A Thesis

entitled

Study and Optimization of D2 Steel Lapping Using a Tribological Designed Plate

by

Yiying Zhang

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Ioan D. Marinescu, Ph.D., Committee Chair

Ahalapitiya H. Jayatissa, Ph.D., Committee Member

Yong Gan, Ph.D., Committee Member

Dr. Patricia R. Komuniecki, Dean
College of Graduate Studies

The University of Toledo

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Steel and iron, as the indispensable industrial materials, have a wide range of applications in mass production and everyday life. Good or super performance of these metals is highly needed in many fields, such as medical devices, optical equipments, auto production, aerospace application, due to the rapid developments in science and engineering technology.

Fine lapping on these materials have been studied for many years to improve the machining process and thus to produce smooth surfaces with favorable properties. FriCSo patented polymer lapping solution made an important breakthrough in lapping on steel or cast iron surfaces. Compared to traditional lapping, this technology provides dramatically improved surface finish and friction performance of the treated metal surfaces.

In this study, research is focused on analysis and optimization of polymer lapping process on D2 steel samples. The tribological mechanisms of lapping for different modes are analyzed. The polymer lapping method and polymer-based lapping plate are...
introduced in this study. Morphological and composition investigations are conducted to reveal the mechanism and characteristics of polymer lapping. In addition, experiments are carried on and ANOVA statistical analysis is performed to determine the effects of lapping time, lap rotation speed, lapping pressure and abrasive particle size on the lapping process for D2 steel discs with the polymer-coated plate. Regression models are put forward and verified for predicting surface roughness and MRR (material removal rate) as a result of the control variables. An optimal regime of process parameters is given for optimizing the polymer lapping process.
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Chapter 1 Introduction

1.1 Overview

Material science has made remarkable progress, and the application of newly developed machining technology to achieve both high quality and efficiency has increased rapidly. Lapping, as one of the oldest machining processes, remains a leader in surface finishing on a very wide range of materials, such as metal and their alloys, ceramics, plastic, optical glass and silicon wafers, due to its incomparable advantages in obtaining high surface quality, form accuracy and very tight dimensional tolerance. However, it is essential to improve conventional lapping techniques or add new working principles to ensure the highest quality and accuracy on worked surfaces. Therefore, research should focus on improving lapping process by studying significant process variables, based on fundamental knowledge and experience.

Several terms need to be introduced in order to illuminate lapping process in a scientific view. In the engineering field, tribology is defined as the science and technology of interacting surfaces in relative motion and of related subjects and practices [1]. "Tribology‘ is derived from the Greek word ‘tribos‘, which means rubbing or sliding [2]. A tribological system includes a workpiece, which has a working surface adapted for moving relative to a counter-surface in a presence of a lubricant and in a load-bearing environment. The working surface includes: (i) a metal surface layer; (ii) a
plurality of organic particles incorporated in the metal surface layer; and (iii) a plurality of inorganic particles incorporated in the working surface [3]. Tribology deals with every aspect of friction, lubrication and wear. Wear is defined as the damage to a solid surface, generally involving progressive loss of material, due to the relative motion between that surface and contacting substances [4]. There are five types of wear: abrasive, adhesive, erosive, fatigue and fretting. Abrasive wear, caused by hard particles that are forced and moving along a solid surface, has a contribution of at least 60% of the total cost due to wear [5].

Lapping is classified as a process of abrasive wear. It can be defined as the removal of material to produce a smooth, flat, unpolished surface. It is a free abrasive machining process, compared to grinding, which is a bonded abrasive machining process. Lapping mainly includes a lap plate, abrasives, vehicle or carrier, conditioning rings, and work holders [6].

Lapping, with a wide range of application, is used in the production of components of high quality in terms of form and finish accuracy and surface integrity. Typical examples of the processed components by lapping are: pump parts (seal faces, body castings, rotating valves, impellers), transmission equipments (spacers, gears, shims, clutch plates), cutting tools (tool tips, slitter blades), hydraulic and pneumatic applications (valve plates, seals, cylinder bodies, castings, slipper plates), aerospace parts (lock plates, gyro components, seals), inspection equipments (test blocks, micrometer anvils, optical flats, surface plates), stamping and forging devices (spacers, type hammers, bosses and a variety of other complex shapes) [7].
Recent research has studied the effects of important variables on the lapping process for different materials. Ahn and Park [8] investigated the effects of abrasive particle size, concentration and lapping pressure on the surface roughness and material removal rate and developed a model to explain the lapping process. Tam et al. [9] proposed and verified a two-stage fabrication process to improve the efficiency of fabrication of RB-SiC and analyzed the process parameters. Chang et al. [10] designed and performed a lapping and polishing experiment on a gauge block using the Taguchi method and analyzed the factors by ANOVA. Yuan et al. [11] discussed the lapping and polishing process to obtain the damage-free surfaces of quartz crystals and put forward a basic formation model of surface roughness. Deshpande et al. [12] observed the surface finish and flatness of stainless steel and bronze after flat lapping and quantified the influence of abrasive material properties in this process. Dobrescu and Dorin [13] performed and analyzed the plane lapping by ANOVA and selected an optimal variable combination for improving surface roughness.

Lapping is a very complicated and random process with the main outcomes, such as stock removal, roughness and flatness, as a result of numerous variables affecting the process quality. For these reasons, it needs to be analyzed based on experiments rather than only on theory to get the relative effects of process parameters.

1.2 Objectives

This study aims at obtaining the optimal combination of process parameters, thus the optimization of lapping on D2 steel with a tribological designed plate. Furthermore, investigations on the lapped metal surfaces were performed in order to understand the
mechanism on micro/nano scale and topographical effects of the tribological designed lapping plate. A briefing of each chapter is summarized as below:

In Chapter 2, the fundamental concepts of lapping process are stated, and the material removal mechanisms in different modes are explained.

In Chapter 3, FriCSo patented lapping solution is introduced, the topography and composition of lapped metal surfaces are investigated, and the effects of polymer plate on lapping mechanism are analyzed.

In Chapter 4, lapping experiments are designed and proposed for D2 steel discs using a tribological designed lapping plate, and the system and methodology of experiments are introduced.

In Chapter 5, statistical analysis of variance (ANOVA) is performed to find lapping process parameters of statistical significance, and regression models are generated and verified. The effects of process parameters on surface roughness (Ra) and material removal rate (MRR), including duration, rotational speed, lapping pressure and abrasive grit size, are investigated to optimize the lapping process.
Chapter 2  Fundamentals of Lapping Process

Lapping is the removal of material to produce a smooth, flat, unpolished surface and achieve ultra-high finishes and close tolerances between mating pieces. This process is characterized by its low speed, low pressure, and low material removal. It also can be considered the balancing of abrasive grit size and proper hardness (type of abrasive) against lapping time and the pressure of the part on the plate in a certain rotational speed. The good balance is achieved when all abrasive particles break down completely into inert sizes, while removing the desired amount of material and wearing out the abrasive power of the particles [14]. The main purpose of lapping is to obtain greater dimensional accuracy and a smoother surface. Lapping processes are very complex since there are many process factors and various working conditions that may influence quality and efficiency. Hence it is necessary to study the fundamentals of lapping and thus investigate and analyze the significant variables of this process by experiments based on knowledge and theory.

2.1  Two-body and Three-body Abrasions

As mentioned in Chapter 1, one of the most important mechanisms of the wear process is abrasive wear: the detachment of material from surfaces in relative motions caused by protrusions and/or hard particles between the opposite surfaces or fixed in one of them [6]. In abrasive machining, the main objectives are usually to minimize
friction and wear of the abrasive while maximizing abrasive wear of the workpiece [15].

It is widely accepted by researchers that abrasive wear is classified into two-body abrasion and three-body abrasion. The current dominant view interprets that two-body abrasion is a process in which particles or asperities are rigidly attached to the second body whereas in three-body abrasion, the abrasive particles are loose and free to roll [16], as shown in Figure 2.1. Therefore, in a two-body abrasion, the abrasive grains can cut deeply into the workpiece due to the sliding motions, whereas in the three-body mode, the particles spend part of time in cutting and part of time in rolling. Therefore, on the same process conditions, the former mechanism is expected to produce three times higher wear rates than the latter mechanism [6].

![Figure 2.1. Two-body and Three-body Abrasive Processes [15]](image)

Gates stated that this classification of abrasive wear can be used only when describing whether abrasive grains are rigidly held or free to roll. From a tribological point of view, one should take into account the severity of wear behavior: mild, severe, and extreme [17]. Also, he cited several examples where the application of the current
dominant interpretation leads to inconsistencies.

However, in 1999, Trezona et al. indicated that it was not possible, just by reference of severity of wear, to determine how the wear was occurring due to a range of conditions near the transition between wear processes. They put forward two new terms “grooving abrasive wear” and “rolling abrasive wear” to replace the two-body and three-body abrasion respectively [16]. “Grooving abrasive wear” describes an abrasive wear process in which the same region of the abrasive particle or asperity is in contact effectively with the wearing surface throughout the process. Yet, “rolling abrasive wear” represents an abrasive wear process in which the region of the abrasive grain in contact with the wearing surface is continually changing. Wear surfaces produced by grooving abrasion are characterized by grooves parallel to the direction of sliding while the ones produced by rolling abrasion are characterized by a heavily deformed, multiply indented appearance and little or no directionality [16].

Lapping is mainly considered a three-body abrasion, which is wear caused by free and loose abrasive particles existing as interfacial elements and rolling or sliding between a solid body and a counter body; although, some grains become embedded in the lap, leading to two-body abrasion for a short period of time. Figure 2.2 shows two-body and three-body abrasion in microscale during lapping. In this process, there are collisions between abrasive particles and the workpiece, the plate and other particles, which lead to energy dissipation [15]. However, the advantage is that new cutting edges can be brought into action as the grains rotate.

In tribological terms, besides of lapping, polishing is also considered as a
three-body abrasion process, while grinding and honing involve two-body abrasion.

Figure 2.2. Micro-mechanisms of Two-body and Three-body Abrasion [6]

2.2 Classification of Lapping Processes

Generally, all lapping processes can be divided into two main groups: lapping with shape-transferring counterpart and lapping without shape-transferring counterpart. The latter one is used only if the surface is to be improved without considering the form and geometrical accuracy [6]. More specifically, the most used lapping processes can be classified as following, according to the generated surfaces, process kinematics and tool profiles.

Single-side surface lapping (Figure 2.3) is the most widely used lapping method to achieve the desired flatness and surface roughness. This process can machine more than one piece at one time, and it has simple work holdings, consistent cut rates and close accuracies. A single-side lapping machine has a rotating annular-shaped lap plate, on which the workpieces are applied to. One machine usually has three to four conditioning rings. The workpieces are placed in these conditioning rings. During the
lapping process, a certain load is applied and abrasive slurry is provided. In this way, the parts are pressed against a film of abrasive slurry that is continuously supplied to the rotating lapping plate. The most influential factors on the surface finish, which should be taken special care of, are keeping the lap flat, applying a uniform and predictable pressure, and maintaining a constant and consistent flow of the abrasive slurry [15].

