A STUDY ON MATCHED-PIECE
LAPPING PROCESS FOR PRODUCTION
OF
PRECISION MACHINE ELEMENTS

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A study on matched-piece lapping process for production of precision machine elements

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ABSTRACT

A STUDY ON MATCHED-PIECE LAPPING PROCESS FOR PRODUCTION OF PRECISION MACHINE ELEMENTS

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The process of lapping has been long regarded as an art. Since the quality of lapping differs from one operator to another, significantly and the results are often time inconsistent. The material removal rate, surface finish and geometry all depends on proper control of lapping parameters (e.g. lapping speed, lapping pressure, lapping material and size and type, workpiece material and hardness, etc.).

Furthermore, to attain the desired outcomes, it is imperative to select proper values for lapping process control parameters. In this research lapping processes are studied via several experiments to investigate the effects of the initial/boundary conditions of the process on the overall geometry of the final workpiece. Hence a general-purpose mathematical model of the process (and lapping rules) is proposed based on the relevant literature and the experimental results obtained.

Keywords: Matched-Piece Lapping, Modeling and Experimental Results of Matched-Piece Lapping Process.

ÖZ

Hassas Makina Elemanları İçin Lepleme Sureci Üzerine Bir Çalışma

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Bir bilimden çok zanaat olarak kabul edilen lepleme işleminde elde edilen kalite, bir operatörden diğerine önemli farklılıklar arzeder ve nihai sonuçların çoğunlukla birbiriyle tutarsız olduğu görülür. Malzeme kaldırma hızı, yüzey kalitesi ve geometri gibi özellikler; lepleme işlemi parametrelerinin (lepleme basıncı, hız, karşı yüzey malzemesi, ağırlık, ebat, aşındırıcı büyüklüğü ve tipi, iş parçası malzemesi, sertliği, vs.) uygun olarak kontrol edilmesine bağlıdır. Ayrıca, istenen sonucun elde edilebilmesi için, lepleme kontrol parametrelerinin doğru olarak seçilmesi büyük öneme haizdir. Bu araştırmada, lepleme işlemiyle ilgili birçok deney yapılarak, başlangıç ve sınır koşullarının leplenen parçanın nihai geometrisine etkisi incelenecektir. Böylece, ilgili literatür ve deneysel sonuçlar kullanılarak, lepleme işlemi için bir matematiksel modelin (ve ilgili kuralların) geliştirilmesi mümkün olacaktır.

To my family

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CHAPTER 1

INTRODUTION

Everything that have relative motion in contact, wear out. Some are undesired and some are favorable. In manufacturing, most of the processes are due to wearing and hard tools are used in order to cut the work to the desired shape. Carbon steel tools, High speed steels, Cobalt Alloys, Cemented Carbide, CBN and Diamond tools are the most commonly used tools in industry. Turning, Milling, Drilling, Reaming, Tapping and Sawing are the most favorable traditional manufacturing processes that use above mentioned tools. In addition to that, geometrically undefined edge shape tools exist. Abrasives plays vital role in industry as very hard and small cutters. Abrasive cutting processes like Lapping, Polishing, Grinding, Honing, Blasting and Sanding are finishing processes using abrasives for different aims. Nowadays, in precision engineering, designers tighten dimensions to have better products and so need very close tolerances. In order to produce high precision parts and assemblies human needs precision manufacturing processes. One of the common processes in industry to obtain close tolerances is lapping.

The lapping process is an abrasive cutting method to obtain flat surfaces with very fine surface finishes. High dimensional accuracies are attainable with lapping process. This method a rotating lapping plate wears out the parts placed on it to produce flat surface or perfect forms like ideal cylinders, ideal sharpness, ideal smoothness and ideal accuracy. A prevalent glamorous belief is that, polishing process gives better results in flatness than lapping. The reason seems to be the mistaken belief or understanding of flatness. It appears that the surface finish and smoothness of the surface is taken as flatness at first. Although lapping gives good flatness, it is difficult to obtain perfect surface finishes; yet, it is claimed that very good surface finishes are obtainable in the amount of half of micron and even less. The process mechanism depends of various variables. So that, the process is described as an art rather than science! However many attempts are done to methodize the process and to predict and optimizing the best initial conditions of lapping.

Proper abrasive selection, proper lapping load, proper lap stone, good slurry and process duration and velocity are of most important variables in this process to obtain good flatness and surface finishes.

1.1. Motivation and main goals of the thesis

Motivation:

Effects of different parameters are already studied either in practice and experiments or via modeling, in the literature. A general summary of these studies are concisely given here:

- Effects of abrasive size on the MRR and surface roughness
- Effects of abrasive shape and material on MRR and surface roughness
- Effects of speed of lapping on MRR
- Effects of machining load on MRR and surface roughness
- Effects of lubricant on MRR and surface Roughness
- Effects of load and speed of the process, on wear mechanism
- Obtained results of abrasive methods on mechanical properties[1]

In the literature, grinding and honing machines are assumed to be precise enough, as well as other CNC machines, also in the lapping process; stones (laps) are assumed to be flat enough. But the question is how to attain that precision or flatness or roundness? There is a huge gap in the literature about the methods of producing perfect geometries just rarely some comments are made by machinists and operators about the process in some websites.

[1] For example; wear resistance hardening of machined materials, noise of high speed gears, and etc.

So the question is:

> *What is the guideline for obtaining precise geometries with in-hand methods, without using more precise tools or machines?*

However a good example of this kind of work is available in the book of *Mechanical Foundation of Accuracy* by (Moore, 1970). In this book a method of flattening is described that is named scrapping method. In this method three workpiece are to put on each other and high spots are to remove by scrapping. This method needs very high skilled operators and is tedious and time consuming and automation of this technique seems to be conflicting. So another method should be defined and methodized to give good results in less time and be able of being automated.

Apart from scrapping method mentioned above that is defined and exampled almost enough in Moor's book, the other methods like continuously measuring and scrapping method or matched piece lapping method are not documented unfortunately. Continuously measuring and scrapping method seems not to be a feasible technique to produce desired geometries as it is desired; because this method requires a more precise measuring technique than the desired result of precision.

Also in the case of matched-piece lapping, there is no any documented work with a scientific method approach! There is no any experiment result and even there is no any claim about the process and the method. However, the method seems to be a practical and possible solution for the question asked above. Producing perfect geometries might be able and be wisely with this method because of capability of precision improving characteristic of the process; like super-flat surfaces (from un-flat ones) or ultra-precision orthogonal plates (from non-orthogonal ones) or complete circles (from circle-like geometries)

In this thesis work, it is tried to study the method of matched-piece lapping with considering the literature in chapter 2. about the manufacturing processes, specially machining processes and measuring techniques beside flattening methods including section 2.2 mechanism of wear process, characteristics of the abrasives and effects of loads and time on the final in hand works are considered. Works around the material of the workpiece is studied and effects of brittleness and ductility are taken to account. Also it is considered; the speed of process and abrasive carrier lubricant, how to affect the results of work. So then, a model of the process is prepared via MATLAB to simulate the process to see the response of the system to variables and affecting parameters such as: applied load, lapping speed, abrasive size, hardness of material, duration time of the process and others. Chapter 3. concerns with this topic. In chapter 4. Experimental studies are given. An experiment setup is designed and manufactured in order to precisely study the subject and to make it possible to control the affecting parameters well.

The main objectives of this research are:

- To simulate the matched-piece process and find the relationships between the parameters as:
    a. Effects of initial shape of the plates in the final result of lapping.
    b. Effects of abrasive grit size on the material removal rate.
    c. Flatness obtained during the simulation and its procedure by passing time.
- To study the effects of parameters practically, in the matched-piece lapping method, on the obtained flatness. Effect of initial shape is to be studied.

1.2. High and Ultra High Precision Machining Processes

1.2.1. High Precision Machining Processes

First, obtaining high tolerances in specific machining process like CNC (Computer Number Counting) milling Turning, Boring or etc., is called precision machining. Although the lathe and mill are well-known precision machine tools, they finish steam supply at times. For the first step, only an, accurately aligned, neatly shaped and very sharp tool, as well as a decent tool-workpiece balance in terms of softness for the workpiece, on one hand, and toughness and hardness for the tool on the other, can account for even half of micron, cut, enjoying an admirable surface finish. The second stage involves abrasive approaches, specially grinding, honing and lapping.

The dictionary defines “lap” as "a rotating wheel or disk holding an abrasive or polishing powder on its surface, used for gems, cutlery, etc." Lapping in particular, seems like a wondrous approach: Utilizing only simple-handed tools, absolutely perfect products turn out in flatness, roundedness, and smoothness, accuracy, and sharpness. The surface accuracy of the lapping process depends on the skill of operator and it is claimed that the surface accuracy of $280\,nm$ is attainable. Also surface finishes of sub-nanometers are attainable by lapping. (Mark Irvin)

Precision grinding deals with improvement of milling and turning with the difference of a grinding wheel being applied in place of a cutter or a tool bit .This results in a number of betterments: The potentiality of applying harder material, more elegant cuts enforced, and a smoother finish attained. This is while in the lathe and mill, the machine precision degree plays a key role in the outcome accuracy rate. Cylindrical grinding, for instance, can be done in the lathe using a toolpost grinder. Although, more elaborate cuts can be taken, with no better roundness and flatness in comparison to turned work. In addition, since normal forces in grinding prevails the same forces in turning, accuracy and surface finish may degrade on account of chatter or deflection. Important enough, it is to take into consideration that both the machine and the wheel are deciding factors of how accurate the grinding product is. Let it not be unsaid, though, that there is another abrasive operation categorized under the title of honing and lapping, where the precision of the machine results in trivial or no final quality enhancement.

Finally, close tolerances are determined by the type of the machine applied. Precision machining is aimed to produce high tolerances, and still, in fine measurable scale. Number Controlled machines, compared to Machines of CNC type have proven to produce tolerances of slightly lower rate, yet bearing close comparison with the latter type, considering the highly tolerant processed material resulted from both types. Precision machining is often arranged in three *milling*, *turning* and *boring* machinery classes. Leave it not unsaid, cutting machinery, too, is occasionally included in the precision machining classification. These cutting machines particularly employed in conjunction with both mathematical and computerized controllers, are intended for deduction, refinement or material customization, delivering applicable portions or parts. Water cutters and laser cutters comprise the most current cutting tools in precision machining field, and from accuracy point of view, turn out well enough to be accepted as common precision devices.

Lapping in particular, seems like a wondrous approach: Utilizing only simple-handed tools, absolutely perfect products turn out in flatness, roundedness, smoothness, and accuracy and sharpness terms. Even if not as perfect as above-mentioned, lapping can give to hand remarkable achievements too; under favorable set of circumstances it can:

- Grant or amend geometrical precision (like roundness, sharpness, flatness, etc.)
- Improve fit
- Grant extreme dimensional accuracy (diameter, length, etc.)
- Improve surface finish
- Enhance surface quality
- Augment angular accuracy
- Sharpen tools

1.2.2. Ultra High Precision Machining

Over the decades, manufacturing processes are developed to satisfy the needs of industry. Optical properties, micro structures and other ultra-precision structures require a new field of machining processes.

Development of various industrial techniques such as material properties of machine structures, hydrostatic oil bearings, Measuring techniques like laser interferometer, accurate linear motors, vibration absorption techniques, heat change control and air conditioning systems for stabilizing of temperature, bearings without mechanical contact between elements, sensor developments and control engineering techniques, tool making techniques in sub-micron scale, high speed computer processors, and Developments of rotary and linear servo motors, makes the ultra-precision machining a possible manufacturing technique.

The processing time in ultra-precision machining technique might be long till several days of high cost machining. In long duration of machining, thermal analysis and temperature controls should be done as well as, tool wear prediction and loads on tool and machine structure during the cutting process, to be able of reduction of positioning errors less than one micrometer (Taniguchi, 1983). Even with limitations of damping of mechanism and coulomb friction, better positioning accuracies of 5 nm is attainable. (Maeda, 2008)

UPRM: Ultra Precision Raster Milling (Schematic is presented in Figure 1-1 (Zhang, 2013).), is an ultra-precision machining method to obtain excellent surface roughness (nanometric) and ideal (up to fraction of micron) geometric form. In UPRM, a cutting tool attached to a vibrating spindle is rotating and removing material from the surface precisely in five degree of freedom. In Figure 1-2 a) a UPRM machine is shown and in Figure 1-2 b) a schematic of the design is presented (Zhang, 2013). Figure 1-3 demonstrates the horizontal and vertical designs of a UPRM machine which has different feed directions as shown in part "**a"** and "b" of the figure. In Figure 1-4 shows the accuracy of the machine in nanometers. Part "a" of the figure relates to horizontal milling and part "b" shows the accuracy of vertical milling.

SPDT: With high frequent vibration and variation dampers of Single Point Diamond Turning; an ultra-precision machining method, submicron accuracies in surface form and nanometric surface finish characteristics are attainable Figure 1-5 and Figure 1-6 (S.J. Zhang S. T., 2013).

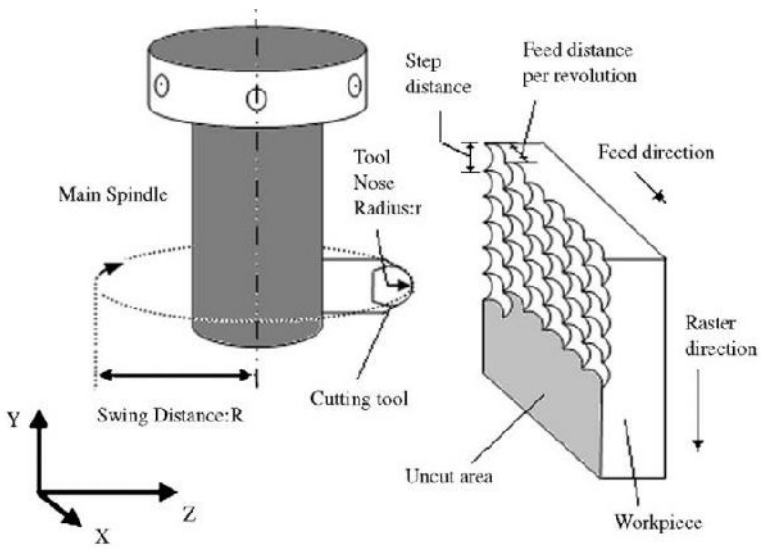

Figure 1-1 Raster milling (Zhang, 2013)

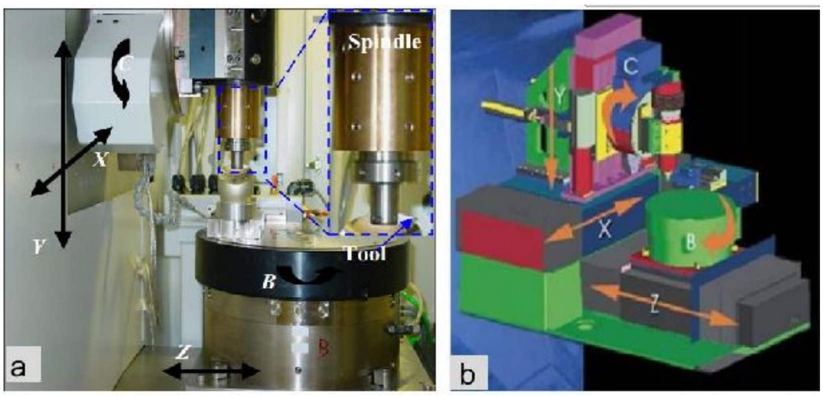

Figure 1-2 UPRM machine: (a) PrecitechFreeform705G and (b) its schematic configuration (Zhang, 2013)

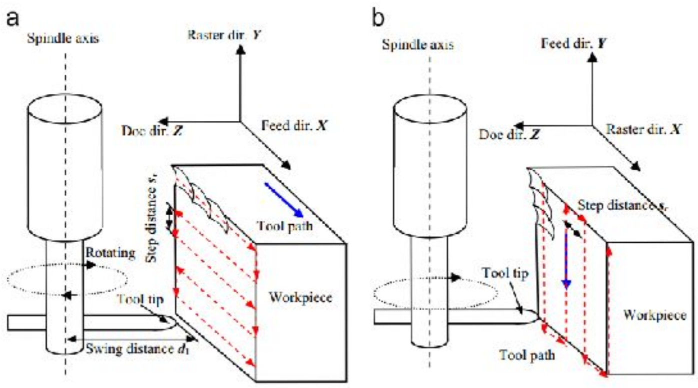

Figure 1-3 Design of UPRM a) Horizontal feed direction b) Vertical feed direction. (Zhang, 2013)

