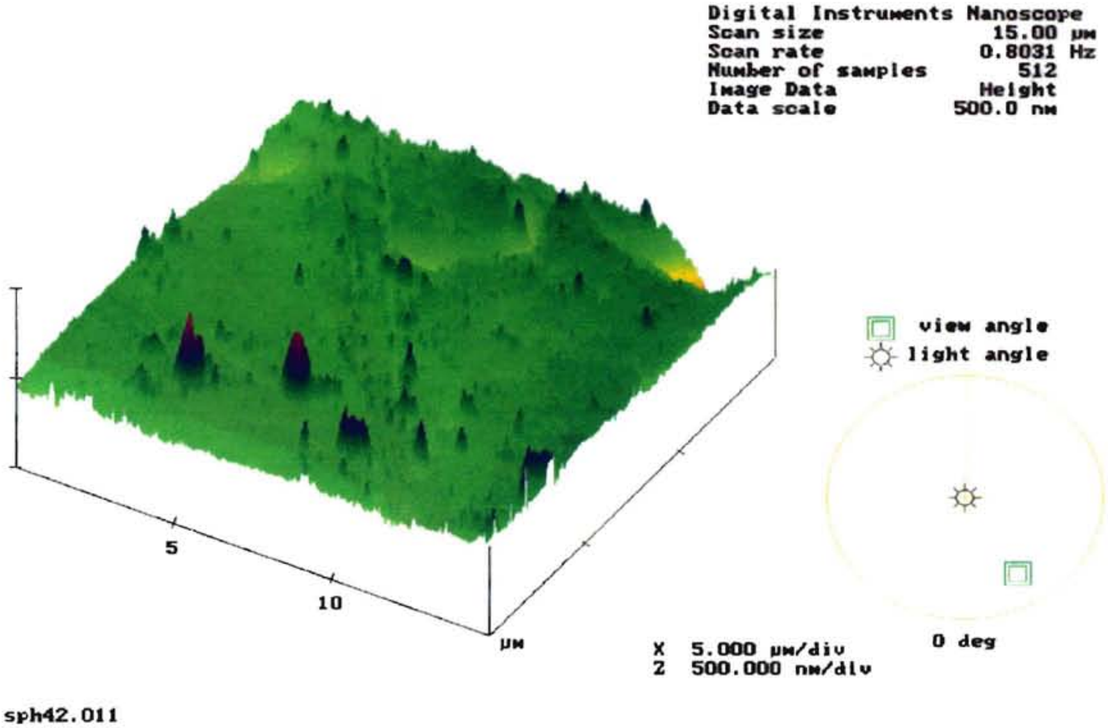
Img. Z range	45.935 nm
Img. Mean	0.126 nm
Img. Raw mean	9.624 nm
Img. Rms (Rq)	5.637 nm
Img. Ra	4.371 nm