![Single-side Lapping Process](image)

**Figure 2.3. Single-side Lapping Process [6]**

Double-side surface lapping (Figure 2.4) is considered the most accurate method in terms of parallelism and uniformity of size as two parallel even surfaces are simultaneously lapped during this process [6]. It is the process of choice for achieving best flatness, thickness and parallelism on all types of metal parts. The process is stress free without thermal distortion and is suitable for ferrous and non-ferrous materials.
Typical double-sided lapping applications include precision piston rings, precision spacers, gage slacks, seals, computer components, engine components and pump components.

Figure 2.4. Double-side Lapping Process [6]

Cylindrical lapping (Figure 2.5) is a machining process with aim to finish cylindrical parts or cylindrical portions of a particular component to a high degree of geometric accuracy, with low surface roughness, by means of lapping on a lapping machine equipped with a holder. The work holder has openings with the form and size

Figure 2.5. Cylindrical Lapping Processes [6]
corresponding to the dimensions of the workpiece [15]. Applications of cylindrical lapping are mainly for cylinders of injection pumps, hydraulic cylinders, and high-precision machine components with precision turned or reamed surfaces.

Besides this, there are some other types of lapping processes, such as lapping with bonded abrasives, thread lapping, roll lapping, profile lapping, ultrasonic-assisted lapping, pairwise lapping, vapor lapping, dip lapping etc, which are used to meet different profile, dimensional and other requirements.

2.3 Components of Lapping Tool

Lapping is a loose abrasive machining process that combines abrasive particles within an oil or aqueous medium depending on the material being finished. Fine abrasives are applied, continuously or at specific intervals, to a work surface to form an abrasive film between the lapping plate and the parts being lapped [15]. Therefore, the important components of lapping tool influencing the lapping characteristics are the type of the lapping plate, the type and size of the abrasive grains, the lapping fluid type and amount.

2.3.1 The Lapping Plate

As we know, a mixture of just oil and abrasives is not good enough to serve as a lapping medium. The abrasive granules should be held in a film on the plate to resist the movement or rolling of themselves. Lapping plate selection can play a critical role in the production of high quality specimens. The material and the lapping plate design are selected depending upon the desired material removal rate, the desired surface finish,
the hardness of the specimen being lapped and the flatness requirement.

The mainly significant characteristics of lapping plates are the materials, mechanical properties, structure, macro-geometry and surface topography [6]. The mechanical properties and the structure of the plate material are critical to the plate resistance to the abrasive granules, and the effect on the generated surface. The macro-geometry of the lapping plate influences the distribution of the slurry in the working gap and thus the formation of surface topography.

The hardness of lapping plate is of great importance since a workpiece can be badly scratched and contaminated with abrasives if the lap plate is too hard [15]. If a hard wheel is applied, more rolling than sliding of the grains may cause stress-induced micro fractures, and the grains will become embedded in the workpiece. Whereas a soft wheel keeps the grain on the surface and results in more sliding motions, and a fine surface is formed by scratching and ploughing.

Since samples to be lapped are placed face down, and held in place over the lapping plate within a conditioning/retainer ring, both the condition and planarity (i.e. concavity or convexity) of the lapping plate will be transferred as a mirror image to the sample being lapped. Therefore it is important to properly check and adjust/correct the planarity of the lapping plate before and during the lapping process. It also helps the uniform distribution of the abrasive slurry between the workpiece and the lap and thus the production of a plane surface. Therefore, during the lapping process, good planarity is achieved by controlling the lapping plate flatness through periodic conditioning.

In addition, the operator should charge the lapping plate periodically with fine
abrasives to produce a perfectly smooth surface for free from scratches. When the entire surface of the lap is charged, one should examine the lap for bright spots; if there are any visible bright spots, the charging will continue until the entire surface has a gray appearance [7]. After a lap is completely charged, it should be used without applying more abrasives until it ceases to cut. If a lap is overcharged and an excessive amount of abrasive is used, there is a rolling action between the workpiece and the lapping plate that results in inaccuracy. Moreover, the plate should be heavy and properly designed to prevent distortion in use.

Lapping plates can be plain or grooved depending on the desired material removal rate. Plain plates are best suited for lapping cylindrical work and for extreme accuracy. Grooved plates, preferred for lapping flat work, avoid slurry stasis, improve chip removal, and prevent the abrasive from squeezing out between the plate and specimen. This is particularly advantageous in the case of machining large surfaces.

Examples of existing plates, which are widely used in industrial production, are introduced as the following.
**Cast Iron (Fe) Plates** (Figure 2.6) are the most commonly used lapping plates. They are used for general surface engineering purposes, especially for rough lapping and stock removal of materials. Specimens around 8-10 on the Mohs Hardness Scale can be lapped using cast iron plates. Lapping plates made of cast iron can produce a gray surface finish and provide high material removal rates. These plates are also superior for pre-polishing operations.

**Copper (Cu) Plates** (Figure 2.7) can be used for both rough and fine lapping and stock removal of materials, but mainly for softer materials where fine lapping and polishing are the primary requirements. Specimens of 5-9 on Mohs Hardness Scale can be lapped on copper plates. They are normally used with a medium range of diamond to produce high quality surface finishes with intermediate removal rates.
Tin Plates and Tin/Lead Plates (Figure 2.8) are very soft lapping plates, usually used for fine lapping, an alternative of polishing pads, on a wide range of materials, such as metal, ceramic and optical materials. They are typically used with very fine diamonds to minimize fracturing and chipping tendencies when lapping crystal components. Tin/Lead Plates can produce a mirror finish on fiber optic terminals, carbon seal faces and many other hard materials such as tungsten carbide, with low material removal. Tin plates are often applied in the processes where lead-type contamination cannot be tolerated, and are suitable for charging extra-fine particles.
Ceramic Plates (Figure 2.9) are one of the hardest types of lapping plates. Their general applications are in lapping or polishing ceramic parts and other stain-sensitive, hard materials where a “clean” process is necessary. Ceramic plates are also used in the finishing processes where metallic-type contamination cannot be tolerated. Composite ceramic plates are affordable, more machinable, and alternative to natural ceramic
plates. Their working conditions are very flexible and hence can be used with coarse to
fine diamond abrasives. Ceramic plates provide fine surface finish with moderate stock
removal.

**Composite Lapping Plates** consist of a combination of metallic and non-metallic
constituents (powdered metal or ceramic), held together in a resin system. Composite
plates are used for rough lapping and stock removal of materials. Specimens of 7-10 on
Mohs Hardness Scale can be lapped on composite plates. If working with diamond
particles, these plates can take a more uniform charge of diamond, compared to pure
metal plates. Therefore, composite plates efficiently remove stock and produce high
quality surface finish and flatness with diamond superabrasives in both large volume
operations and hand lapping and polishing applications. These plates are also excellent
in applications where lapping and polishing are combined into one step. Examples
widely used in industry are composite copper plates (Figure 2.10) and composite steel
plates (Figure 2.11). Table 2.1 shows the comparison in some material properties of
composite copper plates and traditional cast iron plates.

<table>
<thead>
<tr>
<th></th>
<th>Composition</th>
<th>Hardness</th>
<th>Thermal Stability</th>
<th>Dimensional Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast iron plates</td>
<td>Iron</td>
<td>Very hard</td>
<td>High: material is thermally conductive</td>
<td>High</td>
</tr>
<tr>
<td>Composite copper plates</td>
<td>Powder Cu &amp; Resin</td>
<td>Medium</td>
<td>Low-Medium: excessive heat can cause material to breakdown</td>
<td>Low-Medium: slowly creeps over time</td>
</tr>
</tbody>
</table>
Design of the plate for a lapping process is very important due to the tribological effects on the finished surface. The polymer lapping plate designed for tribological purposes in this study will be introduced in Chapter 3, with respect to its technological background, polymer tribology, and material removal mechanisms.
2.3.2 The Abrasives

The lapping abrasive is defined by its material characteristics, the shape of the grains, and its grain sized distribution, which are in close connection to each other. There is a wide selection of abrasives to choose for a lapping process. Selecting an abrasive is dependent upon the specimen hardness, desired surface finish, desired removal rate, lifetime, and price.

Lapping abrasives are considered cutting tools with geometrically unspecified cutting edges. They are characterized by high hardness, sharp edges, and good cutting ability. The shape or the sharpness, represented by edge radius and apex angle, is crucially affected by the materials properties such as grain structure and cleavage, which are connected with the ability of cutting grains to the regenerated new sharp cutting edges and points [15]. Materials used as abrasives are either natural minerals or artificial products. The most widely used abrasives in industry include five different types of materials: silicon carbide (SiC), aluminum oxide (or alumina), garnet, diamond, and cubic boron nitride (CBN) [15]. The first three are conventional abrasives, and the last two are superabrasives. They are quite different in properties and costs from each other.

Silicon carbide (SiC) is a fused, hard artificial crystalline abrasive of Mohs 9.5. SiC generally has a needle or blocky structure. It is the most common lapping powder, and has high hardness and sharp crystal edges, thus possessing a very good cutting ability. It has a low thermal expansion coefficient which decreases with increasing temperature. SiC is used in many applications for rough lapping with gray finish
produced. Yet, it is not suitable for cases that require very smooth polished surface.

Aluminum oxide (Al₂O₃) is tougher than SiC. It is relatively hard (Mohs 9) and has a sharp, angular structure. Alumina abrasives are derived either by electofusion or by chemical precipitation and/or sintering [15]. Alumina is commonly used on high tensile strength materials, rough lapping operations, hardened gears, ball bearing grooves, or applications where pressure can be exerted to break down the crystals [7].

Garnet is a natural abrasive (Mohs 8-9) with a wide chemical composition. It has the blocky crystalline structure that does not easily embed itself in lapped parts. Garnet is used for abrasive paper to grind wood. As a loose abrasive, garnet is applied in finishing plate glass to a mirror finish and the edging of lenses. Applications of garnet are also on glasses, leather, and varnished and painted surfaces.

Diamond is the hardest and sharpest known abrasive of Mohs 10. It is both a natural and man-made synthetic abrasive. Diamond is extremely useful in lapping and polishing due to its removal rates and surface finishing qualities. Despite its high cost, the use of diamond is economically efficient in many cases because of the reduced machining time compared to softer lapping abrasives.

Cubic boron nitride (CBN) is a man-made allotropic crystalline form of boron nitride almost as hard as diamond. CBN is well suited for machining a great many kinds of materials, such as bearing steel, cast iron, die steel, tool steel, satellite, super alloys, and ceramics, because of its hardness, thermal resistance (higher than diamond’s) and good chemical resistance to ferrous alloys.