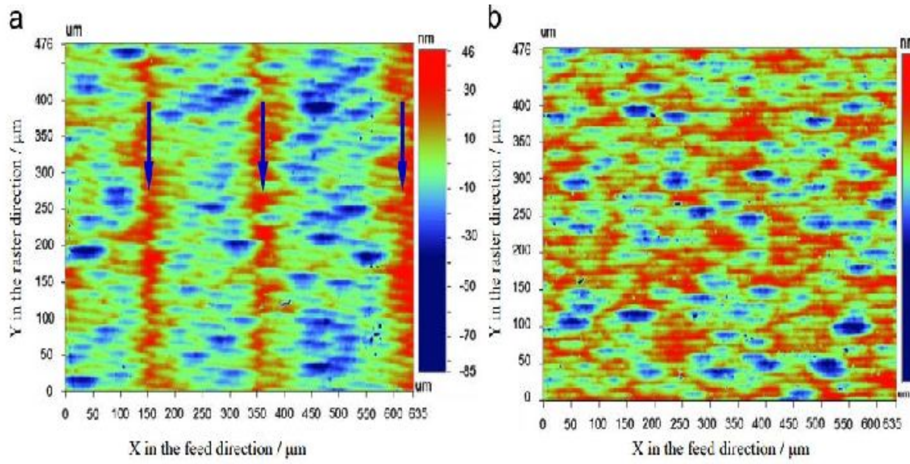

Figure 1-4 Ultra-Precision Raster milling with (a) Horizontal Milling and (b) Vertical Milling (Zhang, 2013)

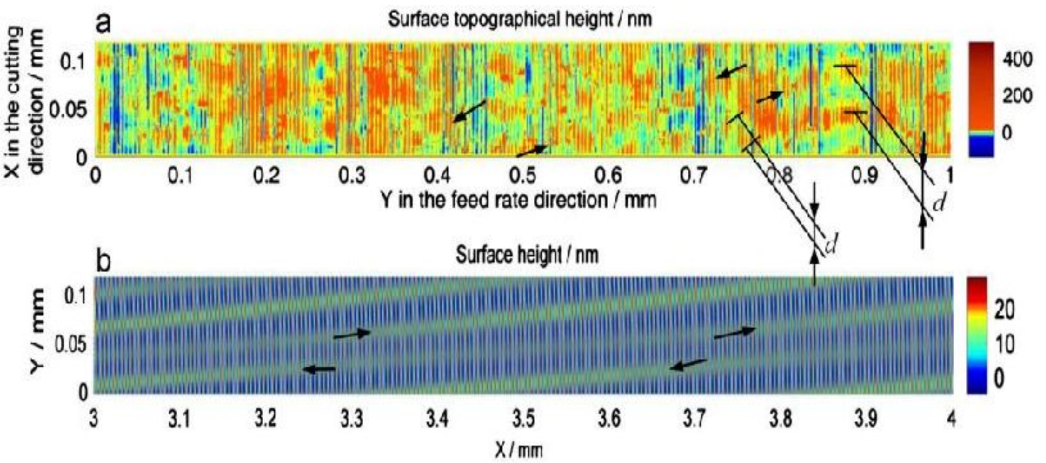

Figure 1-5 Surface Topography (a) measured and (b) Simulated under the cutting conditions (S.J. Zhang S. T., 2013)

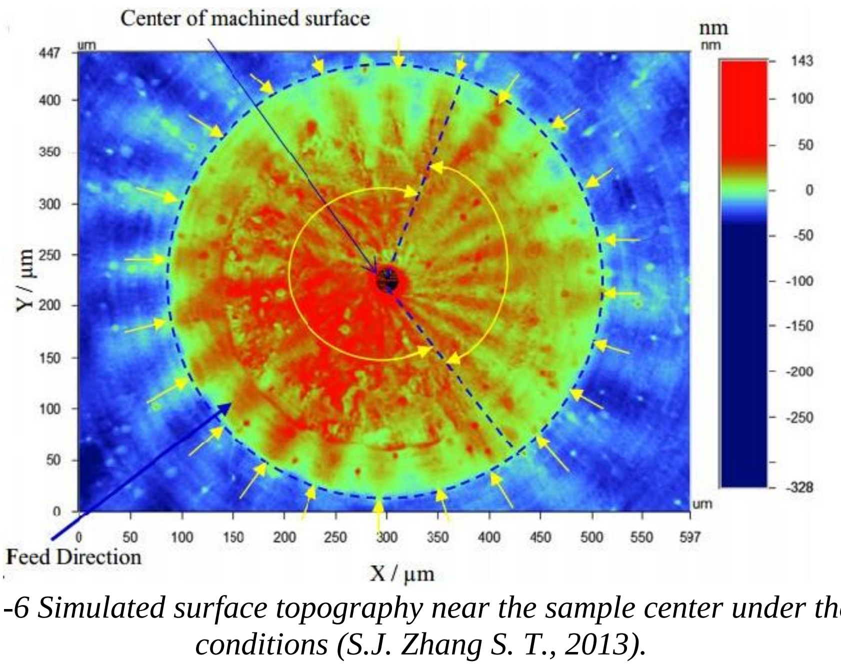

Figure 1-6 Simulated surface topography near the sample center under the cutting conditions (S.J. Zhang S. T., 2013).

1.3. Measuring Techniques

1.3.1. Dial Indicator

Dial indicator or height gauge can easily measure the surface height of the workpiece. By mounting of the dial indicator on its leg and choosing a flat surface like flat granite as a reference surface, measuring of the surface will be possible by putting it on a tripod and moving on the perfect surface.

1.3.2. Universal Length Measuring Machine

To measure length of precision equipment and part used in aerospace and automotive industries and metrology laboratories. The measuring uncertainty of the PRECIMAR CIM 530002 is $0.055 + l/1500$ where l is the length of measured part and is in millimeters.

1.3.3. Coordinate Measuring machines

CMM are well-known in the industry to control the size tolerances of manufactured parts with capability of high precision three-dimensional, online and offline measuring (R. Raghunandan, 2007). Nowadays CMMs are used in aerospace automobile industry and other mass production lines and branches of precision engineering.

1.3.4. Capacitive Sensors

Capacitive sensors provide a high accuracy and stable measuring service at different cases such as measuring of amount of wear and similarly measuring of displacement and also measuring the out of axis in case cylindrical or spherical parts to determine the roundness. (MICRO EPSILON , 2014)

1.4. Workpiece Material

Each material has its own characteristic which is unique in the field of hardness, heat treatment and strength. The common classification of the materials where the wear is studied is defined as brittle and ductile materials. Brittle materials under stresses fracture suddenly with no large strain. Large Young modules are another characteristic of brittle materials compared with ductile materials. Due to the physical characteristics of the brittle materials; little plastic deformations occur under stresses in comparison to ductile materials. Then relatively high energy is absorbed in the ductile materials before fracture than brittle materials. Ductile materials also withstand more to impact than brittle materials. Fatigue wear is more likely in ductile materials because of the plastic deformation occur and overlapping of the plowed material. (Loan D. Marinescu, 2006) In contrast micro-cracks are more evident in brittle materials and the material wear out is due to propagation of micro-cracks and removal mechanism is due to break off of fractured material. (Lawn, 1993).

1.5. Abrasives

Abrasives are tiny materials with undefined cutting edges with high hardness and almost defined by relatively high toughness comes in different shape and sizes (See Table 1-1 and Table 1-2).

They are used as micro cutting tools and are applied to the surface of the workpiece with or without slurry solution. Where an abrasive grain is sitting on the workpiece, given that a force is exerted, a high rate of stress will be engendered right at the touching point. Provided the grain is of higher hardness than the work, penetrating the surface is expected. If the pressure is in elastic range, the material is supposed to go through a temporary deformation.

The more the pressure surges, the deeper the impression gets on the surface. The quality of the impression is a full function of the material nature and trait. When the elastic limit is surpassed, a bare difference appears in material behavior depended on its nature: As for a ductile material, the material goes through a displacement course caused by a plastic flow as against to a brittle material, in which, under the same condition, a brittle fracture will cause chip dislodgement.

Table 1-1 Type and Hardness of Abrasives (Sunanta, 2002)

ABRASIVE	Hardness (MOHS)
Diamond	10
Borazon CBN	9.7
Norbide, boron carbide	9.1
Crystolon, Silicon Carbide	9
Alundum, Aluminum Oxide	9
38 White Aluminum Oxide	9
Fused Alumina	9
Corundum	9
Garnet	8-9
Quartz	7
Unfused Alumina	5-7
Linde Powers	~9
Green Rouge (Chromium oxide)	8.5

Table 1-2 Grit Size of Abrasives (Sunanta, 2002)

Grit Size Number	Average Microns
120	142
150	122
180	86
220	66
240	63
280	44
320	32
400	23
500	16
600	8
900	6
1000	5
1200	3

Due to increase of size of wafers in the semiconductor manufacturing, and need of perfect geometries and surface finishes, (Xiaohai Zhua, 2013) investigated the effects of mixed size abrasives on Material Removal Rate in wafer lapping, via modeling the process and experimental studies.

Optoelectronic devices are components used in electro-optic industry; control devices and sensors as an example. One of the important materials in these components is ceramic glasses. Lapping of these materials is the case of importance and Byoung-Jun Choa et al. (Byoung-Jun Choa, 2013) studied the affective parameters like lapping pressure, speed, time and load on MRR. Effects of slurry ratio and hardness of materials and viscosity of fluid is determined for fixed diamond abrasive, double sided lapping of Sapphire using alumina as abrasive material (Hyuk-Min Kima, 2013). An abrasive wear modeling for the case of polishing is done by (Cheng Fan, 2013) and the effect of parameters like volume concentration of slurry and abrasive particle size and standard deviation of distribution of polishing pad is studied on the material removal rate. Shifting our attention from the material removal to the grain, the question arises: what does it experience, in the course of action, and how does it behave? One thing is for sure; despite of its being hard, the grain does not resist extreme pressure and is exposed to failure. If local stresses grow beyond the elastic limit, it fractures due to being completely brittle. Taking into account that sharpest points bear highest stresses, these points are at the breakdown frontline. As a variable of its friability, the grain one way of the two: It either fractures in such a way as fresh sharp corners or edges, or smooth, and worn out and blunt edges. Also wear can be chemically expedited. For example, the reciprocal likeness of carbon and iron implies that a diamond will wear effortlessly, when utilized to grind steel, in spite of its much higher hardness (Loan D. Marinescu, 2006).

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1. Material Removal

Suppose the case in which, having pressed the grain into the surface, it gets moved laterally. Now, under a slight pressure which has not exceeded the elastic limit, the material gets removed ahead of the grain and re-occupies its initial place behind, as a boat behaves, floating smoothly on water. This range of pressure simply causes an onward force to get imposed to the workpiece surface. Needless to say, the friction between the two surfaces eventuates in heat form of energy.

Supposed that the force goes beyond the yield point, a groove, induced by material displacement, will be permanently formed, of which the outer edges from either side outstand the whole work surface as in a plowed furrow Figure 2-1. This is called plowing and engenders heat, as a result of both the external friction between two surfaces chafing each other, and the internal friction within the work material bringing about deformation process. As the pressure and the consequent depth left on the surface, gradually grow, the amount of material, displaced ahead of the grain, exceeds the corresponding amount in the sides, and thus, a chip is formed Figure 2-1, and this is where cutting regime opens.

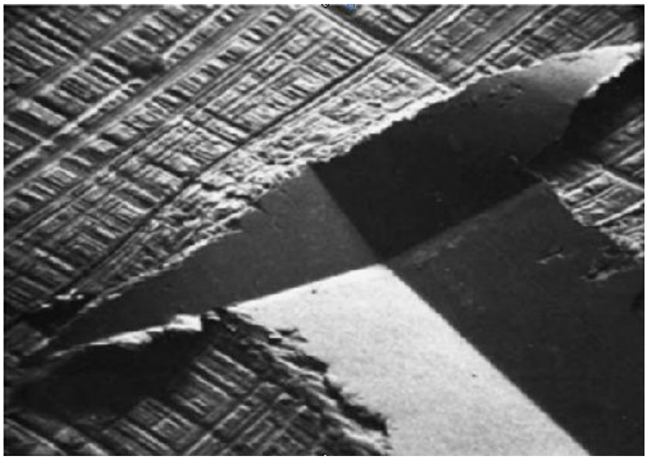

Figure 2-1 Chip formed by a Vickers indenter (Torrance, 2006)

This resembles the process in which a chip is produced by a cutting tool, in this process extrusion takes place instead of shear fraction and that is because of extreme rake angle. The remarkable point here is both rubbing and plowing, exist. In a brittle material, there will be a chain of fractured chips, rather than a single continued extruded chip. The *specific energy*, defined as the amount of effort required to remove a given amount of material, varies in terms of the chip size. Without regard for the chip size, a fixed amount of laterally exerted force gets devoted to rubbing and plowing, resulting in no material removal. These forces prevail when the cutting dawns and therefore a large force is required to breed a tiny chip. As a result of an increasing normal force, the penetration depth and hence the chip thickness increase and a greater rate of the employed force engages in creating a chip. The amount of effort (work) required to displace a certain volume of material decreases by increasing the chip size. Here from, derives the fact that the coarser a grit is, the faster it removes the material. A coarse grit, in comparison to a finer one, carves deeper penetrations sharing fewer grains of larger size with the work surface, producing fewer, but larger chips with higher efficiency. In contrast, in case of a finer grit the normal force gets allotted to more grains of smaller size and therefore the penetration depth diminishes; And as a significant point, more lateral force, is put forth to rubbing and plowing and less to removing material. M. Bigerelle et. al predicted the amount of Extreme Amplitude of peaks to valleys (EAPV) in three different regimes of abrasion for three size intervals of abrasives and proved it by experiments (Maxence Bigerelle, 2012). The removal rate in grinding of glasses directly depends on depth of penetration of tool. Beyond the elastic zone micro-grooving and micro-plowing happens. As shown in (Figure 2-2) deeper penetrations cause micro-cutting and micro-crack generation removing mechanism (E. Brinksmeier, 2010).

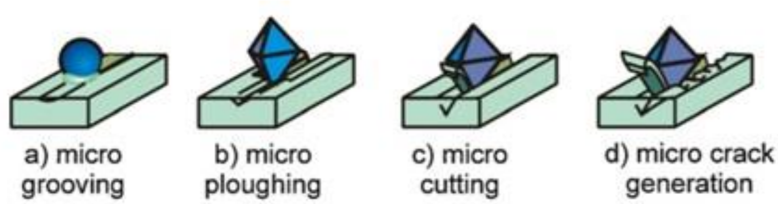

Figure 2-2 Wear out mechanism in grinding process of glass (E. Brinksmeier, 2010).

2.2. Flatness and Flattening

"The distance separating two parallel planes between which that surface can just be contained" (BSI, 2009). This definition has two main problems due to (J Meijer, 1990); first, definition cannot separate exactly the state of flatness and roughness because of using 10 mm in diameter of the measuring instrument. Second; lack of calculation method for calculating the peak to valley distance in the standard. By the way, the definition is not wrong so that, in the definition or calculation of RMS it can be used for the aim of reference plane. Also in order to have a good mathematical method to define the surface geometry, other methods are used to present better statistical characteristics of it. *Sphericity*, *Torsion* and *Waviness* are as those characteristics.