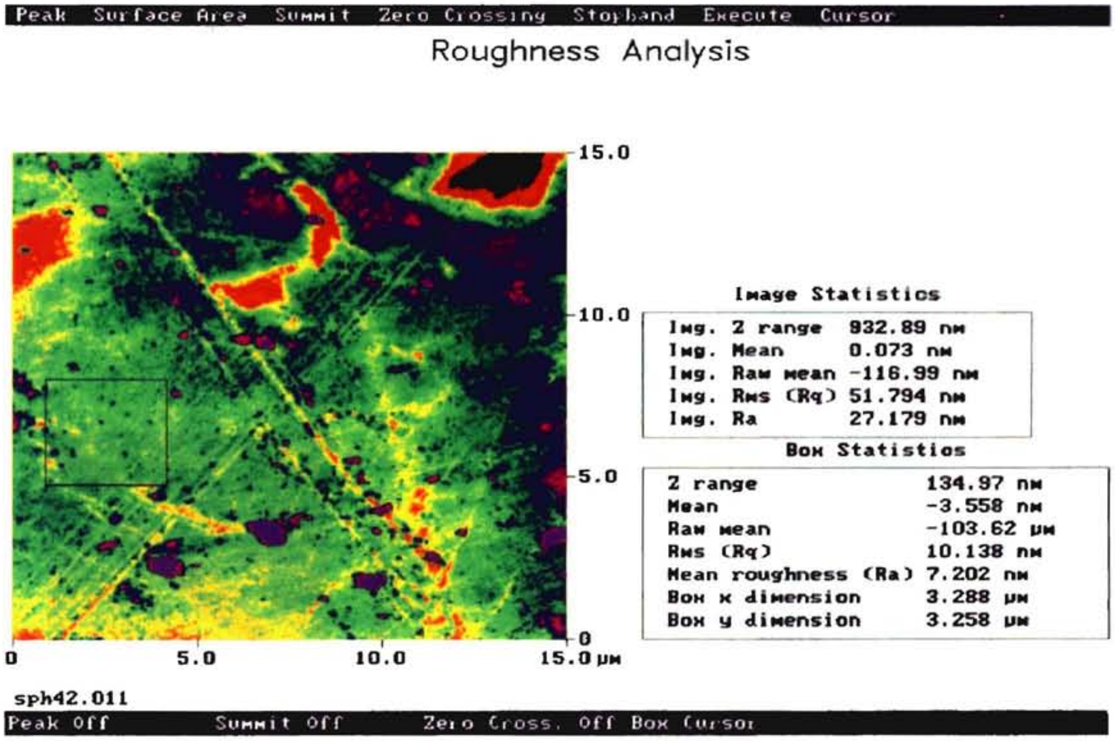
Box Statistics

Z range	13.056 nm
Mean	-4.485 nm
Raw mean	608.57 nm
Rms (Rq)	1.883 nm
Mean roughness (Ra)	1.489 nm
Box x dimension	272.02 nm
Box y dimension	250.49 nm

sph42.002

Figure 8.21 Analysis of Surface Roughness of Glass Ball Polished by MFP

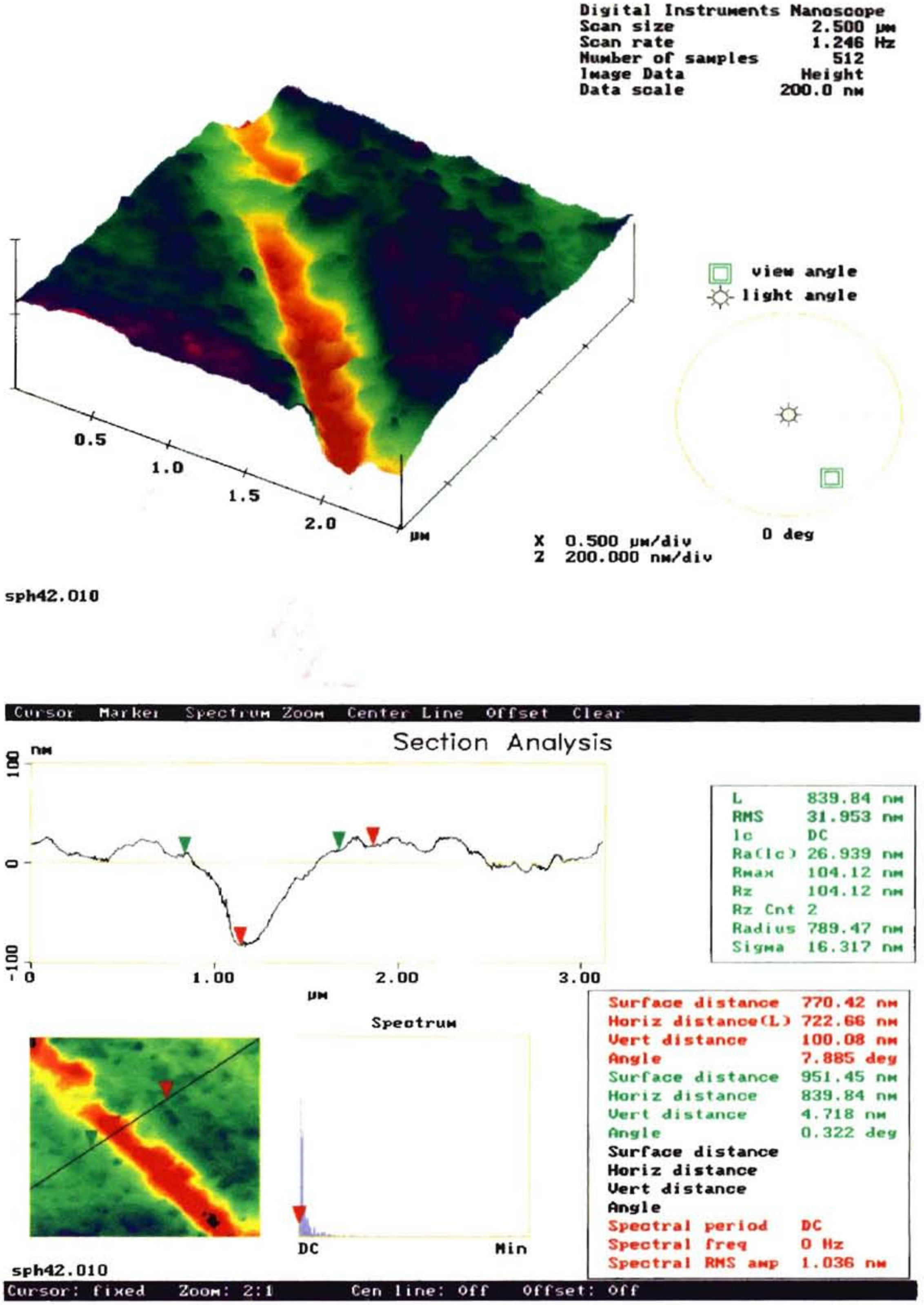




```
Image Statistics
Img. Z range    932.89 nm
Img. Mean       0.073 nm
Img. Raw mean   -116.99 nm
Img. Rms (Rq)   51.794 nm
Img. Ra         27.179 nm

Box Statistics
Z range                   134.97 nm
Mean                      -3.558 nm
Raw mean                  -103.62 µm
Rms (Rq)                  10.138 nm
Mean roughness (Ra)       7.202 nm
Box x dimension           3.288 µm
Box y dimension           3.258 µm
```