In addition, there are some other types of abrasives used in lapping processes,
such as corundum, boron carbide (B₄C), quartz, norbide abrasives, fused and unfused alumina. The Mohs scale of hardness of some abrasive materials is listed in Table 2.2.

<table>
<thead>
<tr>
<th>Abrasives</th>
<th>Mohs Scale</th>
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<tbody>
<tr>
<td>Diamond</td>
<td>10.0</td>
</tr>
<tr>
<td>Cubic Boron Nitride (Borazon CBN)</td>
<td>9.9</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>9.5</td>
</tr>
<tr>
<td>Aluminum Oxide</td>
<td>9.0</td>
</tr>
<tr>
<td>38 White Aluminum Oxide</td>
<td>9.0</td>
</tr>
<tr>
<td>Corundum</td>
<td>9.0</td>
</tr>
<tr>
<td>Chromium Oxide</td>
<td>8.5</td>
</tr>
<tr>
<td>Garnet</td>
<td>8-9</td>
</tr>
<tr>
<td>Quartz</td>
<td>7</td>
</tr>
<tr>
<td>Alumina (hydrates)</td>
<td>5-7</td>
</tr>
</tbody>
</table>

In general, the grain size of lapping abrasives is characterized by the specification of the average equivalent diameter of the sphere, called average grain diameter or equivalent diameter, and its standard deviation [6]. These parameters can be used for description of the grain volume and the grain concentration in the slurry.

The grain size parameters of lapping abrasives are always random values with a characteristic distribution function. For grain collectives, this is usually the normal distribution function. During lapping, only a part of the grains in the working gap is able to engage in the material as active grains, the amount of which is always at the upper limit of the distributive function [6].

2.3.3 The Lapping Fluid

During lapping processes, to maintain the even and continuous distribution of the
abrasives across the whole plate, an oil or aqueous medium is needed to hold and transport the abrasive particles to the working zone. This medium is lapping fluid, which also serves as a lubricant. Lubricants are used for interposing a layer of low shear-strength in the interface between the elements of the friction pair, with the main purpose of preventing or diminishing solid contact to reduce adhesion wear [15]. Lapping fluid is usually present as complex mixtures and can be used for many other purposes besides lubrication, that is, cooling and the control of wear and friction. Probably the greatest contribution of lapping fluid to the process is its ability to suspend and uniformly disperse abrasive granules throughout the interface between the workpiece and the lapping plate and also to remove the abraded debris from the lapping zone [7]. It is essential for lapping operation to continuously and properly replace the abrasives with fresh slurry in order to maintain constant cutting conditions.

2.4 Process Parameters of Lapping

Lapping may be considered, to some extent, an artistic creation rather than a scientific process. Since it is a very complex process influenced by many significant process variables and probably also their interactions between each other. Moreover, the control of some factors still requires an operator’s skill, experience and even psychology, for example, to charge a plate very well or to maintain enough but not surplus slurry supply. However, researchers are trying to minimize the uncontrollable effects and characterize process parameters quantitatively. The different variables and work parameters that are of great significance to lapping process are: the size, type, shape and distribution of abrasives; properties of the lapping plate; the lap rotation
speed; the normal pressure; lapping time; the workpiece material; the type of the lapping fluid and so on. More details will be discussed in the case study in Chapter 4 and Chapter 5.

2.5 Material Removal Mechanisms

The main requirement of lapping is to meet the process specification including workpiece geometry, dimension tolerances and desired surface roughness. In order to maintain the reliability and lifetime of the produced workpieces, it is essential to improve the machining processes by optimizing both the material characteristics and the consideration of the process parameter influences [15].

A wide range of work materials, including metals and their alloys, ceramics, glasses, and semiconductors, are lapped to meet their special service requirements. Different materials have remarkably different properties and thus their effects on lapping mechanisms. A qualitative comparison of ductile metals with nominally brittle non-metals (ceramics, glasses, semiconductors) indicates the differences and difficulties in finishing of the later with fine abrasives compared to metals and their alloys, as shown in Table 2.3. In general, metals are quite advantageous for fine abrasive finishing; while non-metals have many undesirable features for this process. The absence of plasticity in brittle materials can be ascribed to their nature of bonding, which leads to narrow dislocation and a high resistance to movement [19]. In contrast, the non-directional metallic bonding enables extensive movement of dislocations at low stresses.
Table 2.3. Comparison of Salient Features of Ductile Metals and Brittle Non-metals

<table>
<thead>
<tr>
<th>Properties</th>
<th>Metals</th>
<th>Non-metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of atomic bond</td>
<td>metallic, no directionality</td>
<td>ionic/covalent bond, directional</td>
</tr>
<tr>
<td>Crystal structure</td>
<td>high symmetry</td>
<td>low symmetry</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>high</td>
<td>Low</td>
</tr>
<tr>
<td>Density</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Mode of deformation</td>
<td>Ductile</td>
<td>Brittle</td>
</tr>
<tr>
<td>Microstructure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intergranular structure</td>
<td>Relative simple</td>
<td>Complex</td>
</tr>
<tr>
<td>Porosity</td>
<td>practically no pores</td>
<td>generally pores remain because of the consolidation processes used</td>
</tr>
<tr>
<td>Purity</td>
<td>high purity can be obtained</td>
<td>high purity is difficult</td>
</tr>
<tr>
<td>Heat resistance</td>
<td>low to moderate</td>
<td>moderate to high</td>
</tr>
<tr>
<td>Chemical resistance</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Strength considerations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toughness (MN/m²)</td>
<td>210 (carbon steel), 34 (Al alloys)</td>
<td>5.3 (Si₃N₄)</td>
</tr>
<tr>
<td>Strain at fracture</td>
<td>5%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Weibull index</td>
<td>20</td>
<td>5-20</td>
</tr>
<tr>
<td>Failure mechanism</td>
<td>plastic deformation</td>
<td>brittle fracture</td>
</tr>
<tr>
<td>Breaking energy (J/cm²)</td>
<td>10</td>
<td>10-2</td>
</tr>
<tr>
<td>Thermal shock resistance</td>
<td>high</td>
<td>Low</td>
</tr>
</tbody>
</table>

The nature of working materials determines material removal mechanism in lapping process. It is in ductile mode when metals or their alloys are lapped. However, it is more complicated for the mechanisms when lapping brittle, non-metal materials. It is well accepted that there are three material removal modes during processing of brittle materials: brittle mode, brittle-ductile transitional mode, and ductile mode. In this section, these three modes of mechanisms will be introduced respectively.
2.5.1 Mechanism of Lapping on Ductile Materials

During lapping on ductile materials, the material removal mechanism includes rolling, sliding and charged plate mechanisms, which simultaneously occur [6]. Rolling abrasives and sliding abrasives act very similarly except that the former are more round in shape while the latter are more plate-like and act like tiny scrapers between the lap and workpiece surface; charged plate abrasives are those imbedded into the lapping plate, ploughing to scratch on the surface. Abrasive grains used for lapping have sharp, irregular shapes. When a relative motion is induced and pressure applied, the sharp edges of the grains are forced into the workpiece material to either make an indentation or chip away microscopic particles [6]. Thus, the cutting action takes place continuously over the entire contact surface with a large quantity of abrasives, regardless of their irregular shapes. The movements and effects of abrasive grains in lapping film are identified in chronological sequence, as shown in Figure 2.12.

In the steel lapping process, the wear due to ploughing, as one of the abrasive wear mechanisms, is the major cause of material removal. In addition to abrasive wear, shifting or relocation of the material due to plastic flow occurs more than material cutting, which signifies the dominance of ductile material removal over brittle material removal [12].
On the other side, it is also important to note that the softness of some metals can induce lower forces on the abrasive particles and long chips, which tend to clog and load the pores of the abrasives, and thus quickly destroy the cutting ability of the grains [15]. In this sense, a free-machining iron or steel exhibits better machinability than a soft homogeneous material due to the graphite or other elements introduced into the structure to break up the chips.

Though the D2 steel, which is used as the work material in this study, has desired features with regard to machinability, the lapping procedure is very complex with many variables and work parameters in this polymer lapping process. It is essential for an operator to attach importance to the main factors, which affect the lapping characteristics, such as the type of lap, the type and size of the abrasive grains, the
lapping pressure and the lap rotation speed.

2.5.2 Material Removal Mechanism in Brittle Mode

The mechanism of material removal during lapping on brittle-hard materials is very different from that on ductile materials which are deformed plastically well. For brittle non-metals, the machining processes fail predominantly by microchipping, microcleavage, grain boundary cracking or grain dislodgments. As mentioned in the beginning of Section 2.5, the nature of atomic bonding determines the hardness (H) and Young's modulus (E) of the material. The ratio E/H is about 250 for ductile metallic-bonded materials, while for brittle, covalent-bonded materials, the ratio is about 20 [20]. Different atomic bonding structures determine the different material removal mechanisms. When machining brittle materials, the stock removal is based on the generation, propagation, and networking of microcracks, due to the stress fields induced in the material. Observations during lapping of brittle solids confirm the fact that fracture plays an important role in material removal except in ductile regime machining [20]. The brittle fracture is analogous to indentation on brittle material by a hard indenter, which causes vertical cracks when a load applied and lateral cracks when the load removed (Figure 2.13). Cracks are generated by the mechanical contact between workpiece and abrasive particles and the stock removal of workpiece is mostly done by lateral one among the cracks [8]. The formation of vertical cracks influences the surface and subsurface damage. It is well observed that a lateral crack is typically produced by a sharp indenter in a brittle solid. The depth at which the lateral crack originates under a sharp indenter is usually about the same as the maximum depth of the
plastic zone under the indentation [21].

![Figure 2.13. Plastic Zone, Radial and Lateral Cracks Caused by Indentation](image)

2.5.3 Brittle-Ductile Transition Theory

It is well known that the brittle materials can experience ductile behavior similar to metals if machining processes are performed in a small enough scale (nm to μm). The brittle-ductile transition can be achieved if certain machining conditions are carefully controlled to maintain the depth of cut below a critical value with regard to a specific material [22-26]. The widely accepted theory, dislocation nucleation, explained the brittle-to-ductile transition, where the brittle or ductile behaviors result from a competition between crack propagation and spontaneously dislocation emission at the crack tip [27, 28]. An advantage of ductile machining over brittle machining is the minimal subsurface damage with a surface roughness of the order of a few nanometers [29].

The nominally brittle materials, such as hard-brittle semiconductors and ceramics, do not behave in a ductile manner under the regular conditions; but their high pressure metallic counterparts are ductile and plastically deform. The dual nature of these
materials enables the brittle-ductile transition. Ductile chip formation in finishing brittle materials is due to the enhancement of material yield strength in the chip formation zone, such that the brittle materials can undertake a much larger cutting stress in chip formation zone without fracture [30]. It can be achieved by dislocation hardening and strain gradient by having a nanometric scale of undeformed chip thickness during the machining processes.