2.2.1 Scrapping

In order to produce flat and smooth surface on a conceivably hard workpiece; it is assumed to be “almost flat”. Besides, assume a reference surface (e.g. a surface plate), with sufficient flatness. Scraping is a way to indirectly transfer the flatness of the reference surface: prominent (high) spots are stained by a layer of dye on the surface plate and removed by erosion. But if the reference surface makes an abrasive pad, its flatness can be transferred directly. In scrapping technique high skilled operators are needed to scrap the peak points of the workpiece and the result of the work differs from one operator to another. Scrapping of three same workpiece and rubbing the relative peaks gives a very good flatness. (Moore W. R., 1970)

2.2.2 Grinding

Grinding is an abrasive machining process with abrasives, bonded to the very high speed grinding wheel, separating chips or plowing the material from surface of the workpiece. The process is usually used as finishing process and also used to obtain accurate-enough geometries (forms). Surface grinders and cylindrical grinders are of mostly used grinding machines in industry with high forming accuracies and surface finishes. With CNC grinding machines the capability of obtaining machine resolution of fraction of a micron is claimed. Ultra precision grinding is used in literature as a process to obtain nanometric surface finishes and an accuracy bellow 1 micro meter Figure 2-3. (E. Brinksmeier, 2010)

Figure 2-3 Micro-pencil grinding tool with 30-40 micro meters of tip diameter (E. Brinksmeier, 2010)

2.2.3. Flat lapping

2.2.3.1. Lapping with Bonded Abrasive

Assuming the sandpaper flatly set on the plane surface with its gritted side upward. Settling the work's flattened-to-be side, down on the plate the projecting spots will touch the abrasive grains, while the sunken will inevitably keep a distance from the reference surface. Moving the work sideways over the plate the prominent spots will get marked, with scratches on it. Advancing the slide moves, the high spots will erode away, approximating the case in which, the work surface lies over the sandpaper surface, and is necessarily flat as the sandpaper is. But there is more to this than such a plain description. One reason is, although the plate is flat, the paper isn't, since its thickness fluctuates regionally. Furthermore, the grains are not exactly of the same size and the thickness of both paper and the rough layer cannot be thoroughly controlled. The other obstacle comprises the paper's being soft comparing to the grains. This issue, in its own turn, causes the soft paper backing to undergo compression, when the work is pressured to the plate and therefore the sunken (lower) spots get rubbed as well as the prominent ones. Albeit this problem isn't of high significance, since the pressure rate for the prominent (higher) prevails that of the sunken (lower), and brings them about a quicker wear, in comparison. The point with higher significance is, the surface underlying the work (like a shallow basin) is regionally, uncontrollably, located lower than the neighboring surface. Considering the work being adapted to the grit surface (which is a surface with curvedness at the edge of the work), these edges will get worn off and bowed. The same basin is expected in case a particular segment of the paper grains is used, leaving the idle ones higher and sharper, of course. Apart from its drawbacks, well enough, the procedure responds in practice. This is the method woodworkers tap into as lapping, and use to flatten the backs of plane irons and chisels and the soles of planes. The same pattern (i.e. transferring a precisely flat abrasive surface to the work) is exploited when grinding and oilstone sharpening. However, having worn and lost their rubbing trait, the wheel and the stone need to be re-surfaced via dressing operation

Figure 2-4; this is while a worn sandpaper revives in sharpness and flatness terms, if simply replaced. An experiment done by (Byoung-Jun Choa, 2013) showed the effect of lapping speed, time, pressure and hardness of two substrates of quartz and borofloat, using diamond fixed abrasives Figure 2-5 and Figure 2-6. Bonded abrasives are not limited to sandpapers. Grinding wheels and lapping pads are also profit from this technique (E. Brinksmeier, 2010).

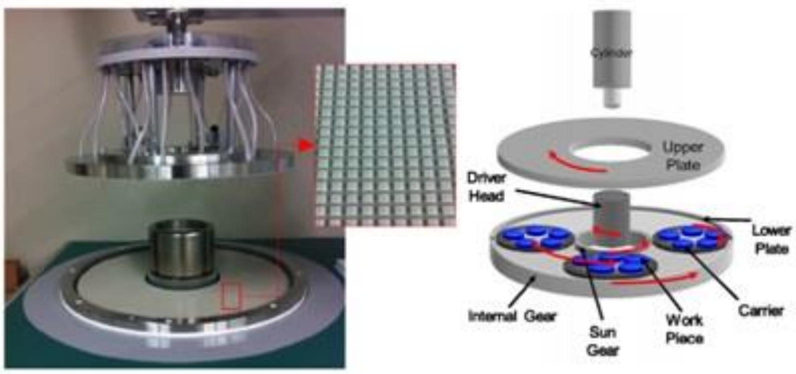

Figure 2-4 Lapping machine with fixed abrasive pad (Byoung-Jun Cho, 2013)

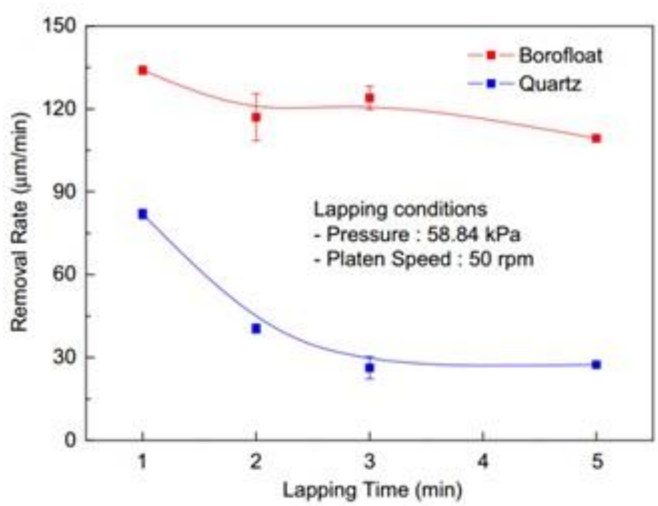

Figure 2-5 Time dependency of material removal rate for borofloat and quartz (Byoung-Jun Cho, 2013)

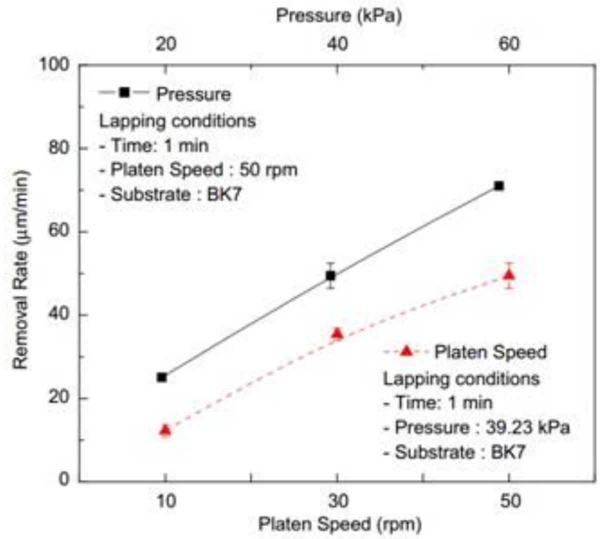

Figure 2-6 Effect of platen speed on MRR (Byoung-Jun Cho, 2013)

2.2.3.2. Lapping with Free Abrasive

The problem induced by uneven coating and springiness could be eradicated by locating the abrasive grains straightaway on the reference surface. Loose grit or a grit-and-oil blend is what watchmakers use on a piece of glass, as their first step, when polishing flat steel pieces. The second approach woodworkers apply, involves using the lapping plate, the hardened and ground piece of steel, dusted with loose grit and rubbed with the plane iron or chisel to get flattened. As for the optic workers, slurry of water and grit is used between pieces of glass or cast iron, to create utterly accurate flat or spherical surfaces. To get vivid glimpse of how it works, assume two pieces of material, a tool which is flat enough, and the work which is almost flat, plus abrasive grains between them. Figure 2-7 illustrates the site of one of such grains. For the moment let the two pieces be of the same material, hardened steel, for instance. In case a force is applied between the tool and the work, a test with three elements is established: the element grit, playing the intender role, and the tool and the work as test pieces. Inasmuch as the two pieces are of same material, it wouldn’t be too far off if we expect the same penetration depth for each.

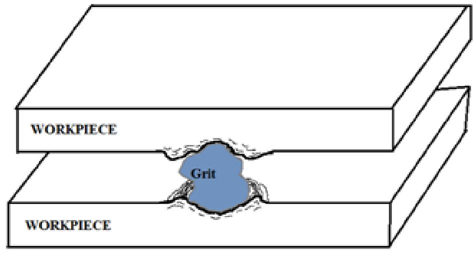

Figure 2-7 Plowing area around the abrasive

Figure 2-8 represents the grain being rolled, as the work is slides over the tool. Provided the penetration is deep enough, the leading edge of the grain will eject a chip from, at least, one of the work and the tool. This chip, as opposed to bound abrasive, turns out to be a small fragment, rather than long narrow silver. It is un-surprising that a pit with an emerged edge is dug behind, by the grain, due to plastic deformation, just as plowing, created by a sliding grain. Almost the same result turns up in case the work and tool are brittle (glass, for example), with the difference that the chips will result from brittle fracture, and the pits will lack any raised edges. Since, in practice, there are numerous grains rolling between the two surfaces, the model can be treated as a sandpaper, but different in terms of grains' being in direct touch with the reference surface, besides, being free to move rather than being circularly and/or linearly immovable. So all in all, assuming that the tool and work are brushed against each other, the rolling grains, in connection with the surfaces, will leave displaced, dust-like chips behind.

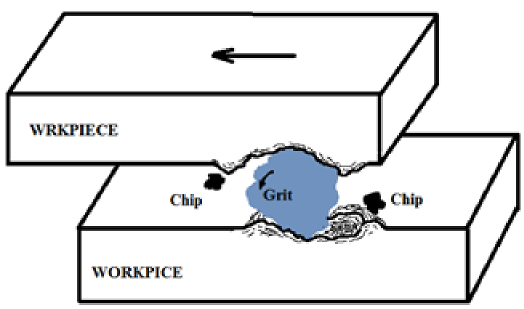

Figure 2-8 Rolling effect of abrasive between two same workpiece materials

The pits, on ductile materials, comprise a trivial portion of the grain size (2-5% for hardened steel). As regards a brittle material, the contact strain can easily spread out of contact range. In such case, the pit dimension is not negligible in comparison to the size of the abrasive grain, deep enough to net some of the rolling grains in. If the grit is free to roll, the surface of both the tool and work will seem gray with unaided eye and similarly pitted with unaided eye. In case the rolling procedure is hampered by heavy grease (for instance), or if the grains are occasionally trapped in either surfaces, then, that will look dim and dull in the background with shiny linearly-guided scrape on it.

Plastic-deformation is a material flowing mechanism on the surfaced of the work, and not always results in material removal (Figure 2-9). Medium loads and low speeds are often the case of obvious plastic deformation on the surface with no fractions and high loads and speeds although make large plastic deformations, are followed by material removal. (C. Taltavull, 2014)

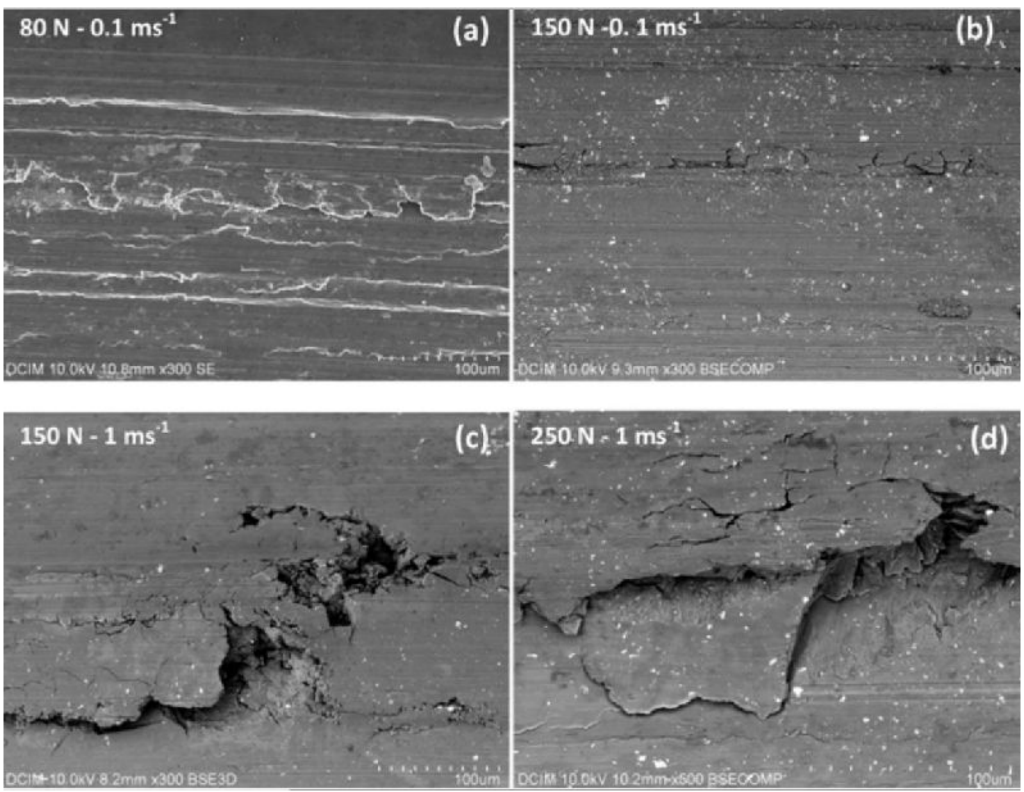

Figure 2-9 Plastic deformation of AM50B magnesium alloy, at moderate and severe test conditions a)Low load and low speed (b) moderate load and low speed (c) Moderate load and high speed (d) High load and high speed (C. Taltavull, 2014)

2.2.3.3. Lapping with Embedded Abrasive

On contrary to what was basically assumed in the three latest sections, as to the surfaces' equal hardness, we aim, in the current chapter to study how a noteworthy difference in hardness levels can affect the behavior of the work-grit-tool set. The work harder than the tool, yet both softer than the grit, is what Figure 2-10 suggests.

As expected, the softer (the tool), is more openly exposed to deeper penetration, since the pressure imposed from the grit upon both surfaces, is approximately equal. In case a lateral force is applied, the grain implanted more deeply in the tool, will cause a long chip get displaced from the work (Wise, 2006).

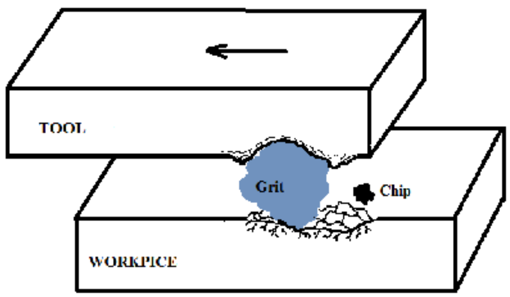

Figure 2-10 Hard Workpiece and soft Tool, both softer than embedded Grit

If the grit is sprinkled on the tool and gets rubbed by the work, it's predicted that a number of grains must have been rolled around, prior to getting implanted, and, similar to a hard-work-and-lap case, some wear will happen on the lap. Before using the lap, coating it with grit and force it into the lapping stone without rubbing, using either a hardened plate or a hardened roller, is how the lap is charged. This, albeit, doesn't completely stop the grains from being dislodged and yielding some lap wear while working, The rate of this wear, however, is significantly less than the works, so the lap is predicted to maintain its form well, especially if the whole surface gets uniformly rub-participated. Although some rotary embedded laps, especially those with diamond grit, (perhaps mainly regarded and handled as diamond-grinding wheels rather than laps) can be found, with no need to a second charge for a long time, they have to be charged on a regular basis, adding fresh abrasives.

The tool's being softer than the work, is the common rule to lap with embedded abrasive. Soft laps make abrasives easier to embed the work. That's why copper and lead laps are applied for works with more softness and finishing. The outward indications on the surface derive from the essence of the work material: rolling is characterized by a dull, pitted surface, while a bright, scratched one betrays embedding.

Delamination-wear mechanism, due to brittleness of working material and can be determined from separation of material because of crack formation in the surface of material. Plate-like chips are the other characterization of this wear mechanism. A pin on disk test done by (C. Taltavull, 2014) at first 80 N and 0.5 m/s and second 20 N and 1m/s. A SEM micrograph of the tested surface is shown in Figure 2-11.