Figure 8.22 Analysis of Surface Roughness of Glass Ball Polished by MFP

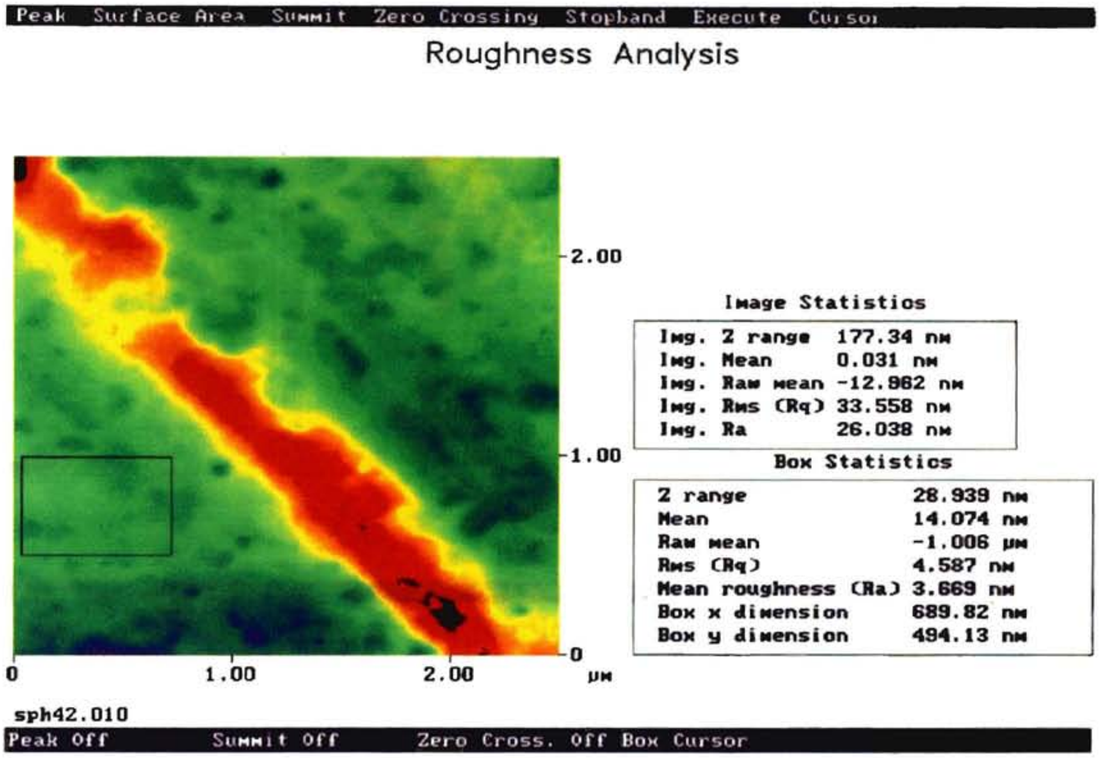


```
Digital Instruments Nanoscope
Scan size                 2.500 µm
Scan rate                 1.246 Hz
Number of samples          512
Image Data                Height
Data scale               200.0 nm
```

```
L         839.84 nm
RMS       31.953 nm
Ic        DC
Ra(Ic)    26.939 nm
Rmax      104.12 nm
Rz        104.12 nm
Rz Cnt    2
Radius    789.47 nm
Sigma     16.317 nm
```