The transition from a brittle to a ductile mode during the machining of brittle materials is described as the result of “size effect” [31, 32]. Considering the significance of the chip dimension (s), the size or scale effect is characterized as competition between plastic deformation, which is a volume effect ($s^3$) and brittle fracture, which is a surface area effect ($s^2$) [31]. Consider it takes a given amount of energy (Es) to cause plastic deformation and fracture. At small scales the energy for plastic deformation (Es$^3$) is less than that required for fracture (Es$^2$), while at larger scales the opposite is true. The brittle-ductile transition in material removal mechanism is based on cleavage fracture due to the pre-existing defects of these hard-brittle materials [27, 32]. Brittle material removal takes place when the resolved tensile stress on cleavage plane exceeds its criterion under a particular machining condition; while ductile regime is achieved when shear stress on slip plane exceeds its criterion under the same machining condition [33]. Since the criterion of tensile stress is sensitive to pre-existing defects and machining scale, the ductile mode process is favorable in small size machining.

It is considered that ductile regime machining takes place when the proportion of
cracks formed by fracture on the surface of brittle materials is less than 10% [34-36].

Partial ductile lapping of brittle materials is becoming more attractive to the industry due to the low demand for equipment, high efficiency, low cost and excellent surface quality [37]. It is found that high speed lapping on SiC ceramic material with fixed abrasives is a good alternative to obtain the same machining accuracy but much less machining time [36].
Chapter 3 FriCSo Lapping Solution Characterization

FriCSo Inc. develops and provides advanced surface treatment technology for friction reduction between moving parts. FriCSo's single process delivers new surface characteristics that reduce friction and result in performance improvements. The environmentally friendly product is a polymer-based tool that reduces friction on metal surfaces, using existing mass-production in-line machines or hand held air tools, die grinders and drills. It can be delivered in any geometry and size. FriCSo has developed a proprietary technology enabling the provision of application-specific solutions for the automotive, hydraulics, machinery industries as well as for various dies and molds.

3.1 FriCSo’s Surface Engineering Treatment

The lapping plate involved in this study was treated by adding a FriCSo polymer coating on the working surface of a regular 12” grooved cast iron plate. It has 12 radial grooves, as shown in Figure 3.1. In the FriCSo polymer lapping process, the most significant factor is the polymer coating, and it works very well only with the specified abrasive paste and lubricant. The polymer used for FriCSo lapping is confidential and no details can be given except that it is the object of the US patent number. The FriCSo patented polymer lapping process is a rapid surface modification operation that improves the surface finish and the friction performance of treated metallic surfaces without introducing dimensional changes. The polymer lapping process creates a
unique organic layer which is chemically bonded to the metal surface. This layer has oil retention characteristics, similar to the effect of oil additives, improving the friction performance of treated surfaces in various (and especially boundary) lubrication conditions [38]. Using this tribological designed plate for lapping can significantly reduce friction between moving parts, create an oil-retaining nanolayer, especially effective in severe tribological working conditions, harden the metal surface, and produce an extremely flat, smooth surface. In addition, this polymer coated plate helps achieve a ‘mirror like’ finish after a very short lapping time (minutes), as well as significant wear reductions that improve energy efficiency.

One of the benefits of the FriCSo polymer lapping process is on stamping dies. Specially designed tools are used in die grinders to treating area of the dies that experience significant contact with the metal being formed. The benefits can include less die wear, eliminated or reduced galling of the die and workpiece, reduced
lubrication in manufacturing processes, and less required maintenance of the dies and presses. This is mainly due to the tribological effects, as well as the improved topography of the die surface.

3.2 Morphological Investigations and Composition Analysis

3.2.1 Technical Introduction of Observation Devices

The devices and instruments used for observing the topographical characteristics of FriCSO treated surfaces are digital microscope, Zygo NewView 5000 and SEM/EDS.

Digital Microscope

The optical microscope, often referred to as the "light microscope", is a type of microscope which uses visible light and a system of lenses to magnify images of small samples. Optical microscopes are the oldest and simplest of the microscopes. Digital microscopes are now available, which use a CCD camera to examine a sample, and the image is shown directly on a computer screen without the need for optics such as eye-pieces. Other microscopic methods which do not use visible light include scanning electron microscopy and transmission electron microscopy. There are two basic configurations of the conventional optical microscope in use, the simple (one lens) and compound (many lenses). Digital microscopes are based on an entirely different system of collecting the reflected light from a sample. Low power microscopy is also possible with digital microscopes, with a camera attached directly to the USB port of a computer, so that the images are shown directly on the monitor. Often called "USB" microscopes, they offer high magnifications (up to about 200×) without the need to use eyepieces,
and at very low cost. The precise magnification is determined by the working distance between the camera and the object, and good supports are needed to control the image. The images can be recorded and stored in the normal way on a computer. The camera is usually fitted with a light source, although extra sources (such as a fiber-optic light) can be used to highlight features of interest in the object. They also offer a large depth of field, a great advantage at high magnifications.

**Zygo Optical Metrology Instrument**

Zygo Corporation is a worldwide supplier of optical metrology instruments, high precision optical components, and complex electro-optical systems design and manufacturing services. Zygo Corporation’s NewView 5000 is the most advanced 3D surface profiler available today. Surface metrology is critical to process control in many facets of research and manufacturing; from semiconductors and disk drives, to medical implants and fuel injector seals, surface texture controls the performance of the product. Until now, microscopes imaged surface details while surface profilers provided accurate measurements to characterize the details. By combining these two critical technologies, the NewView 5000 provides fast, quantitative, surface texture measurement and analyses on many types of surfaces, in just seconds.

The NewView 5000 characterizes and quantifies surface roughness, step heights, critical dimensions, and other topographical features with excellent precision and accuracy. All measurements are nondestructive, fast, and require no sample preparation. Profile heights ranging from <1 nm up to 5000 μm at vertical scan speeds up to 10 μm/s with ≥0.1 nm height resolution, independent of magnification and feature height. A
continuously variable image zoom, with six indexed positions, is standard on all systems, providing with enhanced 3D profiling capabilities. Also, Zygo’s full range of imaging objectives can be mounted onto 5-position manual or motorized turrets, or used individually with quick-mount adapters. It can resolve submicron x-y features, and profile areas up to 50 x 50 mm and larger using its unique image stitching capabilities.

The NewView 5000 uses noncontact scanning white light interferometry to acquire ultrahigh Z-resolution images. Zygo’s patented frequency domain analysis and proprietary scanning technique provides 0.1 nm vertical resolution – in a single measurement. A closed-loop piezo-based scanner, employing low-noise capacitive sensors, ensures accurate and repeatable linear motion over the full range. The NewView 5000 provides highly-stable metrology; its unique platform design includes an ultra-rigid support structure, reduced-footprint dynamically stabilized vibration isolation table, and a fully integrated ergonomic workstation.

**SEM/EDS**

SEM/EDS stands for Scanning Electron Microscopy with Energy Dispersive Spectrometry X-ray Microanalysis. In scanning electron microscopy (SEM), an electron beam scanned across a sample's surface. When the electrons strike the sample, a variety of signals are generated, and it is the detection of specific signals which produces an image or a sample's elemental composition. The three signals which provide the greatest amount of information in SEM are the secondary electrons, backscattered electrons, and X-rays.
Secondary electrons are emitted from the atoms occupying the top surface and produce a readily interpretable image of the surface. The contrast in the image is determined by the sample morphology. A high resolution image can be obtained because of the small diameter of the primary electron beam.

Backscattered electrons are primary beam electrons which are 'reflected' from atoms in the solid. The contrast in the image produced is determined by the atomic number of the elements in the sample. The image will therefore show the distribution of different chemical phases in the sample. Because these electrons are emitted from a depth in the sample, the resolution in the image is not as good as for secondary electrons.

Interaction of the primary beam with atoms in the sample causes shell transitions which result in the emission of an X-ray. The emitted X-ray has an energy characteristic of the parent element. Detection and measurement of the energy permits elemental analysis (Energy Dispersive X-ray Spectroscopy or EDS). EDS can provide rapid qualitative, or with adequate standards, quantitative analysis of elemental composition with a sampling depth of 1-2 microns. X-rays may also be used to form maps or line profiles, showing the elemental distribution in a sample surface.

### 3.2.2 Metal Surfaces Treated by Laboratory Polymer Lapping

The materials of samples machined in standard laboratory conditions using FriCSo Surface Engineering Treatment (SET) are two types of cast iron: spheroidal cast iron and lamellar cast iron. Totally four sample surfaces are selected as reference for analysis of FriCSo flat lapping. Figure 3.2 shows the spheroidal cast iron surface after
FriCSo SET in different magnifications. Figure 3.3 shows the lamellar cast iron surface after FriCSo SET in different magnifications. Polymer lapping exposed the graphite structure of the cast iron surfaces, for both the spheroidal and lamellar cast iron. More important, the treated surface has an oil-retaining nanolayer, smaller roughness, less friction, improved hardness and great flatness. More details will be discussed in comparison analysis about improvements of FriCSo treated dies in the next section.
Figure 3.2. Spheroidal Cast Iron Surface after SET in Different Magnifications
In order to reveal the reason why FriCSo treated surfaces perform better and thus are preferable in industrial applications, investigations on cross sections are conducted by using digital microscope and SEM.
Figure 3.4 shows some area on the cross sections of the spheroidal cast iron samples in a large magnification. According to the scale, we can get the approximate diameter of each graphite pore. The average value of the diameter is about 20µm, which indicates that the pores are not very large, and the graphite pores exposed on the surface after polymer lapping are not very deep. It is advantageous that under a working pressure, from the counterface, the graphite in the exposed pores on the lapping surface can be touched and even squeezed out to serve as a kind of self lubricant. Therefore, the friction on FriCSO lapped surface is reduced.

It is also observed from the same figure that most of the exposed pores on the lapping surface have rounded edges, or at least not sharp. This is very important to the surface average roughness. Because if the edges of the exposed graphite vanes are blunt or round enough, the motions on the surface will be very easy, and thus the friction will be reduced.

Similarly, we can also obtain the same observations as the above two points from the cross sections of the lamellar cast iron samples.
Figure 3.4. Cross Sections of Spheroidal Cast Iron Samples

Figure 3.5 shows the cross sections of conventionally lapped surface and polymer lapped surface, investigated by SEM. This was done on lamellar cast iron samples based on standard laboratory conditions. The upper surface is not part of the metal part, and is only used as a supporting while making this metallographic cross section. It is found that the graphite enclosures are covered after conventional lapping while they are exposed after polymer lapping.