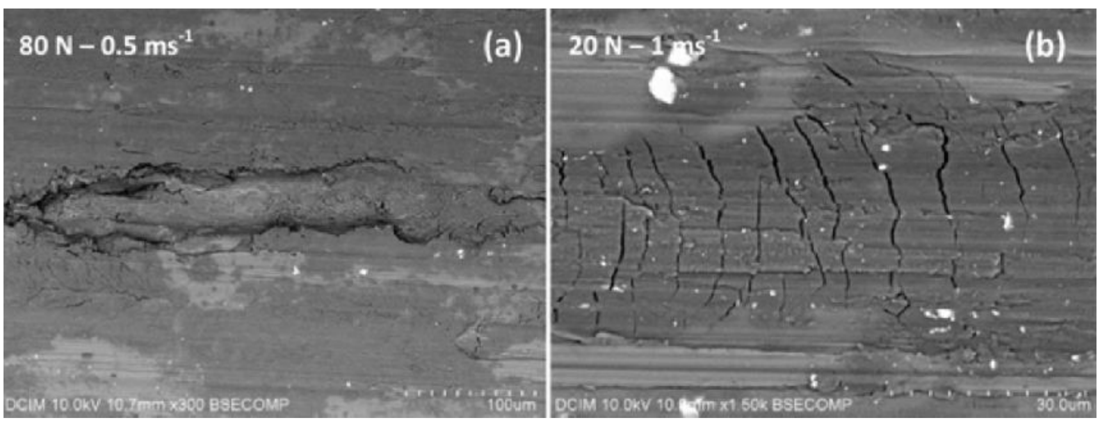

Figure 2-11 Pin on disk test for AM50B magnesium alloy at two different load and speed (a) and (b). (C. Taltavull, 2014)

2.2.4. Flatness Measuring

Areal topography measuring instruments gives a three dimensional surface texture data. Different techniques are used in order to measure the surface forms. directly measurable values are called *Metrological Characteristics* (ISO, 2011). Of various methods of flatness assessing' can be presented (J Meijer, 1990):

1. Whole surface comparison with known reference surface.
2. Comparison of several points with known flat plane

3. Line straightness measuring and gathering data of that to generate surface flatness

The surface texture is studied around surface amplifications linearity and squareness by (Claudiu L Giusca, 2012); a new way of calibrating the x, y and z axis is studied. The instruments that they used are as below:

1. Contact Stylus instrument (CS)
2. Imaging Confocal Microscope (ICM)
3. Coherence Scanning Interferometer (CSI)

2.3. Wear Mechanism

Due to DIN 50320 1979: "Wear is defined as progressive loss of substance from the surface of a solid body caused by a mechanical action , for example, contact and relative motion, with a solid, liquid or gaseous counter body." Sliding, rolling and impact contacts are common in relative motions of solids that cause wear. Material removal happens during the wear process in different known types, such as adhesion, abrasive, Fatigue and Erosion, Chemical (corrosion), impact or percussion wear; however at first material displacement might happen without actually any material removal by moving of the material at upper layers of the surface with no separation from the original material. Then material removal happens by moving trivial small of it to the opposite side or by breaking of superficial chips. Apart from mechanical wear, chemical wear plays an important role in industry by effects of surrounding environment and lubricants around the material and their chemical effects on the material in terms of material removal. In the literature the mechanical wear is divided into four types: (Ernest, 1995)

1. Adhesive wear
2. Abrasive wear
3. Erosive wear
4. Surface fatigue

As shown in Figure 2-12, taken from (Williams, 2005) other types or classified mechanical wear mechanisms can be reduced in these four groups.

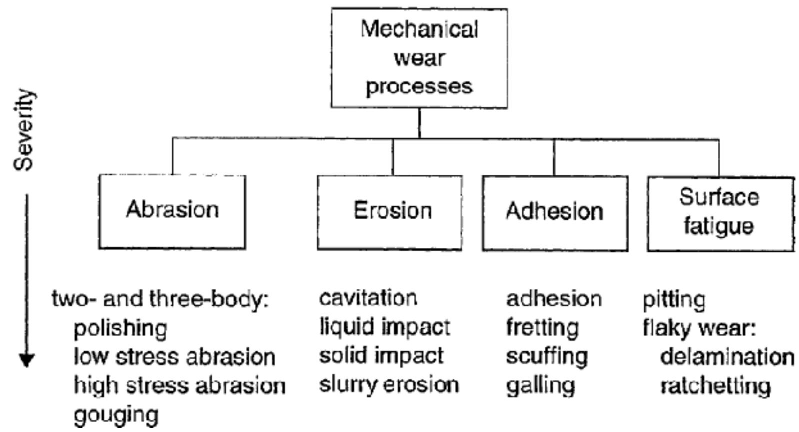

Figure 2-12 A classification of mechanical wear process (Williams, 2005)

2.4. Types of Wear

2.4.1. Adhesion Wear

The tendency of almost all materials to adhere at the contact point is the reason of adhesion (Stachowiak G. W., 2006). Failure of most materials (including non-metallic materials[1]) is due to adhesion wear, and then it is crucial to prevent this type of wear in sliding contact applications. Fortunately the nature itself prevents adhesion under normal placing conditions by oxide contaminants (thin oxide layer on the surface of most metals), water and oil. In the shown figure below Figure 2-13 (Stachowiak G. W., 2006) adhesion coefficient of different metals in four categories is shown versus hardness that express the more hardness, the more resistance to adhesion wear (Stachowiak G. W., 2006). Apart from hardness other parameters are affecting adhesion such as pressure, surface roughness, load, real area of contact and covering contaminants as mentioned above.

[1] Such as Polymers and Ceramics (Stachowiak G. W., 2006)

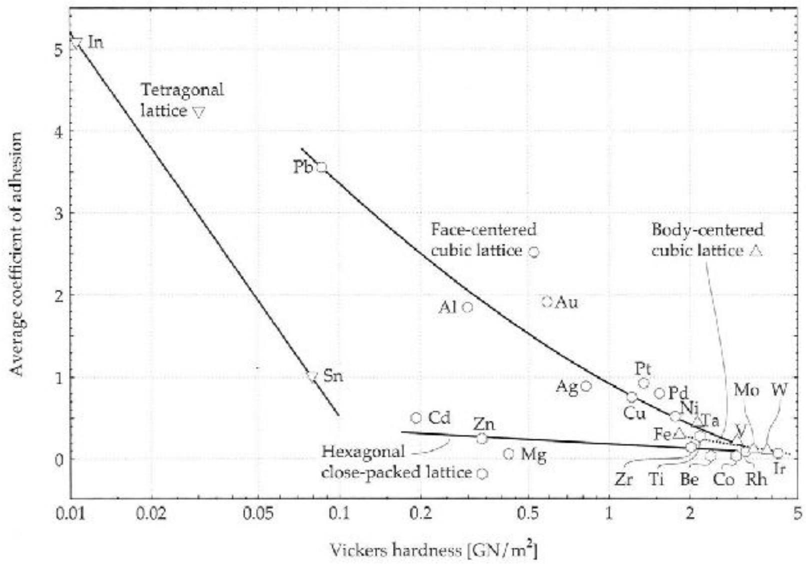

Figure 2-13 Different metals adhesion coefficient versus hardness (Stachowiak G. W., 2006)

Adhesion wear occurs due to unidirectional or reciprocating relative movements of bodies by sliding. It has been claimed that the reciprocating sliding causes more material removal than unidirectional sliding. (Dwivedi, (May 2010)). A pin on disk test done by (C. Taltavull, 2014) studies the speed and load factor on material removal mechanism, (Figure 2-14).

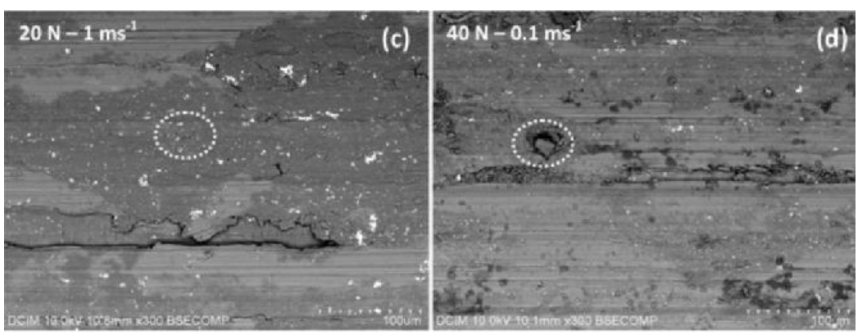

Figure 2-14 Adhesion wear in a Pin on disk test for AM50B magnesium alloy at two different load and speed. (C. Taltavull, 2014)

2.4.2. Abrasive Wear

In the literature abrasive wear is known as very important wear mechanisms and happens in the case of rubbing of hard materials against soft materials. Due to (Moore,

1981) the abrasive wear mechanism takes place when grits are in contact with ductile material by two main processes:

1. The formation of grooves ("plowing") which do not involve direct material removal,
2. The separation of particles ("gouging") in the form of primary wear debris.

If the rubbing parts include no intermediate medium (such as abrasive included slurry, or abrasive stacked in the soft material) the process is called two body wear. In three body wear, rubbing surfaces include loose grit[2] that are in contact with both of surfaces in mood of embedded or rolling between them. Like adhesive wear, in abrasive wear, ploughing, cutting and cracking are the subject of wear mechanism. Yet, in adhesive wear, adhered asperities do the action of separating or wear out, and in the abrasive wear, abrasives (grits) play this role.

In the case of contacting of a soft material with a much harder one straightly, and their interaction, material removal occurs in three ways, micro ploughing, micro cutting and cracking processes. In the ploughing the material is just moved to the scratched area (groove) and there is no material removal in fact. In the micro cutting the separated chips get form because of the asperity (in dry process) or abrasive in slurry included processes. In the Cracking arose in brittle materials, formed chips are larger than track area (scratched by the abrasive) and the reason is surface damage occurred in superficial levels of the brittle material. In Figure 2-15 affecting parameters on abrasive wear are categorized in four groups (Lee, 2002). The grouping is as below:

Design parameters:

1. Transmission of load
2. Type of motion

[2] In lapping and polishing process a soft material acts as a pad for abrasives (grit) that are the hardest material to penetrate in, in order to cut the hard material in the second place of hardness after abrasive; means abrasives are always chosen harder than both of rubbing materials.

3. Shape of the structural part

Operation Conditions:

1. Contact area
2. Contact pressure
3. Surface condition of the parts
4. Degree of lubrication temperature and environment

Characteristics of Abrasives:

1. Hardness
2. Acuteness
3. Size
4. Shape
5. Wear resistance

Material Properties:

1. Alloy composition
2. Alloy microstructure
3. Surface hardness
4. Surface ductility
5. Coating

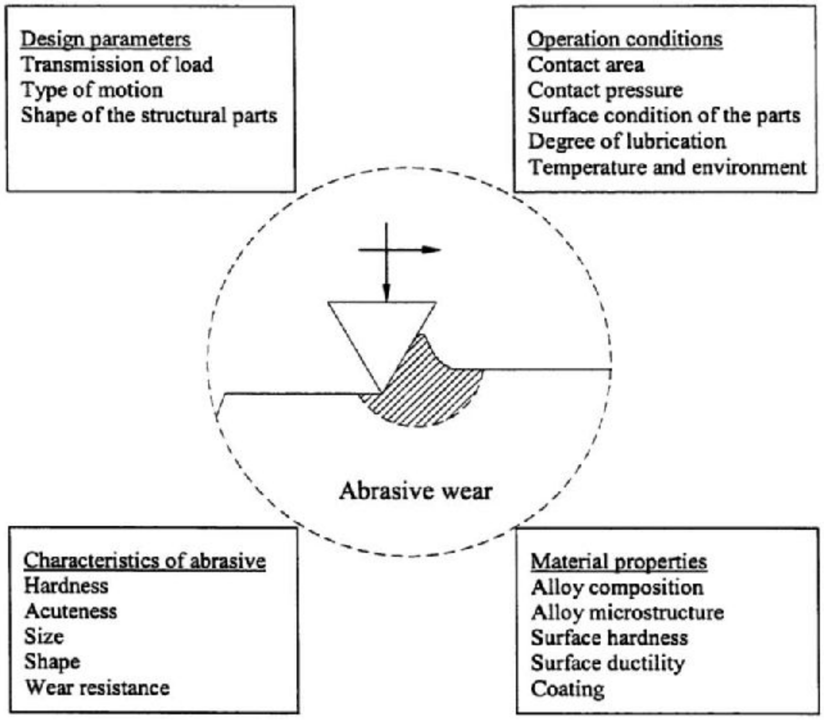

Figure 2-15 Affecting parameters in Tribological concept categorized in four category. (Lee, 2002)

Also in (Lee, 2002) reactions under high load and high pressure are studied causing separation of large debris from the surface with abrasive among causing surface cracks in brittle material and plastic deformation in ductile materials (Figure 2-16 and Figure 2-17).

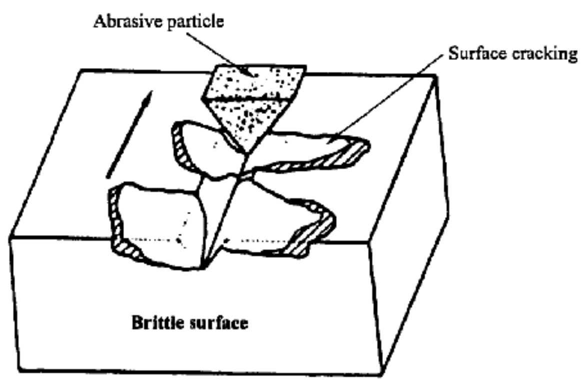

Figure 2-16 Crack developments under high load and pressure on the abrasive causing the material removal as large debris. (Lee, 2002)

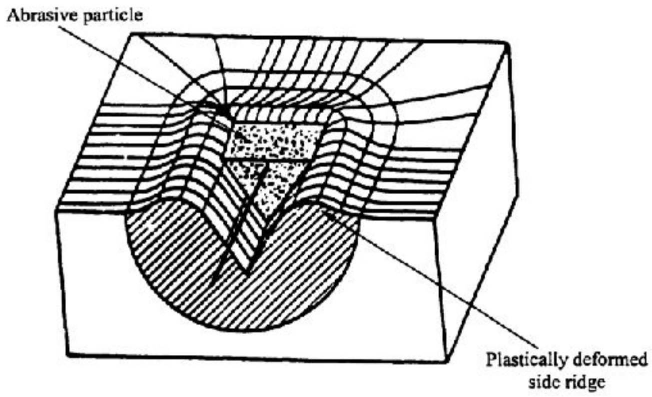

Figure2-17 Mechanism of plastic deformation, and displacement of ductile material (Lee, 2002)

2.4.3. Erosion Wear

Repeated impinging of solid or liquid particles, to the surface of the material and removal of material from the surface and the result is called Erosion wear (William, 2002). A schematic of the cross section of a work under erosion wear is shown in Figure 2-18**.** Also the cavitation of the oil in high speed bearings is a kind of erosive wear that collapsing bubbles causing wave shocks in the microscopic area near the surface of the work such as bearings. Impingement angle is an important factor in the density of two different mechanisms discussed above in erosion wear, as well as the material itself in terms of ductility. Bitter (J. G. A., 1963) studied the rate of wear affected by the angle of impingement. Due to literature, two fundamental wear mechanisms happen during the erosion wear at the same time; Deformation and Cutting wear. Local stresses exceeding the yield point caused by high kinetic energy results in deformation wear by separating of wear materials from the surface of the work is called deformation wear. While cutting wear, is because of impact of solid debris' shearing the surface and displacement of fragments from the workpiece, due to their high kinetic energy (Moore, 1981).

A prediction method for erosion is presented by (A. Gnanavelu, 2011) and CFD model of impingement wear is done and compared with experimental data.

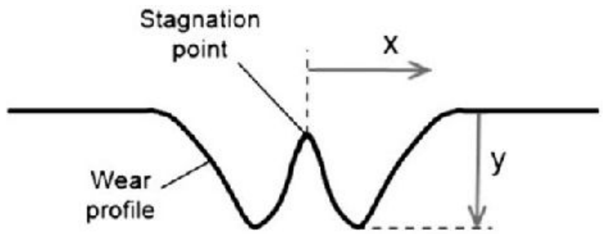

Figure 2-18 Schematic of Erosion Wear (A. Gnanavelu, 2011)

S.S. Rajahram et al studied the erosion-corrosion wear of UNS S31603 stainless steel alloy by using $Si\,O_2$ and $Si\,C$ abrasives which are different in shape and hardness, and compared the effects of abrasives on erosion results. (S.S. Rajahram, 2011) Figure 2-19 shows the state of surface after single impact of abrasive.

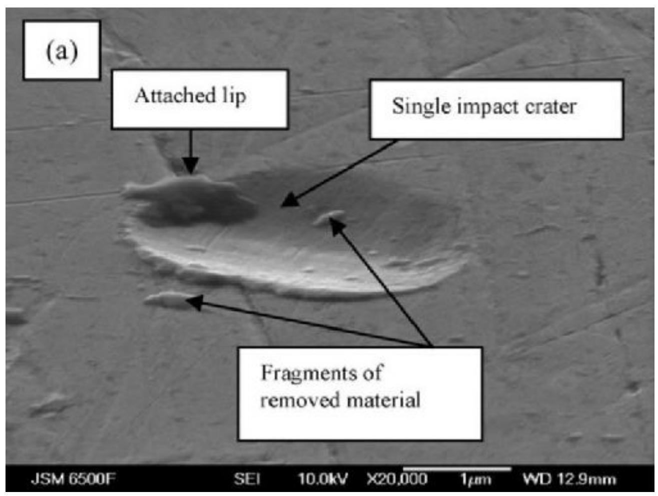

Figure2-19 Area of single abrasive impact (S.S. Rajahram, 2011)

2.4.4. Fatigue Wear

Unceasing, periodic exertion of stress on a surface, in sliding or rolling forms of movement on a track, erupts into the surface's fatigue-induced wear. These periods -if prolonged cyclically for a certain time- imposing positive and negative burden, repeatedly on the material, has proved to be capable of creating cracks in both surface and subsurface scales. Emergence of these cracks constitutes the terminal step leading to a sudden surface breakage with the development of large fragments.