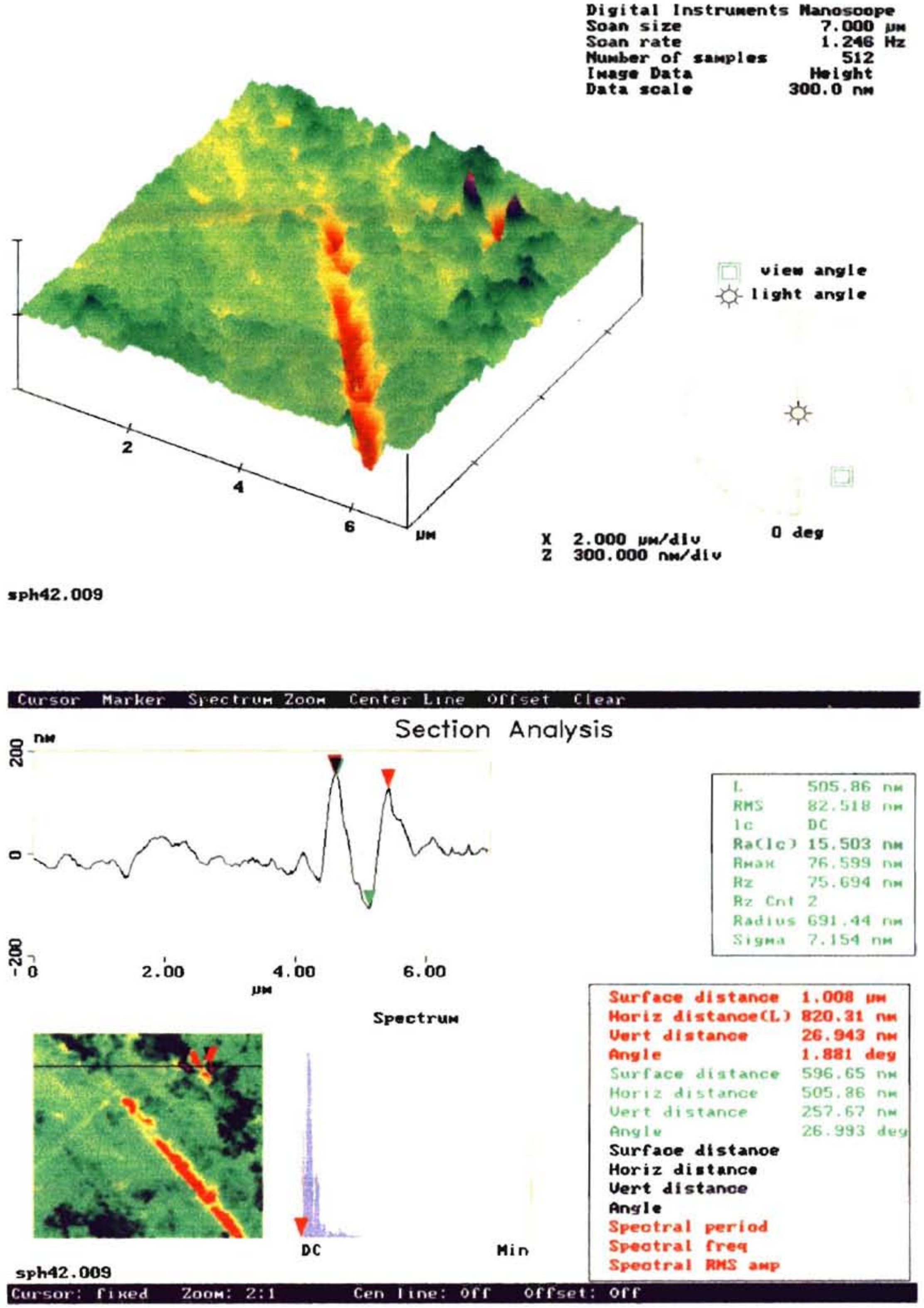
```
Surface distance      770.42 nm
Horiz distance(L)     722.66 nm
Vert distance         100.08 nm
Angle                 7.885 deg
Surface distance      951.45 nm
Horiz distance        839.84 nm
Vert distance         4.718 nm
Angle                 0.322 deg
Surface distance
Horiz distance
Vert distance
Angle
Spectral period       DC
Spectral freq         0 Hz
Spectral RMS amp      1.036 nm
```