Figure 3.5. Cross Section of Lamellar Cast Iron by SEM (Provided by FriCSo)
From either the pictures taken by microscope or Zygo instrument, it is found that the exposed graphite structures on FriCSo treated surfaces appear to be dark no matter in terms of spheroidal pores or lamellar vanes. In order to figure out if the black enclosures are empty or full of graphite, and the visual depth, a regular pen was used to make some small dots on part of the surface of one sample, and a regular pencil was used to scribble on the another part of the same surface. Then they were investigated using Zygo NewView 5000. The profile images and topographical data were generated. Figure 3.6 shows the original FriCSo treated Spheroidal cast iron surface. The surface with ink dots (Figure 3.7) shows the ink dots and the exposed graphite pores and the pores surrounded by ink, which was filled with some ink. The pencil scribbled surface shows that the graphite fills in the pores or part of the pores. Therefore, it is demonstrated that there are many graphite pores on the surface exposed by FriCSo lapping and some graphite are taken out of the pores by FriCSo treatment, which is agreeable with the conclusions based on the investigations above.
Figure 3.6. Zygo Profile Records of Treated Spheroidal Cast Iron Surface

Figure 3.7. Zygo Profile Records of Surface with Ink Dots
3.2.3 FriCSo Treated Oghara Die Samples

One of the important applications of FriCSo SET is in Die Stamping and Injection Molding. The aims of FriCSo Treatment are: to finish a variety of curves, diameters, and cutting edges of dies and molds made of various steels and cast iron alloys, with hardness ranging approximately from 28 HRC to 68 HRC; to achieve mirror like finish after very short lapping time (minutes); and to remove only few microns of stock while not changing the working surface geometry.

Die samples investigated in this study include:

Cast Iron GM241, 39 HRC (Figure 3.9)

Low Grade Cast Iron GGG70L, 50 HRC (Figure 3.10)

Cast Steel GM190, 54HRC (Figure 3.11)
Cast Iron GM238 (Figure 3.12)

Cast Iron – GM241
Flame hardened to 39 HRC

Figure 3.9. Cast Iron Die GM241

Low Grade Cast Iron – GGG70L
Flame hardened to 50 HRC

Figure 3.10. Low Grade Cast Iron Die GM2
The lapping on these samples is processed at the die stamping workshop, which is not controlled with respect to pressure and speed (rpm). The two directions of rotation that characterizes the standard lapping process do not exit in the die stamping process. Contact area of the lapping tool and the workpiece is very small comparing to LAB flat processes or lathe processes. The morphological investigations were taken on the samples both before and after FriCSo polymer lapping. Analysis were focused on the comparison between surfaces with and without FriCSo treatment.
Figure 3.13. SEM Images of Spheroidal Cast Iron GGG70L Surfaces

Figure 3.13 shows the surface topography of spheroidal cast iron GGG70L before (on the left) and after (on the right) polymer lapping. Figure 3.14 shows the surface topography of lamellar cast iron GM238 before (on the left) and after (on the right) polymer lapping. (a) and (b) are in different magnifications. The significant differences between surfaces with and without polymer lapping tell that FriCSo treatment produces very smooth surfaces, and also exposes the carbon structures on both spheroidal and lamellar cast iron surfaces. It is assumed that during polymer lapping process 1-2 microns of graphite is taken out, with sort of sockets remained. However, there is still some graphite remained in the enclosures, which will be demonstrated in the next section by X-ray composition analysis. When load is applied on surface in working
conditions, this part of graphite may come out and serve as the self-lubricant, which will help the motions between surfaces. Figure 3.15 displays Zygo surface profile images of cast steel GM190 before and after treatment. Figure 3.16 shows digital microscope images of lamellar cast iron GM238 surfaces before (on the left) and after (on the right) polymer lapping in different magnifications. Same conclusions can be summarized from these images.

![Figure 3.14. SEM Images of Lamellar Cast Iron GM238 Surfaces](image)

(a)  
(b)
Figure 3.15. Zygo Surface Profile Images of Cast Steel GM190
3.2.4 Elemental Composition of Die Sample Surfaces

Investigations by SEM with EDS also tell the elemental composition and their percentages in the material in addition to surface topography. The data was collected for every sample mainly in three groups: for an area in the smallest magnification on the surface (representative of the whole surface) before FriCSo lapping; for the same size of area on the surface after FriCSo lapping; for a graphite enclosure in a much larger magnification (to investigate the enclosure) after FriCSo lapping. Therefore, the comparison of elemental composition between local and integral area, and the same material before and after lapping can be presented.

All the four types of stamping die samples show similar results on EDS reports. We take Cast Iron GM238 as an example. Figure 3.17 to Figure 3.19 show EDS spectrum of elements with automatic peak identification for Cast Iron GM238. Table 3.1 to Table 3.3 listed the weight percentage of each element in the form of its oxide for Cast Iron GM238. For data about other samples, refer to Appendix A.
Figure 3.17. EDS Spectrum of Elements with Automatic Peak Identification on Cast Iron GM238 before Lapping

Table 3.1. Elemental Composition of Cast Iron GM238 before Lapping

EDAX ZAF Quantification (Standardless)

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Wt%</th>
<th>Mol%</th>
<th>K-Ratio</th>
<th>Z</th>
<th>A</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>35.78</td>
<td>65.9</td>
<td>0.0268</td>
<td>1.078</td>
<td>0.2543</td>
<td>1.0008</td>
</tr>
<tr>
<td>SiO₂</td>
<td>1.77</td>
<td>2.39</td>
<td>0.0048</td>
<td>1.0152</td>
<td>0.571</td>
<td>1.0008</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>62.45</td>
<td>31.7</td>
<td>0.3978</td>
<td>0.8993</td>
<td>1.0125</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.18. EDS Spectrum of Elements with Automatic Peak Identification on Cast Iron GM238 after Lapping

Table 3.2. Elemental Composition of Cast Iron GM238 after Lapping
EDAX ZAF Quantification (Standardless)

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Wt%</th>
<th>Mol%</th>
<th>K-Ratio</th>
<th>Z</th>
<th>A</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>25.4</td>
<td>54.07</td>
<td>0.0179</td>
<td>1.0901</td>
<td>0.2369</td>
<td>1.0008</td>
</tr>
<tr>
<td>SiO₂</td>
<td>2.23</td>
<td>3.48</td>
<td>0.0059</td>
<td>1.0263</td>
<td>0.5474</td>
<td>1.0009</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>72.36</td>
<td>42.45</td>
<td>0.4658</td>
<td>0.9106</td>
<td>1.0107</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.19. EDS Spectrum of Elements with Automatic Peak Identification on Cast Iron GM238 after Lapping (Graphite Pore)

Table 3.3. Elemental Composition of Cast Iron GM238 after Lapping (Graphite Pore)  
EDAX ZAF Quantification (Standardless)

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Wt%</th>
<th>Mol%</th>
<th>K-Ratio</th>
<th>Z</th>
<th>A</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>49.02</td>
<td>76.5</td>
<td>0.0393</td>
<td>1.0624</td>
<td>0.276</td>
<td>1.0008</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>1.32</td>
<td>0.89</td>
<td>0.0032</td>
<td>0.9725</td>
<td>0.4761</td>
<td>1.0006</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>1.47</td>
<td>1.68</td>
<td>0.0042</td>
<td>1.0008</td>
<td>0.6056</td>
<td>1.0008</td>
</tr>
<tr>
<td>Mo$_2$O$_3$</td>
<td>0.64</td>
<td>0.18</td>
<td>0.0039</td>
<td>0.9729</td>
<td>0.9741</td>
<td>1.0001</td>
</tr>
<tr>
<td>CaO</td>
<td>0.38</td>
<td>0.46</td>
<td>0.0026</td>
<td>0.9728</td>
<td>0.9786</td>
<td>1.0261</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>47.17</td>
<td>20.29</td>
<td>0.296</td>
<td>0.8848</td>
<td>1.0139</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on the EDS reports, it is found that the percentage of carbon in a structural aperture is larger than that in the large area. In other words, the percentage of carbon in the graphite enclosure is larger than that of carbon on the whole surface. It is demonstrated that there is still some graphite remaining in the enclosures even though
the polymer lapping process takes some graphite out. Therefore, the remaining graphite may serve for lubrication when squeezed out from the ‘sockets’. However, no evidence is found that the percentage of carbon increases or decreases after polymer lapping. It is probably due to two phenomena: on one hand, on the surface before lapping the carbon structure is covered, while after lapping it is enclosed; on the other hand, even though the polymer lapping process helps expose the graphite apertures, it also takes some graphite away. Hence, the change of carbon weight on surfaces before and after lapping can not be determined.

It is also indicated that there are some other elements in addition to Fe and C in cast iron, such as Si, Na, S, Cl, K, Al, Ca, Mo and Cr, based on EDS report of all the samples. Yet the percentage of these elements is very little. They are likely just the microelements in natural cast iron. Or the cleaning of the surface is not completed. Unfortunately, no data points out that a significant difference in weight of Al on surface between and after polymer lapping. Therefore, no evidence shows the abrasive particles (Al₂O₃) stay or embedded in the lapped surface, based on these reports, though it is possible to be so.

3.3 Tribology of Polymer Lapped Surfaces

Based on the morphological investigations on polymer lapped metal surfaces, analysis of polymer tribology and comparison between polymer lapping and conventional cast iron lapping are carried out for better understanding of FriCSo polymer treatment.

The tribological process in a contact in which two surfaces are in relative motion
is very complex, since it involves simultaneously friction, wear and deformation mechanisms at different scale levels and of different types [39]. Finished mechanical components have a surface layer with properties different from the bulk material depending on the machining process. Energy that goes to the near surface region during machining can result in deformation, strain hardening, recrystallization and texturing [40]. In abrasive machining, the surface layers are plastically deformed with or without a temperature gradient. They become highly strained and residual stresses may be released or created. A deformed layer may also be produced during the friction process [40].

In this section, the aim is to present an overview of the present understanding of polymer tribology, and identify the differences between polymer lapping and conventional lapping.

3.3.1 Polymer Tribology

Polymers are important tribological materials due to their low friction, moderate wear resistance, good corrosion resistance, self-lubricating properties, low noise emission and low cost. Most industrial polymers, which are produced from hydrocarbons, are made up of long molecular chains with a ‘skeleton’ of carbon atoms, these ‘macromolecules’ being themselves formed by the repetition of certain chemical units of varying complexity known as monomers [41]. The specificities of polymer as a tribological material are attributed to the molecular structure, and especially chain mobility, which allows relaxation mechanisms and energy dissipation, notably by internal friction, so the mechanical behavior of polymer is viscoelastic, with time and
Polymer tribology is a multidisciplinary field of research that can be approached from mechanical or from tribophysical point of view. Previous research indicates that the first contact between the surfaces will take place at the top points of the highest peaks of the surfaces. Two metallic surfaces that are pressed together have a real contact area which may be only about 10% of the surface area [40]. It is also stated that the formation of a friction film by adhesion and mechanical interlocking can reduce the counterface roughness when debris particles accumulate between roughness asperities [43]. Then the film increases the true contact area. Therefore, a soft polymer coating does not only reduce the coefficient of friction but also reduce the surface tensile stresses that contribute to undesirable subsurface cracking and subsequently to severe wear.