2.5. Wear Distribution

On the occasion that the work surface is uneven, the pressure on more prominent spots is greater and thereby the wear is of higher intensification. Anyhow, on the contrary to sandpaper case, this kind of wear affects both the raised spots of the work and the reference surface immediately under the mentioned spots. If the hardness of both the work and the reference is equal, they will undergo a wear of the same rate; a procedure through which, the flatness of the work increases at the same rate as the reference's (Master Plate) dwindles.

In fact, the same holds true for the case the work is moved backwards and forwards in a fixed manner. Supposing the work gets rubbed over the tool so that every single spot on it corresponds a point on the tool, then each of the latter will be worn identically. The tool surface maintains its overall flat shape, though it atrophies. This is while, the embossed spots on the work, withal preserving their location, eroding faster than the neighboring points, being leveled off with them.

2.6. Closure

Different types of material removal mechanisms are introduced in the literature and due to it, specific energy is an important factor in predicting the removal rate as it is defined as the amount of effort to remove a given amount of material. Removing chips with abrasives are studied and categorized in groups like micro grooving, micro ploughing, micro cutting and micro crack generation. Among different ways of material removal methods, flattening is taken into consider because of the need of precision engineering demands. Scraping, grinding and lapping are of the most common methods. In order to study the material removal mechanism, types of wear mechanism are studied and adhesion wear, abrasion wear, erosion wear and surface fatigue are main categorized wear mechanisms in the literature. In the case of lapping, the mechanism of wear used in the literature is abrasive wear mechanism. Finally, wear models are introduced in order to simulate the mechanism and predict the behavior of different materials under the lapping conditions. In the next section an abrasive wear model is introduced and discussed.

CHAPTER 3

MODELING AND SIMULATION

3.1. Overall Modeling of the System

In this chapter a modeling process has been done in order to provide basic information about the process. Although there exist some simplifications and reductions in the model, proper modeling and simulation of an engineering process, gives a good prediction of experimental methods and outputs. In the case of newly studied method in the present work, to predict the effects of parameters on the process, a mathematical model has successfully implemented. Also the results obtained in this chapter made it easier to design better experiments; limiting the affecting parameters is an example. However, the experimental design and the modeling process should be performed in parallel, to get satisfactory results in the modeling and attainable results in experiments to have in hand. Generally, the more affective parameters in the experiment are considered in the model and less important parameters are neglected or limited. By screening the affective parameters, the modeling process becomes possible and realistic. The realistic model is to be predictive and then be able to match the reality or at least be comparative.

3.2. Design of 1D Material Removing Model

The model of matched-piece lapping process shown in Figure 3.1 is assumed to be one dimensional lapping operation. Matched-piece lapping of two long flat rail or V-shape rails are similar to this kind of lapping. In this work two workpiece are to be rub against, which, workpiece 1, is grounded and workpiece 2, has relative reciprocating motion on plate 1 in one dimension.

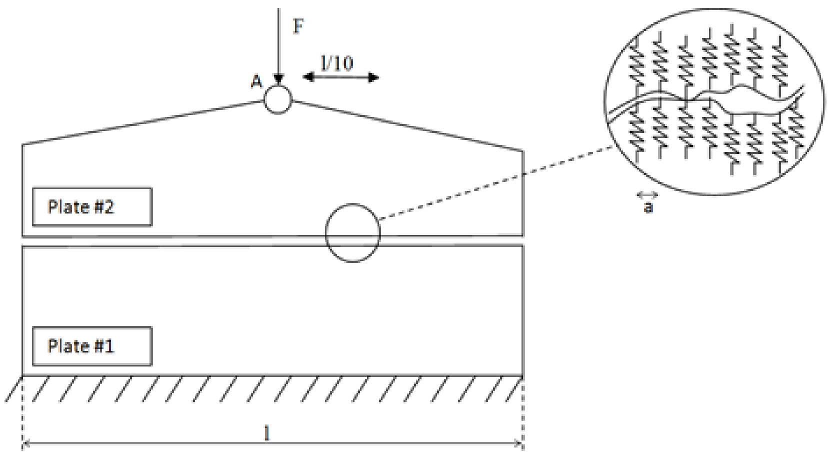

Figure 3.1 Modeling of surfaces with springs

Plates are modeled via elastic springs with lateral distance of **a**. Due to the pressure above; they will be pressed if they are in contact. Each involved spring will carry a small portion of the loaded force above. Since, as more the springs are compressed, the more force they can carry, the amount of compression can be found from summation of forces carried by each spring equal to the applied force. Also the other point which is taken into account in the written computer program is the balancing of moment. Each compressed spring has a moment on the point **A,** where the force is applied. The summation of moments has to be zero for the purpose of upper plate balancing. Then, in addition to the reciprocating movement, it is free to pitch around the lateral axis.

Suppose the case in which, having pressed the grain into the surface, it gets moved laterally. Now, under a slight pressure which has not exceeded the elastic limit, the material gets moved ahead of the grain and re-occupies its initial place behind. This range of pressure simply causes an onward force to get imposed to the workpiece surface. Needless to say, the friction between the two surfaces eventuates in heat form of energy.

Supposed that the force goes beyond the yield point, a groove, induced by material displacement, will be permanently formed of which, the outer edges from either side outstand the whole work surface, as in a plowed furrow. This is called plowing and engenders heat, as a result of both the external friction between two surfaces chafing each other, and the internal friction within the work material bringing about deformation process. As the pressure and the consequent depth left on the surface, gradually grow, the amount of material, displaced ahead of the grain, exceeds the corresponding amount in the sides, and thus, a chip is formed. And this is where cutting regime opens.

However, in the modeling it is assumed that, the material removal rate is a function of applied force *F*, and the lateral velocity *V*. Generally, force and velocity are assumed to affecting the material removal rate linearly, However *m* and *n* in Equation (3-1) and Equation (3-2) are to be found practically, if the effects of force and velocity are not linear, they may not be equal to unity. The constant K, which depends on working conditions, including material properties, abrasive characteristics (such as; hardness, distribution, size and shape), working medium and etc. can be determined from experiment. Deshpande et al (Deshpande, 2008), state that, the material removal rate has linear increase rate with the hardness of abrasive material. Also they mentioned that the factor of fracture toughness is affecting the material removal rate, and it might include unexpected results. In Equation (3.1) and Equation (3.2), f_1 and f_2 indicates the down-plate and upper-plate material removal rate.

$$f_1 = K_1 F^{m_1} V^{n_1} \tag{3.1}$$

$$f_2 = K_2 F^{m_2} V^{n_2} \tag{3.2}$$

Figure 3-2 shows a schematic of the procedure of the material removal simulation. After balancing the forces and moments, the reduction in the length of contacting springs, is calculated as explained in Equation (3.3) and Equation (3.4).

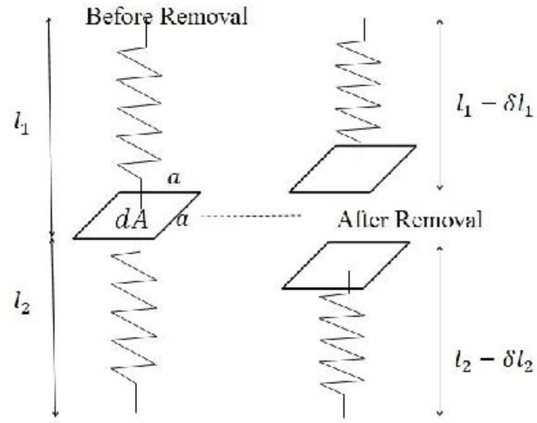

Figure 3.2 Schematic of material removal

$$\delta l_1 = \frac{K_1 F V t}{dA} \tag{3.3}$$

$$\delta l_2 = \frac{K_2 F V t}{dA} \tag{3.4}$$

Where dA is the differential area, δl_1 and δl_2 is the removed material after one removing step for upper and down workpiece. Although the amount of removed material depends on material characteristics abrasive's size shape and hardness, the initial shape of workpiece is also significant. The initial shape of workpiece can affect the pressure distribution of the load on abrasive grains so it indirectly changes it.

After modeling of chip removal process, the next step is moving the upper plate in the proper direction and within the defined interval, at time δt that depends on the lapping velocity (*V*).

3.3. 1D Modeling Results

Based on the methodology discussed in the previous section, different geometries are selected and modeled to gather results. All initial conditions are same for each test such as material, applied force material properties, lateral velocity and interval of the reciprocating movement.

Table 3.1 Assumptions for 1 dimensional modeling

E Modulus [GPa]	Load [N]	Velocity [m/s]	Movement Interval [mm]
69	20	0.2	25

There are four simulations run in this part that considers different geometries rubbing against each other and material removal takes place.

3.3.1. Two Convex Plates

In this case, two convex plates are to be lapped (Figure 3-3). The first point of contact in this case is at the middle of the plates. At first, the maximum MRR is at this point and pressure distribution is low because of the non-even surface contact. In this case, the initial flatness is adjusted to 150 μm, and the process duration is about 9000 seconds. After completing the process, it reduces to 6 μm (Fıgure 3-4). And no better result could obtained after this point. This is because one of two plates relatively wears out more and becomes concave while the other plats' shape has remained convex. The final surface shape becomes circle and the reason is two circles with same radius can remain tangent at the contacting area while one of them has limited reciprocating movement at the center which due to the balance of moments it result in angular movement at the contact area.

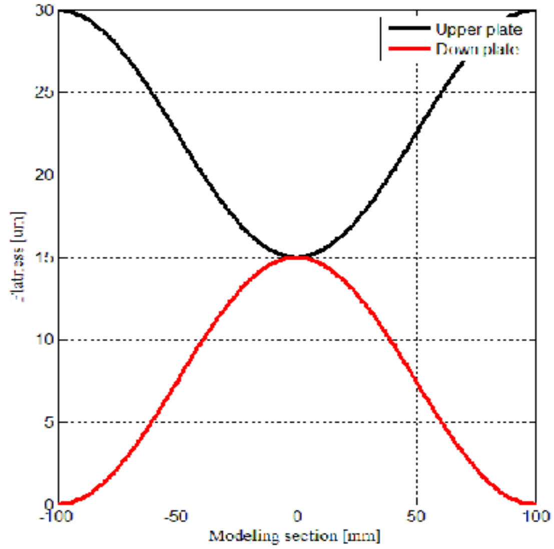

Figure 3.3 Initial form of the upper plate and down plate model of two convex plates

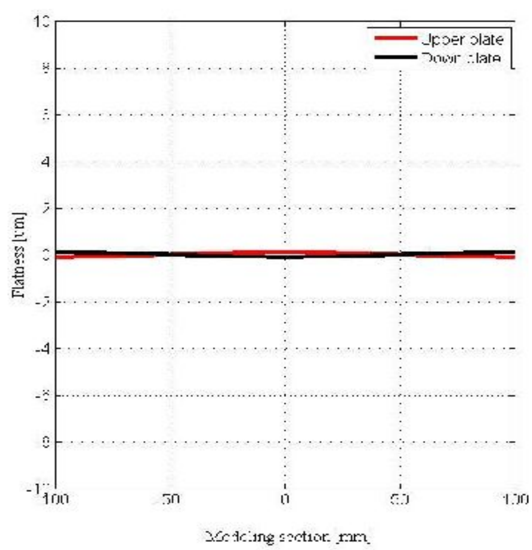

Figure 3.4 Final form of one dimensional lapping model of two convex plates

3.3.2. Two Concave Plates

In the case of two concave plates rub-against process (Figure 3-5) again the initial flatness is adjusted to 150 μm. in this case the process begins at the corner of the plates and the pressure is centralized there. The material removal took place due to reciprocating movement of the upper plate and the initial flatness theoretically reduces to 2 μm in 7000 seconds. From the simulation the result is better in the terms of flatness and duration time of the process compared to the case of two convex plates that can be considered in the practice by examinations around it. Figure 3-6 shows the result of the process before and after the lapping simulation respectively.

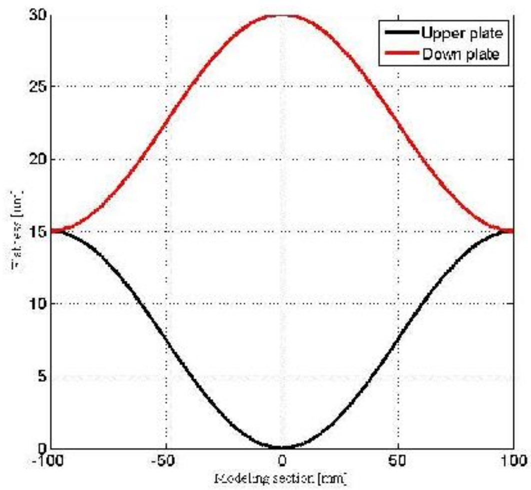

Figure 3.5 Initial form of the upper plate and down plate model of two concave plates

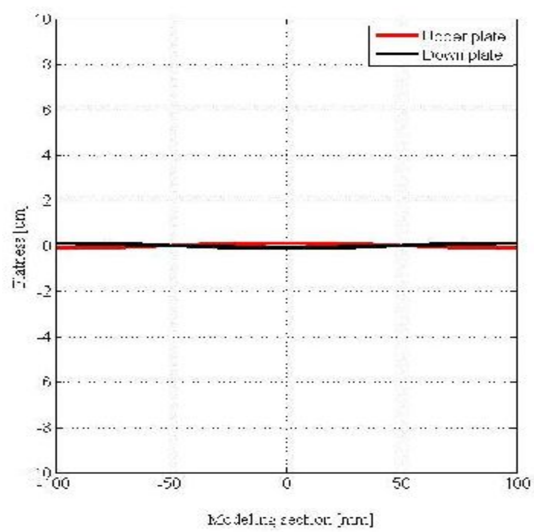

Figure 3.6 Final form of 1D lapping model of two concave plates

3.3.3. Two Random Sinusoidal Plates

In this case, two different sinusoidal plates with very poor initial condition as shown in Figure 3-7 are tested. The initial flatness of both plates is again 150 μm and after 20000 seconds of rubbing the resulted flatness is not better than 20 μm (Figure 3-8).

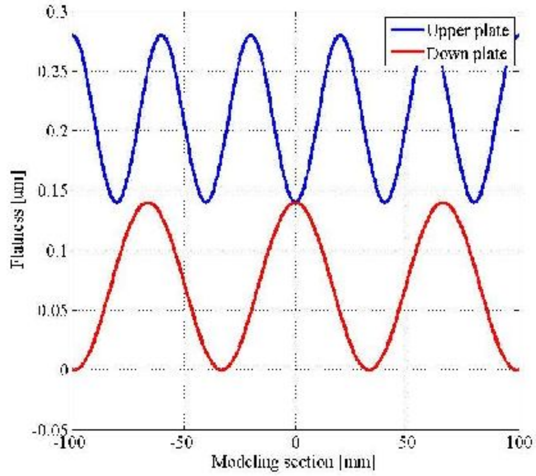

Figure 3.7 Initial forms of the upper plate and down plate model of random sinusoidal plate

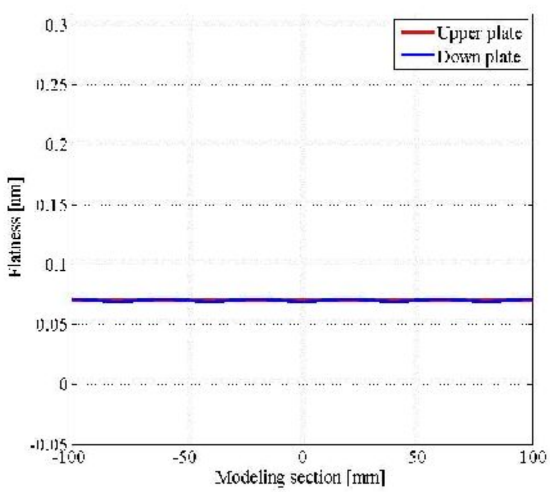

Figure 3.8 Final form of 1D lapping model of two random sinusoidal plates

3.3.4. Concave and Convex Plates

In this case two plates with concave and convex shape come in contact and rub each other with again $150\ \mu m$ of initial flatness for down plate and $90\ \mu m$ for upper plate, Figure 3-9. Despite of previous cases, two concave and two convex plates, no total improvement obtained in rubbing of two concave-convex pair.