Figure 8.23 (a) Analysis of Scratch on Surface of Glass Ball Polished by MFP (Batch 42)



```
Image Statistics
Img. Z range   177.34 nm
Img. Mean      0.031 nm
Img. Raw mean -12.962 nm
Img. Rms (Rq) 33.558 nm
Img. Ra        26.038 nm
Box Statistics
Z range                  28.939 nm
Mean                     14.074 nm
Raw mean                 -1.006 µm
Rms (Rq)                 4.587 nm
Mean roughness (Ra)      3.669 nm
Box x dimension          689.82 nm
Box y dimension          494.13 nm
```

Figure 8.23 (b) Analysis of Surface Roughness of Glass Ball Polished by MFP (Batch 42)

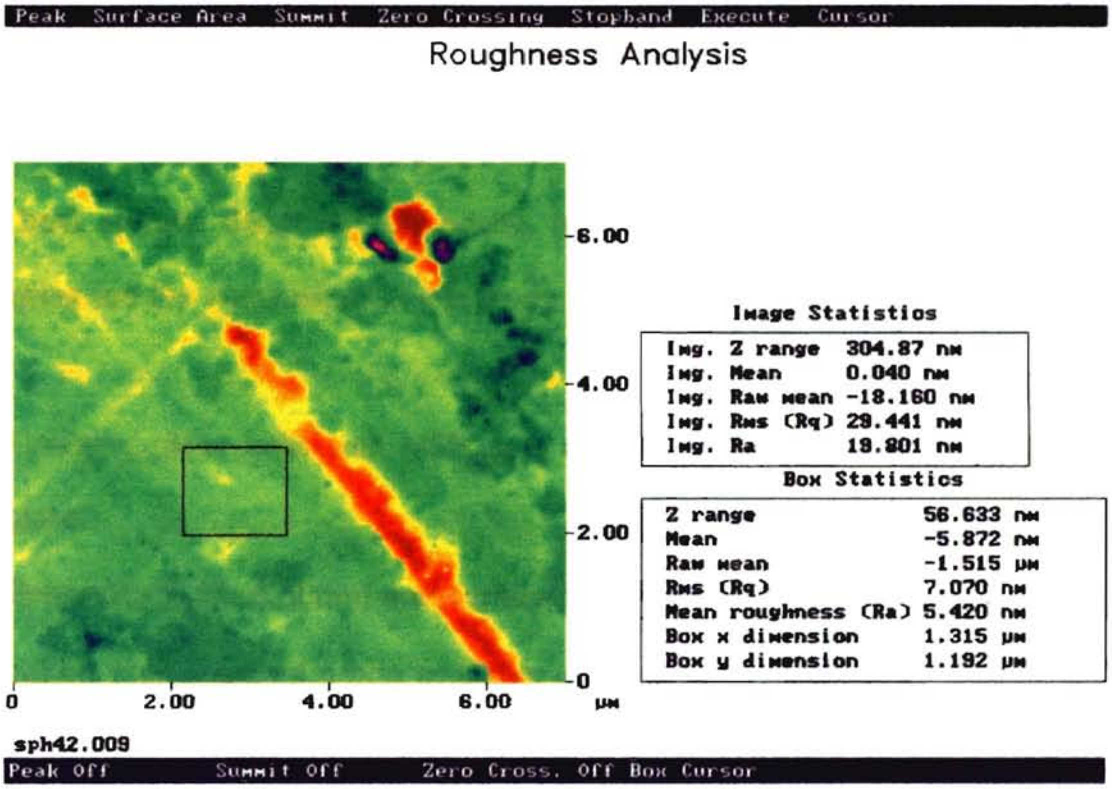


Digital Instruments Nanoscope
Scan size 7.000 µm
Scan rate 1.246 Hz
Number of samples 512
Image Data Height
Data scale 300.0 nm

L 505.86 nm
RMS 82.518 nm
lc DC
Ra(lc) 15.503 nm
Rmax 76.599 nm
Rz 75.694 nm
Rz Cnt 2
Radius 691.44 nm
Sigma 7.154 nm

Surface distance 1.008 µm
Horiz distance(L) 820.31 nm
Vert distance 26.943 nm
Angle 1.881 deg
Surface distance 596.65 nm
Horiz distance 505.86 nm
Vert distance 257.67 nm
Angle 26.993 deg
Surface distance
Horiz distance
Vert distance
Angle
Spectral period
Spectral freq
Spectral RMS amp

Figure 8.24 (a) Analysis of Pits on Surface of Glass Ball Polished by MFP



```
Image Statistics
Img. Z range   304.87 nm
Img. Mean      0.040 nm
Img. Raw mean  -18.160 nm
Img. Rms (Rq)  29.441 nm
Img. Ra        19.801 nm

Box Statistics
Z range                  56.633 nm
Mean                     -5.872 nm
Raw mean                 -1.515 µm
Rms (Rq)                 7.070 nm
Mean roughness (Ra)      5.420 nm
Box x dimension          1.315 µm
Box y dimension          1.192 µm
```

Figure 8.24 (b) Analysis of Surface Roughness of Glass Ball Polished by MFP

Chapter 9

Conclusions

Expanding the process capability of the MFP offers a very suitable "gentle" polishing process for finishing glass balls. The process is optimized to achieve the best surface finish and sphericity, by applying the Taguchi method. The following are the conclusions of this study:

- Finishing glass balls with MFP sets an alternative technology for finishing glass.
- Sphericity (0.55~0.80mm) and surface finish values (Ra=17~21nm) lower (i.e. better) than the best grade available in glass balls (finished by conventional polishing technology), are obtained.
- Polishing conditions are developed for the initial stage of reasonably high removal rates with minimal damage, an intermediate semi-finishing stage with control over sphericity and surface roughness and again minimal damage as well as correct any damage caused from previous stage, and a final finishing stage for good sphericity and finish with minimum or no damage. A diameter target can be set for finishing glass balls and the given diameter can be reached accurately with the three polishing stages of MFP employed on the glass ball blank.

- ☐ A polishing pad is introduced and successfully utilized in the polishing system to improve the surface finish.
- ☐ After investigation of different abrasives suitable for glass, silicon carbide (grit 400 to 8000) is found to form the most effective abrasive slurry with minimal surface and sub-surface damage in the initial and semi-finishing stages with control over size and sphericity. Good sphericity (0.55 to 0.8 μm) and surface finish (Ra: 31 to 41 nm) could be achieved using finer grades of silicon carbide.
- ☐ In the final stage, cerium oxide abrasive is found to be very effective in correcting any damage from previous stages and polishing the glass balls by CMP to a superior finish (Ra: 17 to 21 nm) with the use of polishing pad.
- ☐ A wide range of material removal rates (4~240 μm/hr) are achieved to make the process fast and economically viable. At the same time the process conditions are "gentle" enough to avoid or minimize damage at high removal rates. In this way, the glass balls are polished to a superior finish and sphericity from the as-received condition in less than 18 hours of total process run-time. (for a material removal of approximately 950 μm).
- ☐ The process is developed such that it has a precise control over the material removal rates to finish a batch of balls to any given diameter.