The particular advantages when using polymer surfaces in tribological applications, compared using metals, are summarized by Evans and Lancaster as below [44]:

The physical and mechanical properties of polymers can be varied over a wide range by suitable choice of polymer type, fillers and reinforcement. Some polymers, notably thermoplastics, are cheap and easy to fabricate into complex shapes. Many polymers, particularly fluorocarbons, are highly resistant to chemical attack by aggressive media, such as acids and alkalis. Coefficients of friction during unlubricated sliding against either themselves or metals are relatively low and typically within the range 0.1 to 0.4. Wear rates during sliding against smooth metal surfaces are relatively
low, and polymers do not normally exhibit scuffing or seizure. Periodic maintenance, e.g., lubrication with fluids, can often be dispensed with. This is particularly important in applications in which access for routine maintenance is not possible. When fluid lubricants are present, polymers undergo elastohydrodynamic lubrication more readily than metals.

3.3.2 Comparison of Polymer Lapping and Conventional Lapping

In Section 3.3.2 and Section 3.3.3, research work is done in the Center for Surface Engineering and Tribology at Northwestern University [45].

Investigation by SEM on surface topography of polymer lapped sample is shown in Figure 3.20 (a). Electron beam causes darkening of surface. SEM image of topography of conventional cast iron lapped surface is shown in Figure 3.20 (b). The comparison indicates that conventional lapped metal surface has more asperities, peaks, grooves and few carbon enclosures exposed; while polymer lapped surface is much smoother, and exposes carbon structure. Scenarios behind this phenomenon will be discussed in Section 3.4.

Figure 3.21 shows the cross-sections of the polymer lapped sample and the conventional lapped sample using FIB-X (Focused Ion Beam) cross-section detecting technology. They were treated with coating of Au-Pd and Pt to preserve surface. It is observed that polymer lapping cuts the surface away to leave a surface reflecting the size of grit used to abrade it, as shown in Figure 3.21 (a). Whereas it is found in Figure 3.21 (b) that conventional lapping deforms surface asperities and traps porosity. Therefore, polymer lapping produces a smoother surface with better morphological
characteristics.

(a) Polymer Lapped Surface

(b) Conventional Lapped Surface

Figure 3.20. SEM Topography Investigations of Metal Surface
By comparing the FriCSo polymer lapping method to traditional cast iron lapping process, the advantages of polymer lapping are summarized as below, refer to Figure 3.22.
### Table 3.4. Comparison of the Two Lapping Methods

<table>
<thead>
<tr>
<th></th>
<th>Conventional Lapping</th>
<th>Polymer Lapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece Surface</td>
<td>non-conformal</td>
<td>conformal (favoring polymer transfer)</td>
</tr>
<tr>
<td>Particles</td>
<td>largely free</td>
<td>well confined by polymer, edge rounded, fine fracture</td>
</tr>
<tr>
<td>Scale of Abrasion</td>
<td>micro plowing/cutting</td>
<td>nano abrasion</td>
</tr>
<tr>
<td>pressure</td>
<td>high pressure (spots are in contact)</td>
<td>low pressure</td>
</tr>
<tr>
<td>Surface</td>
<td>plastically deformed</td>
<td>largely elastic</td>
</tr>
</tbody>
</table>

![Figure 3.22. Comparison of the Two Lapping Methods](image)

(a) Conventional Lapping

(b) Polymer Lapping

Figure 3.22. Comparison of the Two Lapping Methods
3.3.3 Polymer Identification on Treated Surfaces

It is considered that the distinguished performance and preferable properties of polymer lapped surfaces are a result of some compositional change or chemical reaction on the treated surfaces in addition to the physical modification. It is highly accepted that during polymer lapping process, a unique polymer layer is formed on the lapped surface. To identify polymer and its distribution, EDS scanning was performed on the FIB-X cross sections for a particle on treated surfaces. Figure 3.23 illustrates the EDS results for the surfaces lapped in two different ways. In Figure 3.23 (a), it is observed that the EDS line scan (~300nm) across particle at surface shows that C and Al peak. C-peak is also found at non-particle locations. However, in Figure 3.23 (b), EDS line scan (~300nm) across particle at surface shows that only Al and O peak. That is to say, EDS scan of FIB cross-section indicates high carbon content at surface of polymer lapped sample compared to conventionally lapped sample. Polymer lapping generates a unique layer mainly consisting of polymer. Polymer prevents cast iron from reacting with oxygen to form the oxides of iron on the surface. Therefore, the carbon structure is exposed after polymer lapping. This may be the reason that on polymer lapped surface C peaks instead of O. More details will be included in the next section.
(a) Polymer Lapping
Effects of the FriCSo Plate on Material Removal Mechanism

As it is highly needed to have metal working surfaces that exhibit improved tribological properties, a lapping method and the tribological system overcome various deficiencies of the known lapping technologies, and thus produce improved metal working surfaces. Polymer lapping is a newly developed super-finishing treatment where ferrous metals’ surfaces are treated with a tool made of a Polyurethane (PU)
based polymer, specifically developed for this purpose, in conjunction with a White Alumina Oxide (WAO) lapping compound [46]. The FriCSo patented lapping plate adopted in this study is made by adding a special consumable polymer layer (with the thickness in milimeters) on traditional grooved cast iron lapping plate, as shown in Figure 3.24.

![Figure 3.24. FriCSo Patented Lapping Plate](image)

The specially designed polymer lapping plate affects the lapping mechanisms in several aspects. Figure 3.25 illustrates the polymer lapping mechanisms in micro scale.

The polymer lapping system is tribologically designed for lapping a metal working surface. It includes [3]: (1) a workpiece having the metal working surface; (2) a lapping tool having a contact surface, with an organic, polymeric material, for disposing generally opposite the working surface; (3) a plurality of particles including abrasive particles for disposing between the contact surface and the working surface; and (4) a mechanism for applying a relative motion between the contact surface and the metal working surface, and for exerting a load on the contact surface and the working surface.

The specially designed polymer lapping plate affects the lapping mechanisms in several aspects. Figure 3.25 illustrates the polymer lapping mechanisms in micro scale.
Figure 3.25. The Micro-mechanisms of Polymer Lapping Process

First, since polymer is not as hard as metal, such as cast iron, the abrasive particles may penetrate deeper into the polymer lapping tool if enduring a high pressure, like ① and ② in Figure 3.25, so large grooves or scratches may be avoided on the lapped metal surface.

Second, the sizes of abrasive particles subject to the normal distribution. So in many lapping processes, at least a portion of abrasives do not participate in the material removal for some time since they are too small or too big to get into the working gap between the two surfaces. Examples shown in Figure 3.25 are ③ and ④. However, the softness of the polymer plate enables some of the very big particles to be involved in the actual lapping, and the pressure is distributed on more contact points. Therefore, the material removal by every particle is reduced, but it remains the same for the whole surface with a same load applied. As a result, better surface roughness is achieved without reducing the material removal rate.

Third, the polymer tool is weaker, compared to the metal tool in regular lapping.
So it does not hold the abrasive particles as firmly as the metal tool. Once the abrasive particle loses its cutting point, due to wear or chipping, as shown in Figure 3.25, there is an increase in friction force between the particle and the surface, which causes the abrasive particle to tear away minute particles from the polymer and swivel [47]. Figure 3.26 (a) shows this phenomenon in a large scale. This allows a new cutting point to touch the surface and continue the abrading process. This abrasive particle repeats continuously this process until losing all cutting points and becoming spheroid.

![Figure 3.26](image)

Figure 3.26. Idealization of rounding phenomenon of an abrasive particle

Forth, in Figure 3.26 (b), relative velocity V is selected such that a corresponding
shear force $Q$ is large enough, with respect to pressure $P$, so that the combined force $F$ on the particle causes the particle to rotate. During this rotation, the elasticity of polymer lapping plate results in less internal strains within abrasive particle, compared to the conventional lapping process, so that the abrasive particle does not shatter, rather, its edges become rounded. It is believed that the polymer lapping technology generates a plastic deformation on the working surface so as to improve the microstructure of the surface [3], as in the case of ④ in Figure 3.25. The greatly increased micro-harness can be considered one of the manifestations of the modified microstructure.

Fifth, in a tribological machining process, energy generated causes high local temperatures into the contacts, and at the same time the wear process results in exposure of pure uncontaminated material surface to the environment. This situation is very favorable for chemical reactions to take place on the newly formed or deformed surfaces [39]. During a conventional cast iron lapping process, an oxide layer formed within seconds after exposing the metal in the air. The oxide layer is tightly bonded to the base metal by strong ionic forces, and in fact becomes an integral part of the metal surface. Therefore, the cast iron lapping process covers the carbon structure by forming this oxide layer, as shown in Figure 3.27. However, the patented polymer is, by its chemical nature, very rich in various polar organic groups. The small polymer fragments torn out from the polymeric lapping plate activate the metal surface and simulate the chemical interaction with the fragments torn from the metal surface, as shown in the case of ⑥ in Figure 3.25. As a result of this mechanical-chemical process, strongly bonded organic fragments cover at least a portion of the metal surface and
form a unique organic layer, which segregates the metal surface from the air. The case of ⑦ in Figure 3.25 is some of the polymer layer formed on the workpiece surface. This may be the reason that polymer lapping exposes the carbon structure and allows the graphite to serve as a self-lubricant.

Figure 3.27. Graphite Structure Covered on Conventional Cast Iron Lapped Surface

The polymer lapping process forms a relative large nanometric organic layer where the population density of the nanometric organic particles is high on the working surface; whereas, in the area with a lower population density of the nanometric organic particles, the lapping process flattens the particles against the contour of surface to form flattened nanometric particles such as organic particles. Therefore, the unique organic layer formed in polymer lapping process is not necessarily a fully-formed layer covering the whole surface. Both of the nanometric organic (⑦ in Figure 3.25) and
inorganic (⑧ in Figure 3.25) layers strongly adhere to the working surface. Consequently, these layers are not subject to the phenomena of peeling, flaking or crumbling.

In conclusion, the mechanical properties that the polymeric contact surface should include are as below [3]:

1) Wear resistance with respect to the abrasive paste used in the lapping process.

2) Elastic deformation to enable the abrasive particles to protrude into, be held by, and rotate between surfaces. The elastic deformation should allow the particles to be absorbed into the polymeric surface in varying depths, with respect to varying pressures. Consequently, the abrasive particles rotate against the metal surface and get more rounded with time, instead of undergoing comminution.