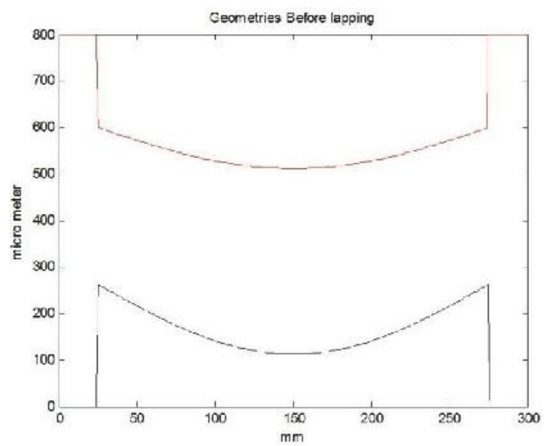

Figure 3.9 Concave-convex plates, before lapping

Two plates after a while become coincident and all the material removal take place at all over the surface which result in no change in the shape. Final flatness obtained in the simulation is $120\ \mu m$ that is between the two adjusted flatness for the upper and down plates. Figure 3-10 shows the graphical result of the modeling. In practice, having made the relative spots of the two surfaces get in contact with each other, if an abrasive layer is brought into use, between the two surfaces, points of tighter contact will erode most rapidly. As this wearing procedure goes on, the spots with previously lower height will join the wear progress, finding contact opportunity with their peers. This results in a full-spot contact between the surfaces while rubbing. In one dimensional modeling, the mere curve fulfilling these conditions is the circle, suggesting the idea that the surfaces should be convex and concave as shown in Figure 3-10.

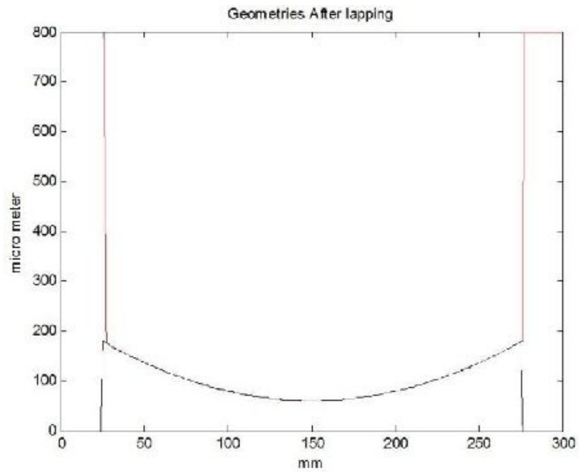

Figure 3.10 Concave-convex plates after lapping

3.4. Modeling of Effects of Loose Abrasives on MRR

Abrasives are tiny hard and sharp material doing the micro-cutting process in metalworking. Many kinds of abrasives are used for different goals in grinding, lapping polishing and other abrasive machining processes. Abrasive effects are in concept, in the modeling of the rub-against process. Their material specs such as:

- Hardness
- Toughness
- Roundness
- Number of abrasive edges
- Size
- Distribution

and their in-contact specifications, such as; durability under different working conditions and rolling or scratching effect the result of the work in terms of material removal rate, surface roughness, surface damage and etc. Two types of abrasive working are performed in industry; machining with bonded abrasives and with loose abrasives. Bonded abrasive machining has more regular grit and size distribution while in loose abrasive process, grit distribution is a challenge for the operator. Hardness, Toughness and Roundness are not time dependent characteristics while, Number of sharp edges, Size and Distribution depend on time. Durability although is a time dependent variable, the time is not prominent variable so that type of in contact materials determinates the strength of the abrasives.

Assumptions:

1. For a certain grain size, the rate of removal of material is proportionate with the pressure locally existing between the work and the grain.
2. The net removal rate from one hand, and the grain size from the other, are inversely related; under same condition of applied load and the penetration depth and scrapes thereby.
3. The grit takes effect from the wear, growing smaller or smoother (round or flat), depending upon whether it’s free to move or restrained.
4. Areas in closest touch, on the surfaces, are subject to rapidest wear.

Assuming that in a specific case, the wear mechanism is due to just abrasive wear, effective parameters on material removal rate can be studied as follow:

$$MRR = K\frac{F\,V\,t}{H} \tag{3.5}$$

Where K, is the wear coefficient and is not a constant value as mentioned above, and in the case, it might depend on time or working conditions. Let's define K as:

$$K = a_H\, a_R(t)\, a_E(t)\, a_S(t)\, a_D(t)\, K_A \tag{3.6}$$

In this equation, a_H is a time independent coefficient and stands for the effect of hardness[1]. $a_R(t)$ is coefficient of Roundness[2], $a_E(t)$ stands for coefficient of Number of Edges, $a_S(t)$, coefficient of abrasive size effect and $a_D(t)$ for Distribution effect.

[1] Assuming unit value for diamond might be a good index for other materials.

[2] Assuming unit value for sphere might be a good index for other shapes of abrasives.

Finally, $K_{A.}$ is a coefficient independent of time and condition just depends on the abrasive material characteristic.

Neglecting all variables but Size effect, the equation above reduces to:

$$K = a_S(t)\,K_A \tag{3.7}$$

The size of abrasives are influenced negatively by the applied force or better to say by the pressure above each abrasive. The more pressure applied, the shorter lifetime. Let's assume that the size of abrasive is time dependent as follow:

$$a_S(t) = \frac{A(t)}{A_f}\,\frac{C}{F_a}\,e^{1-0.01\times t} \tag{3.8}$$

Where C is Abrasive size resistance constant and F_a is the normal load on each abrasive. Ab_{fresh} Is the initial size of abrasive and $A(t)$ is the time dependent size of abrasive. Numerical Assumptions are given in Table 3-2.

$$F_{ab} = \frac{F}{Number\ of\ active\ abrasives} \tag{3.9}$$

Table 3.2 Numerical assumptions for modeling of abrasive size effect on MRR

Initial Abrasive Size	$27\ \ \mu m$
Abrasive Density	$2500\ \ ab/(mm\hat{}2\,)$
Applied Force	$10\ \ \ N$
Nominal Area of Contact	$10^4\ \ \ mm^2$
Ab. Resistance Const.	10^{-6}

Figure 3-11 shows the time dependency of abrasive size wear coefficient to time and the result (abrasive size reduction effect), shown in Figure 3-12, can reduces the MRR in the equation of wear (Equation 3.5). The coefficient introduced here might be used for predicting the proper time of slurry charge and proper choose of normal force applied. The normal force applied changes the force above each abrasive and directly affects the size reduction of the abrasives. For example in Figure 3-11, after 400 seconds it can be claimed that the abrasive has become blunted and the slurry should be changed.

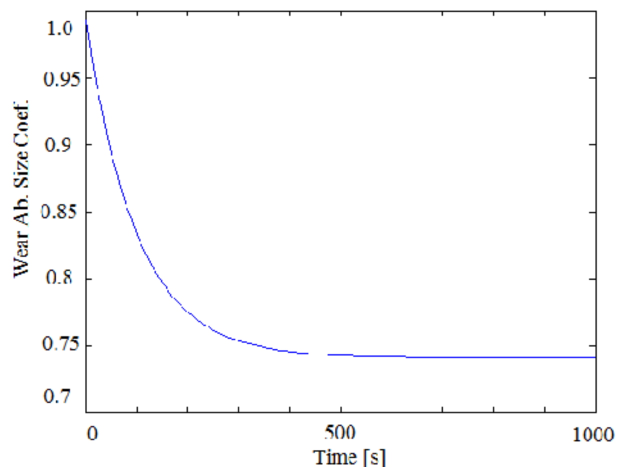

Figure 3.11 Abrasive size coefficient changes with time

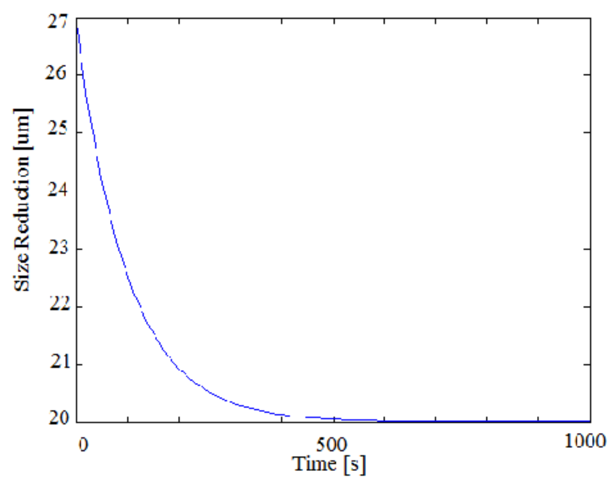

Figure 3.12 Abrasive size reductions in time

3.5. 2-D Modeling and Results

3.5.1. Match of the Two Convex Workpiece

In this section, 2D model of two convex surfaces are shown in Figure 3-13. Two convex plates are to rub against each other under defined conditions as given in Table 3-3 while material properties are given in Table 3-4. The result of modeling is presented in the

Figure 3-13. Part A and B in the figure show the upper surface geometry form before and after lapping and part C and D show these geometries for down plate. In Figure 3-14 it is seen that the flatness of both upper and down plates are reduced gradually and it has decreased to about 2 micrometers.

Table 3.3 Modeling conditions

Load	**Abrasive Hardness**	**Abrasive Size**	**Charging Time**	**Velocity**
19.6 N	9.5 Mohs	30 micron	10 min	0.3 m/s

Table 3.4 Material properties of aluminum used in the model

Material	**Elastic Modulus**	**Poisson's Ratio**	**Density**	**Hardness**
Aluminum	69 G Pa	0.3	7845 kg/m^3	149 Brinell

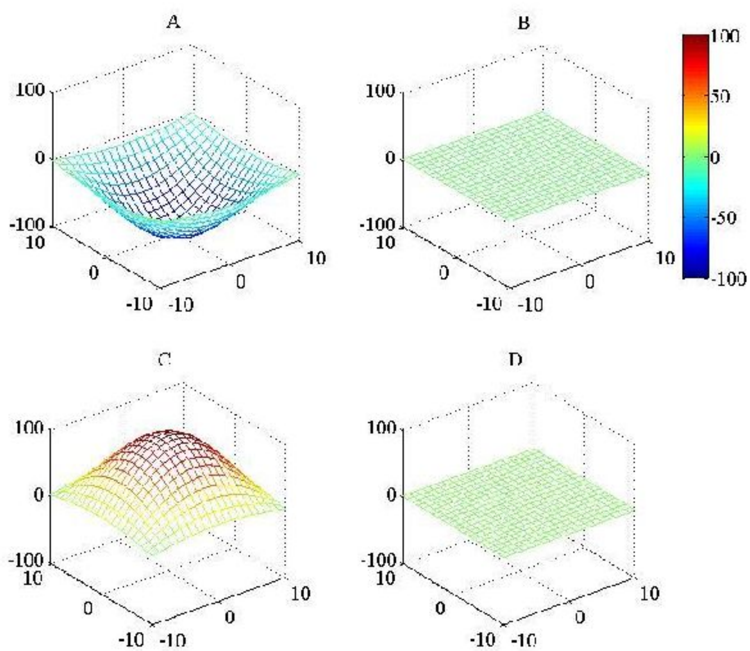

Figure 3.13 A and B:Upper surface form before and after lapping; C and D: Down surface form before and after lapping of two convex plates

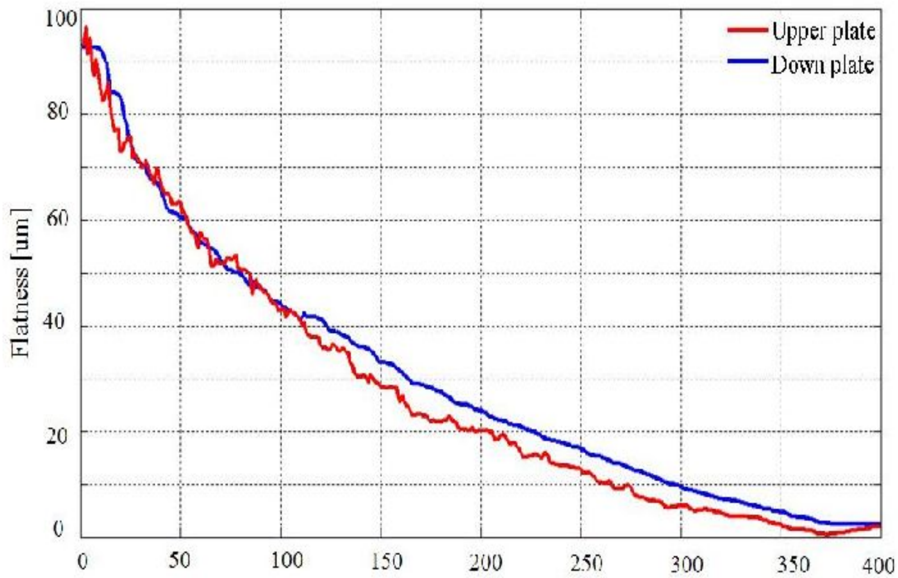

Figure 3.14 Flatness of upper plate and down plate during the two convex plate lapping process

3.5.2. Match of Two Concave Workpiece

All conditions and assumptions of the modeling of two concave plates are as the same of the two convex plates described in the previous chapter. Table 3-3 and Table 3-4 gives the details about the conditions in case of material properties and testing conditions. In Figure 3-15 A and B the initial form of the plates are shown for upper plate whereas in C and D the down plate geometery can be seen in form of before and after lapping. The flatness of the plates converges to a satisfactory point until 320 min, (Figure 3-18) and then it slowly becomes severe so that the flatness of the plates intends to increase.

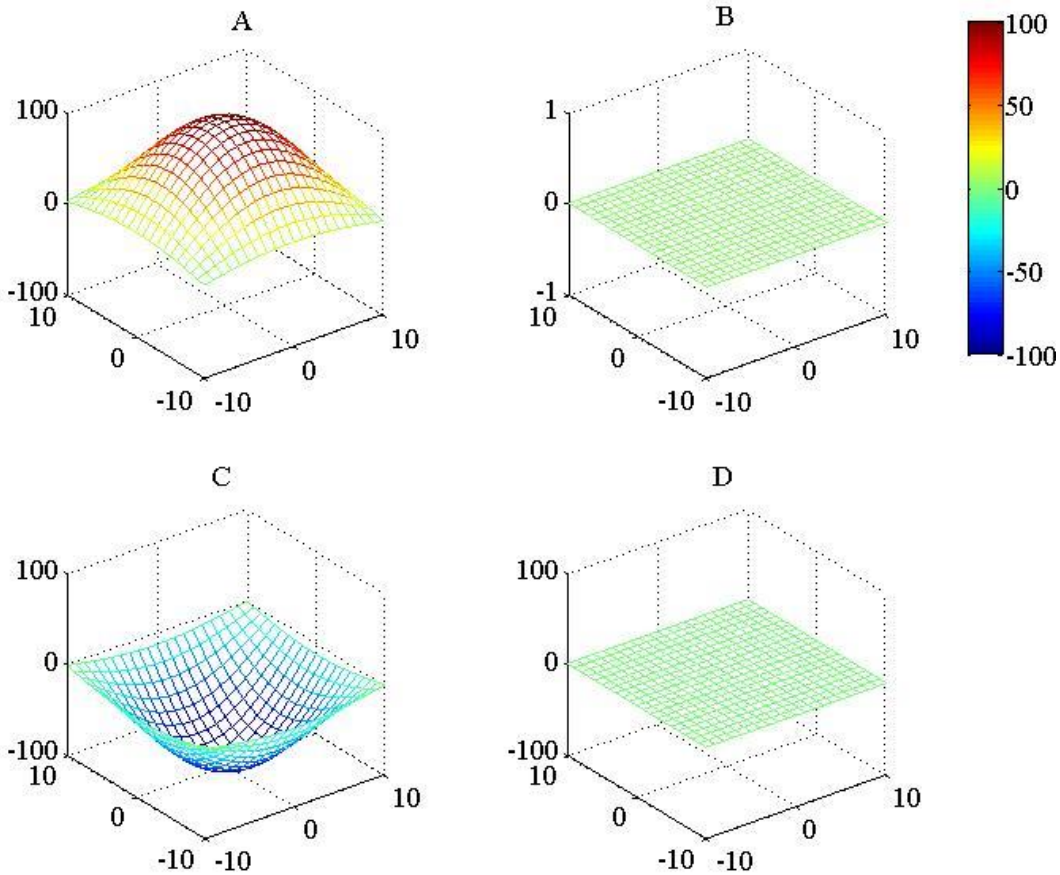

Figure 3.15 A and B: Upper surface form before and after lapping; C and D: Down surface form before and after lapping of two concave plates

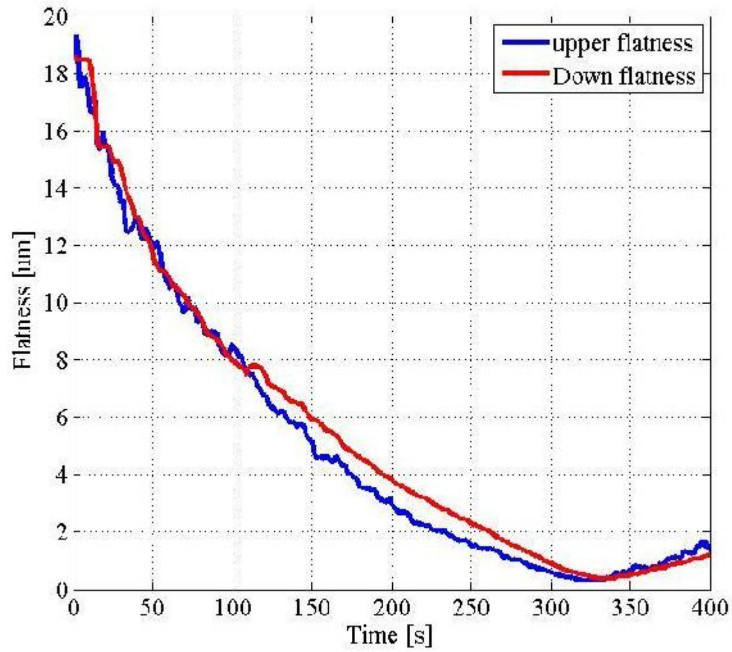

Figure 3.16 Flatness of upper plate and down plate during the two concave plate lapping process.