Chapter 10

Future Work

The MFP technology is successfully modified to finish glass balls of diameter 5.012 mm (0.1973 inch) to a surface finish of 10 nm and a sphericity of 0.55 μm. The future work on this project could be in several areas as mentioned below:

- Finish different diameter glass balls:

  The present investigation develops conditions for different stages from the initial stage of high material removal rates as well as the semi-finishing and final stages where the material removal rates are low. However, the material removal rates vary with diameter. In case of larger diameter balls (>0.5") sliding motion is more predominant than rolling motion due to the higher mass. The data from the present investigation cannot be referred as standard data, as these values are valid for a particular diameter of balls only. An experimental study involving polishing of balls of a wide range of diameters should be conducted to develop a set of standard data.
- Investigate the exact material removal mechanisms associated with the process by studying the wear debris, the polishing pad. Microscopic examination of the glass ball surface with an advanced optical microscope would facilitate in-depth study as clear and detailed images of surface imperfections, such as scratches and pits, can be obtained.

- Investigate the effectiveness of finer grades of silicon carbide, such as SiC grit size 10,000. The use of such abrasives would result in superior finish in the semi-finishing stages. The final finishing stages using cerium oxide would further improve the finish.
- The process can be efficiently used to finish different geometries of glass work-pieces, e.g. flat, curved (lenses).
- Reduce the evaporation rate of water from the magnetic fluid during polishing. This directly affects the performance of the process and the set-up time. If the magnetic fluid retains its water content (without losing it out to the atmosphere) or by addition of precise quantities of de-ionized water, the polishing process will have considerable set-up time reduction, thus making it faster and lowering the costs associated with time. Some suggestions are to develop a covered chamber that is thermally isolated with the surroundings.
- Study effect of polishing pad on float with groove and when mounted on a new float without groove.
- Study effect of different polishing pads with different abrasive slurries.
- Study effect of varying pH values of abrasive slurry.

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APPENDIX A

Table A1: Nominal Composition of Leaded Glass

SiO_2	61%	PbO	24%
K_2O	10%	Na_2O	3%
ZnO	1%	B_2O_3	0.3%
BaO	0.2%	As_2O_3, SbO_3	0.5%

Table A2: Properties of Leaded Glass

Moh's Hardness	5
Specific Weight	3.0 kg/dm3
Poisson's Ratio	0.211
Modulus of Elasticity	5.95 x 104
Tensile Strength	47.5 MPa

APPENDIX B

Ball Grades

The AFBMA (Anti-Friction Bearing Manufacturers Association) specification of different grades of balls is given in Table B1. Glass balls are extensively used in valves and flow meters. The balls used in valves usually require close control of roundness and surface finish to insure leak-tight operation. However, size variations are not critical unless specified. The valve ball grades (from AFBMA from 48 – 500) are denoted by the grade value followed by a 'V' (for valve) for industries using balls for valves and related applications.

Table B1: AFBMA Ball Grading Chart

AFBMA Grade	Roundness		Lot Dia. Variation		Surface Finish (Ra)	
	μ-inch	μm	μ-inch	μm	μ-inch	nm
3	0.003	0.08	0.005	0.13	0.05	12
5	0.005	0.13	0.01	0.25	0.08	20
10	0.001	0.25	0.02	0.5	1	25
24	0.024	0.4	0.048	1.2	2	50
48	0.048	1.2	0.096	2.4	3	76
100	0.1	2.5	0.2	5	5	125
200	0.2	5	0.4	10	8	200
500	0.5	13	1	25	-	-

APPENDIX C

Samples of Polishing Pads Used in the Present Investigation:

The polishing pads used in this study are made by Buehler Ltd. and sold under the trade names 'Chemomet', 'Microcloth', and 'Nylon'. A pressure sensitive adhesive (PSA) which allows for easy and convenient installation of pad backs these pads. The samples of each of these polishing pads are provided below.

1. Chemomet	
2. Microcloth	
3. Nylon	

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Thesis: FINISHING OF GLASS BALLS BY CHEMICAL MECHANICAL POLISHING (CMP) USING CERIUM OXIDE – EXPANDING THE PROCESS CAPABILITIES OF MAGNETIC FLOAT POLISHING (MFP) TECHNOLOGY

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