3) Hardness of the polymeric surface should be suitable for the specified lapping process to avoid layer breaking or grinding the abrasive powder.
Chapter 4  Case Study—D2 Steel Lapping with a Tribological Designed Plate

Polymer lapping is a new technology for metal surface finish to achieve improved properties and great finish of treated surfaces. Lapping with a newly tribological designed plate is a very complex machining process since there are many process parameters and various working conditions that may influence quality and efficiency. Hence it is necessary to investigate and analyze the significant variables of the lapping process by experimental research based on theoretical study in order to improve and optimize this unique surface finish process.

4.1 Design of Experiments

The focus of this project is to study and optimize the lapping process on D2 steel with a polymer lapping plate. The primary objective is to examine the quality of surface finish and lapping efficiency, in terms of average surface roughness (Ra) and material removal rate (MRR), with respect to different combinations of lap rotation speed, lapping pressure and abrasive grit size.

A full factorial design of experiments is performed in this study. The process parameters, each with three levels, are lap rotation speed (30 rpm, 40 rpm and 50 rpm), applied load (5 kg, 7 kg and 10 kg) and grit paste number (#220, #400 and #600). Three steel sample discs are lapped together in one run, leading (3^3) = 27 runs and (3^3)*3 = 81
samples needed. Given the area of contact surface, the three levels of lapping pressure are worked out as 58 kPa, 81 kPa and 115 kPa with respect to 5 kg, 7 kg and 10 kg. The different abrasive paste numbers represent different grit sizes, #600 the finest and #220 the roughest. The average surface roughness (Ra) is measured when the lapse of time is 1 minute, 3 minutes, 5 minutes, 8 minutes and 10 minutes. And the material removal rate (MRR) is calculated based on the measurement of weight change before and after a 10-minute lapping period. The Ra of all the 81 discs before lapping is 0.136 μm in average, with grinding treatments.

In order to eliminate the influence of many other variables, such as lapping plate, type and amount of abrasive, lubricant flow rate, metal type and the initial workpiece surface, they are kept constant. Before lapping with a new type of abrasive, the plate is charged with the abrasive until a gray appearance on the entire surface. The abrasive paste and lubricant are applied in the same amount at the beginning of each run and no more is applied during a 10-minute lapping period. When it is done with one type of abrasive, the plate needs to be cleaned, recharged and reconditioned (More details will be included in Section 4.3).

4.2 Experimental Set-up

Figure 4.1 shows experimental setup including the lapping machine and other devices. In this study, one-side lapping (single-side lapping) was conducted. The experimental materials, equipments, devices and workpieces will be introduced in the following paragraphs.

The machine adopted in this study is a Lapmaster Lapping Machine (Model 12C),
with variable speed 90 VDC and 7.5 A motor (0-60 rpm), as shown in Figure 4.1.

The lapping plate is a 12” grooved cast iron plate with a polymer layer (2-3 mm) coated on the top. Please refer to Section 3.1 and Section 3.4 for more details.

Figure 4.1. Experimental Equipment and Lapping Setup

The original workpieces are 19 mm D2 steel sample discs with the average height
of 9.94 mm, as shown in Figure 4.2. Totally 81 samples are involved in this study, and three samples are lapped in one run.

Figure 4.2. Workpieces Used in Lapping Experiments

The abrasive pastes used in the lapping process are provided by FriCSo. They are commercially produced by 3M (US Products Co.). Grit paste #220, #400 and #600, mainly consisting of aluminum oxide, are used in the experiments. As seen in Figure 4.3, the red are #220, the green are #400, and the yellow are #600.
Lapping Lubricant No. LMKT (Figure 4.4.) is employed to dilute the paste and reduce friction. It is also provided by FriCSo and commercially produced by 3M (US Products Co.).

It is observed that there is a good match between the polymer layer and the
abrasive slurry. Previous experiments performed by FriCSo show that the good results are only obtained with the combination of FriCSo patented polymer and this specified alumina oxide slurry. Unfortunately the interactions between the polymer coating and other factors are not clear.

With the aim of retaining parts during processing and maintaining the plate flatness at the same time, three 5” cast iron conditioning rings are used in the lapping experiments.

In order to increase productivity and retain the parts, a plastic workpiece carrier is designed and used to hold three pieces of steel samples in one of the conditioning rings.

4.3 Cleaning, Measuring and Lapping Plate Preparing

4.3.1 Cleaning Method

In order to measure the surface roughness and material removal, every sample needs to be cleaned in each break after lapping for 1, 3, 5, 8 and 10 minutes. To ensure complete removal of the swarf from the workpiece, each disc is thoroughly cleaned in an ultrasonic cleaner with LAP-O-VALVE cleaner/degreaser for 3-5 minutes and wiped dry. Care is taken to avoid damage to the lapped surface during this cleaning procedure.

Each time before changing the type of abrasive paste, the lap plate is cleaned with the LAP-O-VALVE cleaner/degreaser for both the surface and grooves. The contact surfaces of the conditioning rings and the plastic workpiece carrier are also cleaned with the same degreaser and then polished by sand paper to remove the particles embedded on the surfaces.
4.3.2 Surface Finish Measurement

The surface finish is measured by HOMMEL-TESTER T 1000 with ProfileView 3.44 software for processing the surface roughness and profile data. The devices and procedures are shown in Figures 4.5, 4.6 and 4.7.

Figure 4.5. Hommel Tester T1000 E
Figure 4.6. Sample Surface Investigated by Hommel Tester

Figure 4.7. Recorded Data of Surface during Lapping Process by ProfileView 3.44
4.3.3 Material Removal Measurement

For better evaluation of lapping efficiency, material removal rate (MRR) is introduced and calculated according to the following formula [48]:

\[
MRR = \frac{\Delta H}{\Delta T} = \frac{\Delta M \times 4 \times 10^4}{\pi \times D^2 \times \rho \times \Delta T} \text{ (nm/min)}
\]

where

- \( \Delta H \) – material removed in nm
- \( \Delta T \) – total run time in min
- \( \Delta M \) – mass (weight) loss in mg
- \( D \) – effective diameter of substrate (between chamfers) in cm
- \( \rho \) – density (specific gravity) of substrate in g/cm\(^3\).

Since MRR as a result of lapping time is not a focus in this study, material removed is measured only after completing a 10-minute lapping process. Therefore, the variables affecting MRR are speed, pressure and grit size. Every disc sample is weighed before and after a 10-minute lapping period by a Precision Electronic Scale HR-120 (minimum unit weighting—0.1mg), as shown in Figure 4.8. The difference between the two weights is the mass loss (\( \Delta M \)) in Equation (5.1).
4.3.4 Plate Conditioning and Recharging

When it is done with one type of abrasives, the plate needs to be cleaned and then abraded by setting a diamond-plated conditioning ring with load applied and running the lapping machine for 3 minutes to remove the top polymer layer, where some particles embedded in. In addition, this procedure can also help bring a plate back into flatness if the plate has become "out of flat".

Once the plate is considered back again to the original condition, it has to be recharged with the new type of abrasive grits. The recharging procedure is introduced in Section 2.3.1.
Chapter 5  Discussion and Optimization of the Experimental Results

The relative significance among the process parameters for the performance characteristics is investigated using the analysis of variance (ANOVA) method [49] with the program Design-expert 7.1.6 so that the optimal combinations of the lapping parameter levels can be determined comparatively accurately.

5.1 Analysis of Variance (ANOVA) and Regression Models

In order to generate regression models based on natural log transformations, all the parameter values (for time, speed, pressure and abrasive) are transformed to their natural log values. That means all the experimental data, as the variables for ANOVA in Design Expert, is in the form of ln(time), ln(speed), ln(pressure) or ln(grit size).

5.1.1 Statistical Model and Residual Analysis for Ra

For surface average roughness (Ra), it needs to be recorded when lapping for 0, 1, 3, 5, 8 and 10 minutes. Since ln(0) is trivial, the analysis starts from lapping at 1 minute instead of the beginning point. Therefore, for each sample, five values (Ra when lapping for 1, 3, 5, 8, 10 min) are the inputs for analysis. As a result, there are \((3^3) \times 3 \times 5 = 405\) values in total. All the experimental data, including the surface roughness before lapping, is shown in Appendix B.
The analysis of variance (ANOVA) shows the results for analyzing the relative significance of parameters in the lapping process (Table 5.1 and Table 5.2). The influence of grit size on average surface roughness is considerably significant, compared to other variables. Besides, time is the most significant parameter affecting Ra, followed by pressure, which is a little more influential than speed.

Table 5.1 Analysis of Variance Table (Partial Sum of Squares) for Ra

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>25.0547</td>
<td>4</td>
<td>6.2637</td>
<td>576.5629</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>A-ln(time)</td>
<td>1.9182</td>
<td>1</td>
<td>1.9182</td>
<td>176.5697</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>B-ln(speed)</td>
<td>0.1305</td>
<td>1</td>
<td>0.1305</td>
<td>12.0125</td>
<td>0.0006</td>
</tr>
<tr>
<td>C-ln(pressure)</td>
<td>0.3354</td>
<td>1</td>
<td>0.3354</td>
<td>30.8707</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>D-ln(grit size)</td>
<td>22.6706</td>
<td>1</td>
<td>22.6706</td>
<td>2086.799</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Residual</td>
<td>4.3455</td>
<td>400</td>
<td>0.0109</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pure Error</td>
<td>1.0077</td>
<td>270</td>
<td>0.0037</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>29.4003</td>
<td>404</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Model F-value of 576.56 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, D are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Table 5.2. Statistical Quantities

<table>
<thead>
<tr>
<th>Std. Dev.</th>
<th>R-Squared</th>
<th>Adj R-Squared</th>
<th>Pred R-Squared</th>
<th>Adeq Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1042</td>
<td>0.8522</td>
<td>0.8507</td>
<td>0.8482</td>
<td>76.2789</td>
</tr>
</tbody>
</table>

The "Pred R-Squared" of 0.8482, as shown in Table 5.2, is in reasonable agreement with the "Adj R-Squared" of 0.8507. "Adeq Precision" measures the signal
to noise ratio. A ratio greater than 4 is desirable. The ratio of 76.2789 indicates an adequate signal. This model can be used to navigate the design space.