3.6. Closure

In this chapter, a 1D material removing model is introduced following by a more comprehensive two dimensional model. In each model, first, lapping of two convex plates are simulated, second two concave plates are taken into account and then concave and convex plates are modeled. In the models, effect of loose abrasives are considered and flatness progress of upper and down plates are given as results.

CHAPTER 4

4. EXPERIMENTAL STUDIES

4.1. Objectives and Goals

To see the effects of the parameters, three lapping operators were designed for performing hand lapping. These devices grab the upper workpiece and are able to move on top of the other workpiece by the human operator[1]. In addition to this movement, pitch and roll axis of the upper workpiece are free in orientation, to have angular movements. The orientation of the upper workpiece is completely depend on the relative positioning of the two workpiece rubbing each other in the micron level of dimensioning. The yaw axis freedom is designed to be optional and might be controlled by the operator to be free or not.

Results obtained in chapter 3-1, made it easier to design better experiments; limiting the affecting parameters as instance. However, the experimental design and the modeling process should be performed in parallel, to get satisfactory results in the modeling and attainable results in experiments to have in hand. Generally, the more affective parameters in the experiment are considered in the model and less important parameters are neglected or limited. By screening the affective parameters, the modeling process becomes possible and realistic. The realistic model is to be predictive and then be able to match the reality or at least be comparative. From results of modeling with different size

[1] These devices can be modified to mount on CNC machines in order to reduce the consumed time required for the operation.

of workpiece and under different loads, three design concepts are prepared. The main goal of experiments is to consider the effect of initial shapes of workpiece on the final form geometry of them. Also it is possible to study the effects of abrasive size, shape, distribution, slurry lubrication, load and etc. on the material removal rate. The specific characteristic of this design is to allow the upper workpiece to have angular movement in pitch and roll direction. Also the weight on top of the device makes the normal load constant and independent of the human operator’s hand. Three main concepts of designs for the matched piece lapping are studied in order to find the best one to proceed.

4.2. Design Concepts

4.2.1. Design Concept 1

In this design, a *spherical bearing* or *a precision universal joint* is to be used in order to make the upper surface to spin in pitch and roll direction. The main body and gripper of the design are to be machined from aluminum in order to have low weight design. Also three ball casters are to be used instead of wheel. Ball casters are easy to use and have low friction during the movement or changing the direction of movement Figure4-1 shows the schematic of the design. In this figure universal joint might be used instead of spherical joint.

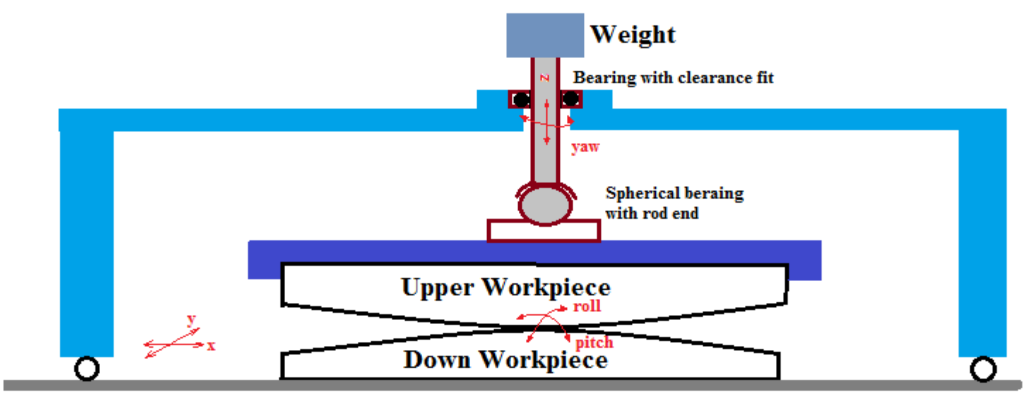

Figure 4.1 Schematic of operator device for Matched-Piece lapping using Spherical Bearing or Universal Joint

4.2.2. Design Concept 2

The system designed has six degree of freedom. Movement x *and* y directions are up to the random movement of human operator and he or she controls the speed of movement and direction and interval of it. The vertical movement depends on amount of wear of both surfaces: as more they wear out the upper workpiece comes down to feed it (Figure 4-2). In second design a gimbal mechanism is used to have pitch and roll degrees of freedom. The rotation in z (yaw) direction might be optional and the operator can state it in order prepare different experiment situations. The 3-D model of this design is shown in Figure 4-3 which has drown by Solidworks.

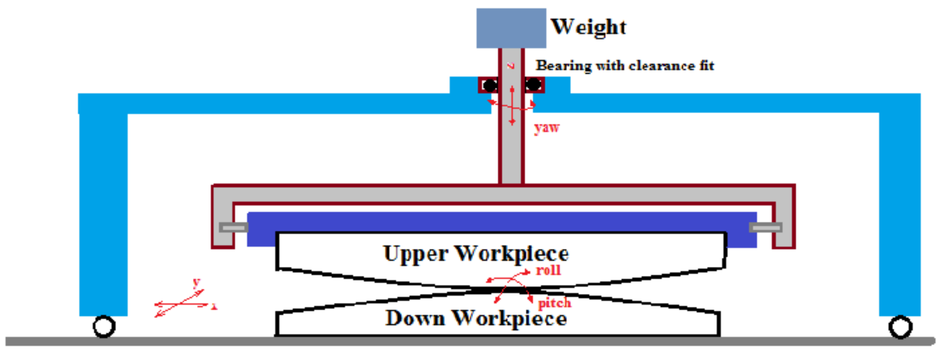

Figure 4.2 Schematic of operator device for Matched-Piece lapping using gimbal mechanism

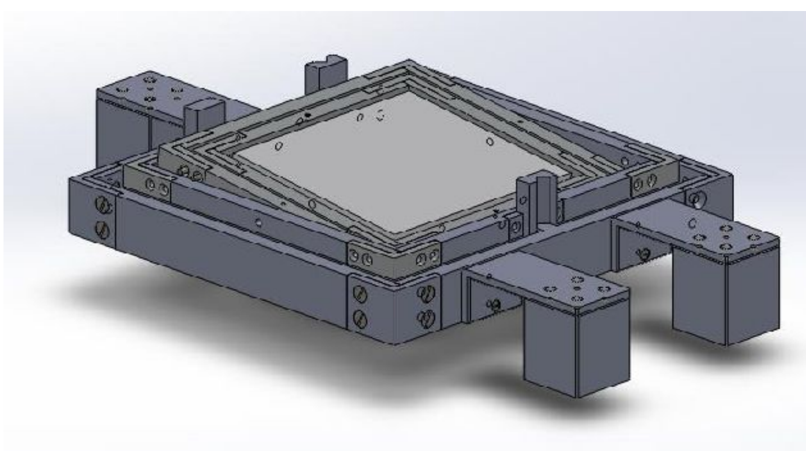

Figure 4.3 Model Design of Gimbal Mechanism

4.2.3. Design Concept 3

As the angular rotation in pitch and roll directions are not that much because of the physic of the system, instead of using spherical joint or gimbal mechanism, it might be better to use a soft resin or rubber-like material on top of the grabber to be able of conveying applied load and let the upper workpiece to settle down on the down workpiece Figure 4-4.

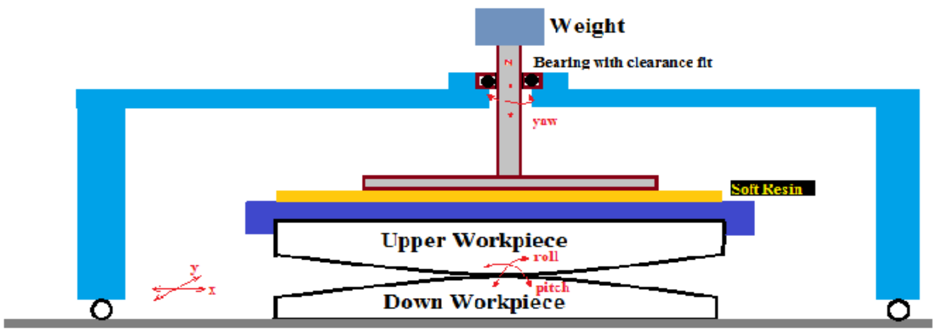

Figure 4.4 Schematic of operator device for Matched-Piece lapping using

From the designs mentioned above each have its advantages and disadvantages. As instant; structure components of design 1 can produced from aluminum profiles which are not heavy and can easily connect to each other via screws. Using spherical bearing or universal joint with dust protective cap characteristic is the disadvantage of this system. For second design although it is precise in movements and angular rotations it is expensive to produce because of providing high tolerances at used hinges of gimbal mechanisms used. The last design is cheap to manufacture and easy to assemble. The soft resin to be used here also will be elastic and able to have pitch and roll movements but it will tolerate small amounts of moments, which is not favorable. However, it is assumed that this amount is negligible and not affecting the result. The second problem is the stickiness of the resin and lasting of it in dirty circumstances of lapping process. Table 4-1 briefly gives currently described information about the advantages and disadvantages of designs.

Table 4.1 Advantages and Disadvantages of the Designed operator devices

	Concept1	Concept2	Concept3
Advantage	Easy to buy already existed components like bearing & spherical bed bearing	Precision of angular movements and capable no backlashes in linear and rotational directions	Simple concept and cheap materials are used
Disadvantage	Relatively complex mounting of spherical bearing and precision rails	High cost of production, large number of parts and mounting Complexity	Sticking of resin in the dirty circumstance of process next to unwanted tolerating of moment

4.3. How to Do

After considering of all advantages and disadvantages it is decided to manufacture the concept one with using a precise universal joint. The CAD design of the device is done with the SOLIDWORKS program and the assembly of the system is shown in Figure 4-5. This system is capable of moving in side directions while the load applied will be added on the weight plate.

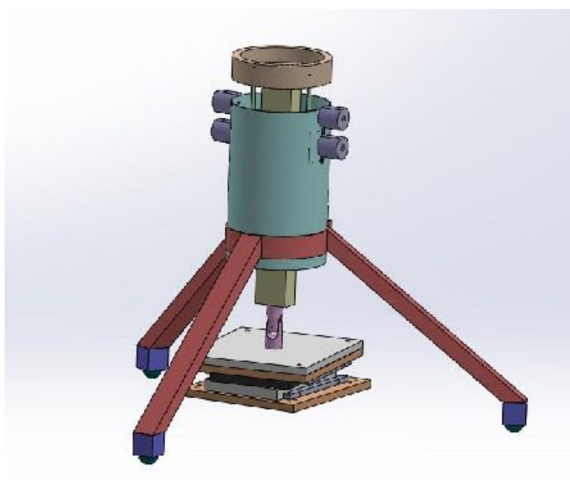

Figure 4.5 Assembly of the total system

To obtain the pre-requisites of the desired experiments such as random movement and constant load on the workpiece, precise holding and easy change of the abrasive slurry, an apparatus has invented (Figure 4-6). The apparatus is available of applying the load directly on the workpiece. This feature is because of using precision rails in the inside the device and using springs to tolerate the weight of the reciprocating parts. The human operator is easily able to move and rotate it randomly as desired and changing the abrasive slurry with easily separating the upper plate from the down one and cleaning the surface of both. In Figure 4-6, the manufactured device is shown which makes the human operator available of lapping the workpiece plate with constant load on them in a random way. Also the rotation in Z direction is not free and depends on random movement of the operator.

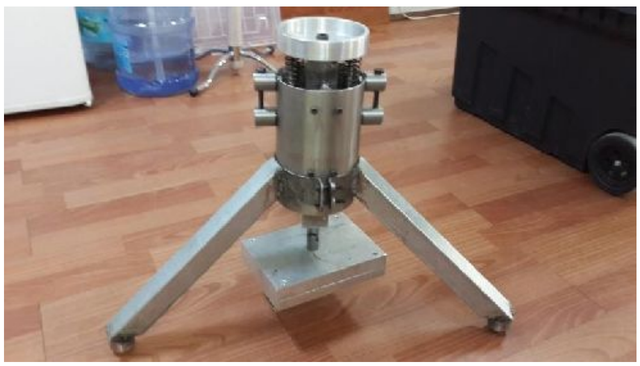

Figure 4.6 Manufactured M.P. Lapping

Workpiece are fastened with screws to the holders from sides relying on back to the workpiece holders and then mounted on the device to be ready for matched-piece lapping (Figure 4-7).

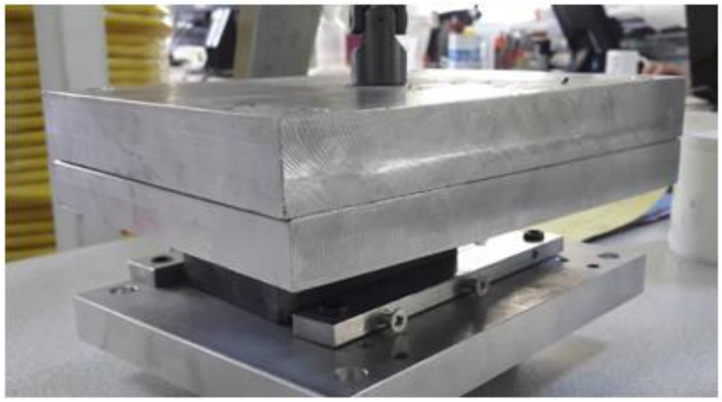

Figure 4.7 Workpiece fastening

In order to not to harm the workpiece with the screw, it is better to use soft resin between the screw and workpiece however because of the elasticity of the soft resin the rigidity of the design would be decreased. The rotation in the x and y directions are permitted with the precision universal joint shown in Figure 4-8.

Figure 4.8 Precision Universal Joint

The movement of the upper workpiece is actualized with precision rails mounted in the main cylinder Figure 4-9. The precision universal joint prevents the wobbling movement of the system.

Figure 4.9 Precision linear rail

The problem is to find a way to control the movements of the upper plate or release it to be free at needed directions. As discussed before, in order to obtain flat surfaces, a relevant experiment is designed to see the effects of initial conditions on the final geometry. In the newly introduced process of lapping, an apparatus is invented which is available of holding the upper and down workpiece to rub them randomly in a proper manner. In the coming words, the experiment process is explained from beginning to the end.

4.3.1. Materials

*Abrasives***:** Silicon carbide, aluminum oxide, and diamond paste are use as abrasives in the process among lapping liquid.

Abrasive fluid material: In order to have a good dispersion of abrasives between the surfaces of the workpiece it is better to use abrasive liquid as a medium. The abrasive liquid might be considered as a kind of machining coolant as it is in other types of processes but, in this case there is no that large heat generation during the process and the main goal of the liquid is to disperse the Water might be used as a lapping liquid during the process.

Soft Towel: Soft towel is used to make the cleaning job Figure 4-10. The parts must be cleaned from the dirt and to make it easier at the first stages of the process a soft towel is used. With the soft towel, the used abrasives can be removed from the surface of the work in a very fast way however, when the flatness of surfaces get better and at the final stages of the process and also if it is important to have good surface finishes it is better to avoid using towel. Apart from its cost, the best way of removing dirt from the surface is to blast new slurry on the surface.