(a) Quadratic Terms and Interactions Included

(b) Linear Regression Model

Figure 5.1 Normal Plots of Residuals for Analysis of Ra
It needs to be pointed out that there are some interactions between these factors. However, by eliminating these interactive terms and quadratic terms from the regression model and comparing the fitted model curve to actual values, there are only a few points away from the model curve. That means the interactions only affect several runs with specific combinations of parameters. There is a lack of evidence showing a significant effect of interactions or quadratic terms in the model. Based on the diagnostic analysis on normal plot of residuals, as shown in Figure 5.1, little difference is found between the residual plots for linear and nonlinear models. Moreover, from Figure 5.1 (b), only 26 points among 405 points (6.4%) are away from the ideal curve, which is basically acceptable. Therefore, to develop a model in exponential form, which also complies with empirical equations, the model process order is set linear. Thus, a linear regression equation based on a natural log transformation is generated as below.

\[
\ln(Ra) = 7.81129 - 0.083836 \ln(t) - 0.085848 \ln(n) \\
+ 0.10297 \ln(p) - 0.57412 \ln(s) \\
\] (5.2)

which can also be written as

\[
Ra = e^{7.81129 - 0.083836 \ln(t) - 0.085848 \ln(n) + 0.10297 \ln(p) - 0.57412 \ln(s)} (nm) \\
\] (5.3)

or

\[
Ra = \frac{e^{7.81129 \ln(p) + 0.10297}}{e^{0.083836 \ln(t) - 0.085848 \ln(n) - 0.57412 \ln(s)}} (nm) \\
\] (5.4)

where

- \( t \) – lapping time in min
- \( n \) – lap rotation speed in rpm
- \( p \) – lapping pressure in kPa
s – type number of grit paste.

It is found from Equation (5.4) that the surface roughness increases with the increase of pressure and decreases with the increase of lapping time, speed and grit number. In other words, better surface quality can be obtained when lower pressure, longer time, higher speed and grit #600 are applied in the lapping processes.

To evaluate the validity of the statistical models, the predicted value and measured value of Ra within established intervals of variation for the parameters are compared. Take the lapping process with 50 rpm and 115 kPa as an example, the predicted and actual curves are shown in Figures 5.2, 5.3 and 5.4 for lapping with different abrasives. Basically, an agreement between the two curves is observed in every figure, which means the generated regression equation, based on experimental results, is acceptable.

![Figure 5.2. Predicted Ra versus Experimental Ra (Lapping with Grit #220)](image-url)
Figure 5.3. Predicted Ra versus Experimental Ra (Lapping with Grit #400)

Figure 5.4. Predicted Ra versus Experimental Ra (Lapping with Grit #600)
Figure 5.5 plots the residual versus the predicted values. These plots don't reveal obvious pattern. Figure 5.6 plots the predicted values versus the actual values. The points fall mainly in the acceptable region. Considering the residual plots, we can conclude that the regression model for Ra is adequate.
5.1.2 Statistical Model and Residual Analysis for MRR

For material removal rate, there are only 3 variables for statistical analysis and they are speed, pressure and grit size. To eliminate the large variance of material removal among the three samples in every lapping process, an average value of the three MRR is calculated as one input data for ANOVA. Therefore, there are $(3^3) = 27$ values in total. All the experimental data of material removal is shown in Appendix C.

Table 5.3 and Table 5.4 show the ANOVA statistical results for analyzing the relative significance of parameters for MRR. It is realized that different sizes of abrasive grits make a big difference in MRR. To some extent, lap rotation speed affects material removal more than lapping pressure.

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<td>C-ln(grit size)</td>
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<td>7.7592</td>
<td>413.1266</td>
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<td>Cor Total</td>
<td>8.7171</td>
<td>26</td>
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The Model F-value of 147.04 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B and C are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.
Table 5.4. Statistical Quantities

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The "Pred R-Squared" of 0.9335, as shown in Table 5.4, is in reasonable agreement with the "Adj R-Squared" of 0.9440. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 33.2296 indicates an adequate signal. This model can be used to navigate the design space.

A linear regression equation for predicting MRR, based on a natural log transformation, is generated as below.

\[ \ln(MRR) = 10.42989 + 0.61405 \ln(n) + 0.19579 \ln(p) - 1.30085 \ln(s) \]  \hspace{1cm} (5.5)

which can also be written as

\[ MRR = e^{10.42989n^{0.61405}p^{0.19579}s^{-1.30085}} \text{ (nm/min)} \]  \hspace{1cm} (5.6)

or

\[ MRR = \frac{e^{10.42989n^{0.61405}p^{0.19579}}}{s^{1.30085}} \text{ (nm/min)} \]  \hspace{1cm} (5.7)

where n – lap rotation speed in rpm

p – lapping pressure in kPa

s – type number of grit paste.

Similarly, from Equation (5.7), it is observed that MRR increases when lapping speed and pressure increase and grit number decreases. To evaluate the validity of the statistical models, the predicted values and measured values of MRR within established intervals of variation for the parameters are compared. Figure 5.7 shows the lapping processes with grit #220 under 58 kPa as the example. As we can see, an agreement is
achieved between the predicted and actual values. Therefore the regression equation for predicting MRR, based on experimental results, is acceptable.

Figure 5.7. Predicted MRR versus Experimental MRR

Figure 5.8. Normal Plots of Residuals for Analysis of MRR
Figure 5.9. Plots of Residuals versus Predicted Values for Analysis of MRR

Figure 5.10. Predicted Values versus Actual Values for Analysis of MRR

Figure 5.8, Figure 5.9 and Figure 5.10 show the diagnostic plots for the MRR model. The good statistical results help conclude that the regression model for MRR is adequate.
5.2 Optimization of the Lapping Process

Figure 5.11, Figure 5.12 and Figure 5.13 show the average surface roughness (Ra) of sample surfaces versus lapping time with different process parameter values. A common trend that Ra decreases dramatically with the lapse of lapping time is observed in all these three figures. Since the abrasive particles blunt and break into small sharp-edged particles with increased lapping time, the lapping pressure is distributed to more particles so that the depth of indentation of the abrasive particles decreases. This leads to improved surfaces on the metal workpiece. Usually Ra decreases dramatically to a specific value and then keeps this value if lapping conditions maintained the same. The duration, from the beginning to the point when the specific value of Ra is achieved, is the best lapping time. After this, if no parameter is changed, the surface will not be improved any more even though being lapped for longer.
Figure 5.11. Average Surface Roughness (Ra) versus Lapping Time Using Grit #220
Figure 5.12. Average Surface Roughness (Ra) versus Lapping Time Using Grit #400
Figure 5.13. Average Surface Roughness (Ra) versus Lapping Time Using Grit #600
Figure 5.14. Material Removal Rate (MRR) versus Lap Rotation Speed
These figures show that the size of abrasive particles has significant influences on surface quality and materials removal rate. The finer are the abrasives, the smaller are the scratches and indentation by a single abrasive; furthermore, the smaller is the micro-crack length, the less is the material removal (Figure 5.14). However, the smoothness that can be achieved by lapping is not unlimited, even when very fine abrasive grains are used [15].

The results also show that increasing loads, with limits, lead to poor surface roughness but large stock removal. Because with the increase of lapping pressure, the number of contact points per unit area increases, and a deeper penetration of abrasive particles leads to deeper groove formation. This causes the increase of the stock removal and the decrease of the surface smoothness. Yet, for lapping processes with grit #400 and #600, the results are not as significant as those lapped with grit #220, and for grit #600 lapped surfaces, the lapping processes under the middle pressure produce even a little better roughness than those under the lowest pressure. One possible reason is: grit paste #600 contains more single particles per unit volume than #400 or #220 does, so the pressure is distributed on more particles; the penetration of a small particle is lower than that of a big one, so smaller particles are easier to be moved due to the friction force; the polymer plate does not hold the abrasives as firmly as an iron plate does; as a result, a larger percentage of the very fine particles tend to roll rather than to slide, under a low pressure; in other words, a relatively high pressure can help the fine abrasives penetrate in the lapping tool and be involved in ploughing process for material removal, so as to improve the surface quality. This may also be an explanation
for the interaction between lapping pressure and grit size. In any case, no distinct difference of surface roughness between the samples lapped with grit #600 under 58 kPa and 81 kPa.

The figures show a slight influence of lapping speed on stock removal and little on surface quality. Actually, lap rotation speed as an active factor affects the surface shaping rate and stock removal rate, since the abrasives cause longer machining micro-cracks if a higher speed is used. Nonetheless, those geometrical characteristics will not be changed obviously, which was also mentioned by Tam et al. [9], and Brown [50].

In order to get good surface finish, the optimum conditions for lapping on D2 steel surfaces with a polymer plate are summarized as the following: grit #600; plate rotation speed 40-50 rpm; lapping pressure 50-80 kPa; best lapping time is between 3 minutes to 5 minutes. A relatively large pressure and speed, within or around this interval, should be applied, if a good material removal rate is also required.
Chapter 6  Summary and Conclusions

This thesis focuses on the study and optimization of the polymer lapping method on D2 steel surface. FriCSo patented polymer lapping solution and the tribological designed plate are introduced. The mechanisms of polymer lapping are analyzed, based on the morphological investigations and composition analysis of FriCSo treated surfaces.

In order to study the significance of variables and characterize the polymer lapping process, experiments are designed and proposed for D2 steel discs using the polymer lapping plate. Statistical analysis of variance (ANOVA) is performed to find lapping process parameters of statistical significance, and regression models are generated and verified. The effects of process parameters on surface roughness (Ra) and material removal rate (MRR), including lapping time, lap rotation speed, lapping pressure and abrasive grit size, are investigated to optimize the lapping process.

The following conclusions can be drawn from the analytical and experimental results of this study:

- Polymer lapping creates an oil-retaining nanolayer improving the friction performance of the treated surfaces.
- The organic layer formed in polymer lapping helps expose carbon structure and enables the graphite to serve as a self-lubricant.
Polymer lapping improves the mechanical properties of the treated surfaces by hardening the surfaces.

Finer abrasive grains achieve a smooth surface but lead to low MRR, compared to larger abrasive grains.

Good surface quality is more likely to be achieved with low or middle lapping pressure, which also results in low MRR.

Higher lapping speeds can achieve greater MRR to some extent, but have little effect on surface roughness.

Regression equations for prediction of Ra and MRR are generated using ANOVA method and verified acceptable within established intervals of variation.

The optimum regime of lapping parameters of D2 steel with a tribological designed plate is determined as: lapping with grit #600, 40-50rpm lap rotation and 50-80 kPa lapping pressure.

A fine surface will be obtained when lapping for 3-5 minutes with the optimum combination of lapping parameters.
References


34. Wei Zhang, Hongxin Yang, Chunmin Shang, Xiaoyong Hu, and Zhonghui Hu (2005). “High Speed Lapping of SiC Ceramic Material with Solid (Fixed)


38. http://www.fricso.com/Site_English/


Appendix A

Elemental Composition of Cast Iron GGG70L before Lapping

EDAX ZAF Quantification (Standardless)

Oxides

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Elemental Composition of Cast Iron GGG70L after Lapping (Graphite Pore)

EDAX ZAF Quantification (Standardless)

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Elemental Composition of Cast Iron GM190 after Lapping (Graphite Pore)

EDAX ZAF Quantification (Standardless)

Oxides

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### Appendix B

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