Figure 4.10 Soft Towel

4.3.2. Procedure

Preparing process:

Before all, it is necessary to prepare the test conditions. Forming the workpieces are necessary as designed in the experiment. In the experiment it is to consider the conditions of lapping of different forms like convex and concave plates, and in order to obtain such surfaces a sandpaper has rolled around a concave or convex cylinder as shown in Figure 4-11.

Figure 4.11 Pre-forming of workpiece with a Turning machine

After preparing the surfaces and limiting the flatness of them by sequent flatness measurements, the down plate should be mounted on a nominally flat table so that later on, the apparatus is to work on it. It might be with the aim of sticker or improvised screws or whatever gives rigidity. After mounting the down plate, the upper plate is to be mounted on the upper gripper of the apparatus. Just like the previous it is to be taken into account that, the workpiece is to be rigid with respect to the holder.

Figure 4.12 Upper workpiece mounted on the gripper of apparatus

Making abrasive medium: Using appropriate abrasive is essential; in the experiment it is used Silicon Carbide because of its sphericity and available different grit sizes in the industry. Using low viscosity abrasive liquid makes easy abrasive penetration among two plates. In addition to Silicon Carbide, Aluminum Oxide has tested in some case studies but because of the low sphericity of it scratches the surface of the work and it is to be taken into account that whenever the surface quality of the work is important, use of aluminum oxide should be prevented. More, Diamond Paste is used and tested at the final stages of the tests. Because of good surface roughness of works that is obtainable with. Note that toothpaste has tiny abrasives in it and with special cares might be used as a finishing abrasive in the experiments (Figure 4-13). At each step of renewing of abrasive 1 gram of Silicon Carbide would be mixed in 1 cc of abrasive liquid and then put on the workpiece to continue on the experiment. And it would last about 5 minutes of matched piece lapping.

Lapping process: Before the lapping process starts, the human operator should adjust the weight of the system in order to tolerate its own weight.

Then applying desired weight on it and then adding the abrasive material on the down workpiece and putting the upper workpiece on it and randomly moving it. The lapping process is a long process has to be done with a patient human operator! During the lapping process of two workpieces matched on each other with the designed apparatus, the upper workpiece is to be moved randomly on the down plate. The operator should take care not to exceed the movement of the apparatus more than which the upper workpiece center get out of the down plates out perimeter.

Figure 4.13 Used abrasives during the experiments

During the process it is necessary to measure the flatness of the work material, so, it is to be separated from the apparatus and measure the flatness of it. After removing it from the device it has to be cleaned and washed perfectly and carefully to have precise measurements. An analogue dial indicator with 1 micron of resolution is used for measurements. In Figure 4-14 the method of measuring is shown.

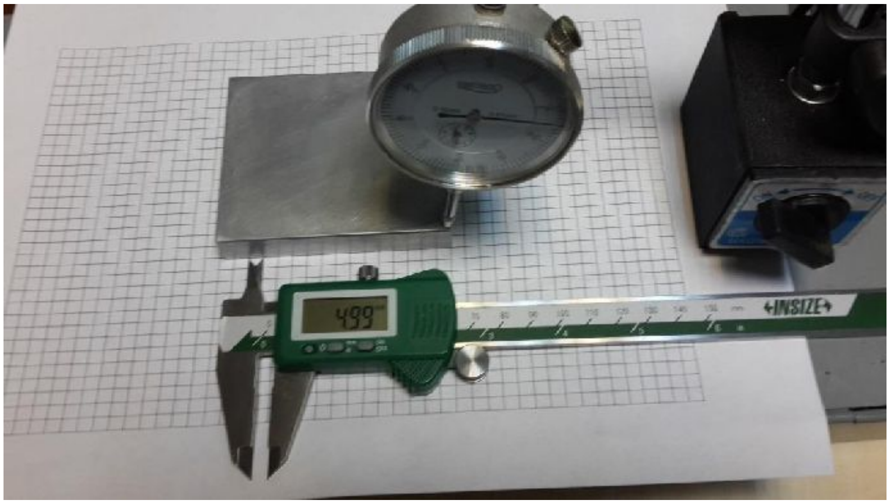

Figure 4.14 Measuring of flatness

To make the measuring process easy enough, an A4 paper is printed with 5 mm squares and the workpiece has put on it. With these squares in hand it is easy to move it and take notes of the measured heights.

To conclude, the process starts with mounting of the upper workpiece plate on the device and the down workpiece plate on a suitable flat surface. Putting the apparatus on the down workpiece it is to be adjusted for not putting extra load on the system. So the extra weight of the guide is to be held with springs. After adjusting the weights with springs, the desired weight will be added on the system. Then 1 gram of silicon carbide mixed in 1 cm^3 of water will be added to the surface of the upper workpiece as abrasive slurry and then starting the process. Several measuring should be done before and after measuring and also during the process. And finally, the process will stop when the desired flatness obtained.

4.4. Experimental Studies

In all experiments two pieces of different materials like granite stones, aluminum, and stainless still were lapped with 400, 600 and 800 grit size of Silicium Carbide abrasives in water and soap slurry, to wear out the imperfection of surface of granite then process completed with diamond paste with 1 micron ingredients in size. In all experiments the slurry is changed after five minutes of lapping. The experiments are done for two convex and two concave and two concave-convex match of workpiece.

4.4.1. Experiment-1; Two Granite Convex Plates

In this experiment the lapping was done by hand and it took about one and half hour of randomly moving the upper plate of Granite in order to wear out the in-contact areas with the down plate of Granite. Contact areas are mostly the center of plates at first steps of the process because the initial shape of plates are convex and were achieved via wearing of the corners of workpiece with sandpaper. Note that, final used sandpaper's grit number was 800. Material specifications are presented in Table 4-2 while operation characteristics are given in Table 4-3. The result of work is shown in Figure 4-15 that shows betterments of flatness in final works. It seems that, the middle of workpiece in Figure 4-16 were more exposed to wear than corners which was predicted and expected from modeling process discussed in section 3-5-1 (Table 4-4) briefly gives initial and final status of the workpiece before and after lapping.

Table 4.2 Material properties of granite stone

Material	Elastic Modulus	Poisson's Ratio	Density
Granite	40-60 G Pa	0.1-0.3	2700 kg/m^3

Table 4.3 Conditions of the test

Load	Abrasive	Abrasive Size	Charging Time	Velocity	Duration
14.7 N	Si C	23, 8 micron	5 min	0.3 m/s	90 min

Table 4.4 Flatness of upper and down plates

Flatness	Initial Flatness μm	Final Flatness μm
Upper Plate	66	13
Down Plate	55	10

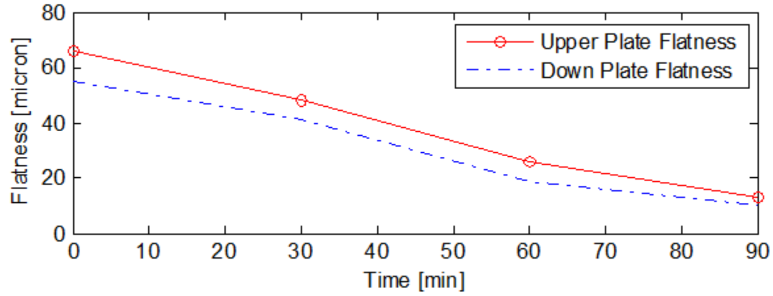

Figure 4.15 Flatness Progressfor two convex Granite plates

In the first 90 minutes of the process silicon carbide grit 400, has been used as abrasive and each 30 minutes the flatness were measured by using dial indicator after washing the workpiece with water; In the lapping process of two granite concave, plates the total process duration were about 90 minutes and the flatness procedure is shown in the figure above.

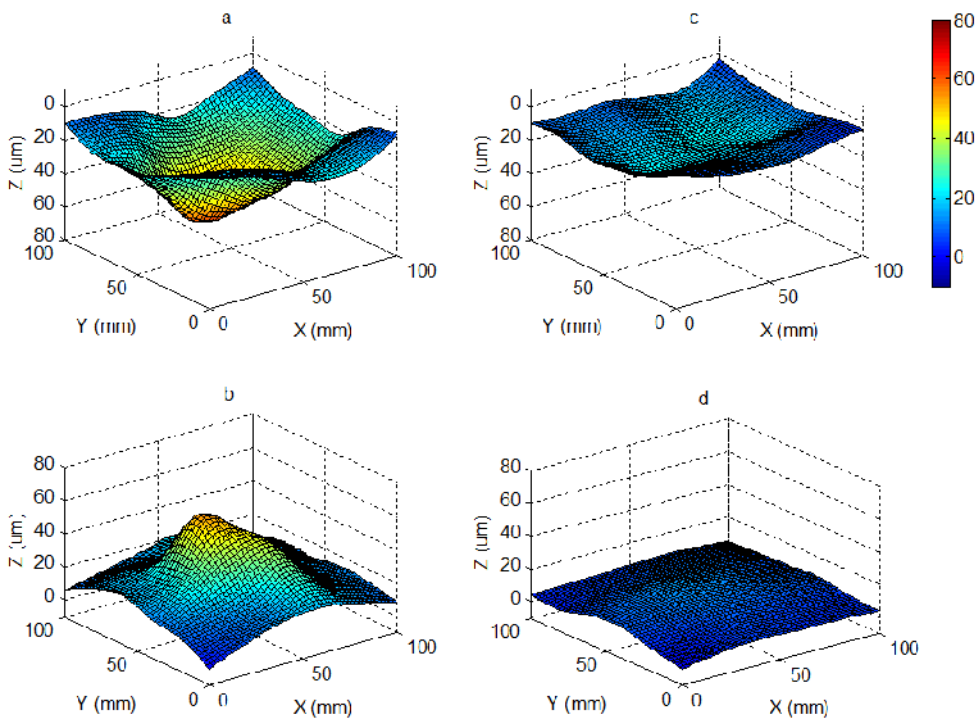

Figure 4.16 Two granite convex plates a) Initial form of Upper plate b) Initial form of Down plate c)Final form of Upper plate d) Final form of Down plate

4.4.2. Experiment-2; Two Granite Concave Plates

In this experiment two piece of granite plates lapped together in order to see the effect of matched piece lapping on the initial form of them. The pieces are 10 [cm] in length and width and 2 [cm] in thickness. Just like the previous mentioned experiment, the initial form was produced with hand and via using sandpaper. The material properties of the workpiece and the applied load on them during the operation are given in Table 4-2. Using 600 grit size Silicon Carbide abrasives the process took two hours where the normal force added to the plates was 19.6 N (Table 4-5).

Table 4.5 Test conditions of two concave granite experiment

Load	Abrasive	Abrasive Size	Charging Time	Velocity	Duration
19.6 N	Si C	23, 8 micron	5 min	0.3 m/s	2 hours

In this experiment the lapping was done by hand and it took about two hours of randomly moving the upper plate in order to wear out the in-contact areas. Contact areas are mostly the corners of plates at first steps of the process because the initial shape of plates were concave and were achieved via wearing of the centers of workpiece with sandpaper. Final used sandpaper's grit number was 2000. The result of work is shown in Figure 4-17 that shows betterments of flatness in final works Table 4-6. It seems that, the corners of workpiece were more exposed to wear than centers, which is in contact with predicted and expected from modeling process discussed in section 3-5-2.

Table 4.6 Flatness of initial and final plates

Flatness	Initial Flatness [μm]	Final Flatness [μm]
Upper Plate	90	15
Down Plate	83	16

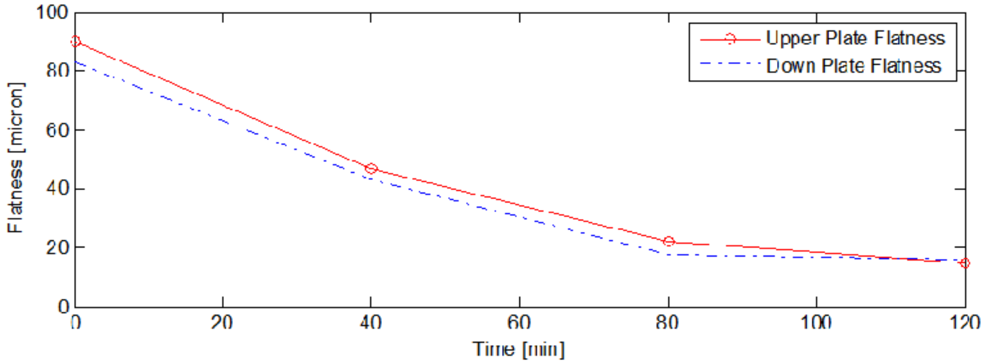

Figure 4.17 Flatness Progress of concave granite lapping

In the previous experiment two convex plates were studied and betterments in the flatness results were obtained so that the flatness of both plates reduced about eighty percent. In this experiment two concave plates are tried to be flatten. The initial form demonstration of the plates are shown in Figure 5-18 a and b. The flatness of the plates are improved in two hours and reduced to about 15 micrometers Figure 5-18 c and d.

4.4.3. Experiment 3; Two Aluminum Convex Plates

In the previous experiments around flatness two pre-prepared granite plates matched piece lapped with silicon carbide abrasive among and specific load above that resulted in better flatness at the end. Granite is a hard material with low density, in the field of interest of scientists however, granite is an impure original material formed in a complex geological reaction and finally extracted from nature. In this experiment Aluminum is studied as another main material in industry to see the manner of, in the case of flatness.

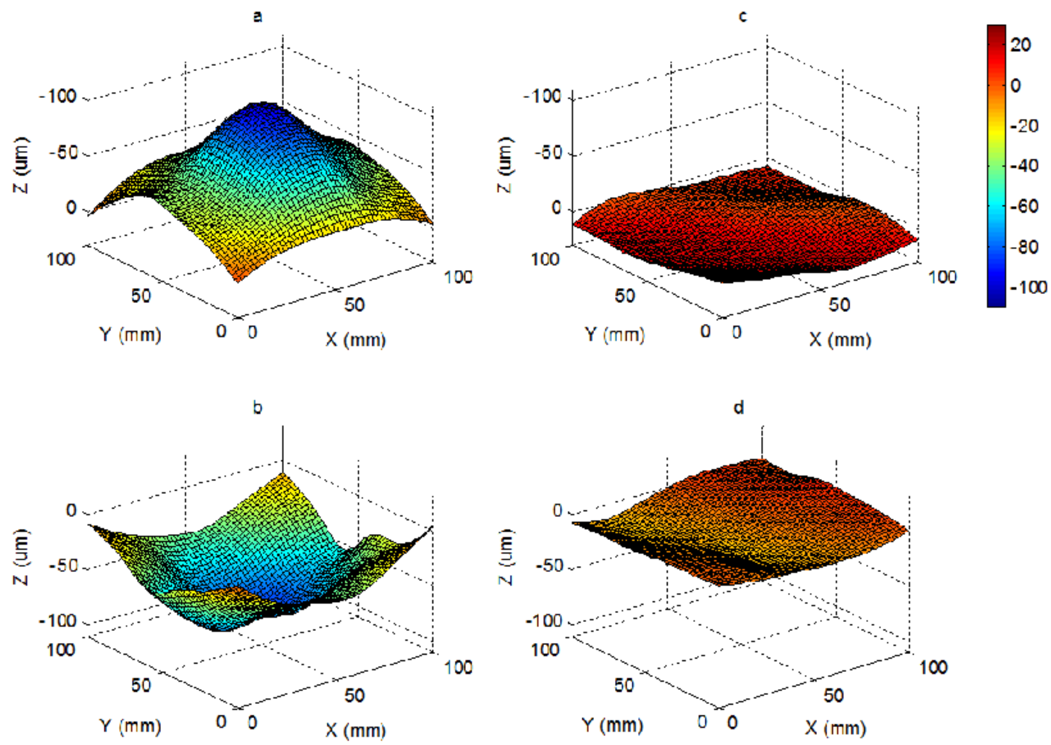

Figure 4.18 Two granite concave plates; a) Initial form of Upper plate b) Initial form of Down plate c)Final form of Upper plate d) Final form of Down plate

Just like the former cases, two square plates of AL 6063-T6 pre-prepared in form of convex with sandpaper and lapped with 600 grit of silicon carbide abrasive to see the final form of work. Table 4-7 shows the material properties of the AL 6063-T6.

Table 4.7 Material properties of Aluminum

Material	Elastic Modulus	Poisson's Ratio	Density	Hardness
AL 6063-T6	68.9 G Pa	0.33	2700 kg/m^3	73 Brinell

In Table 4-8 testing conditions are given. 8 micron Si C abrasives in water as among fluid is used to wear out the imperfections of the surfaces under 19.6 N of load and changed each 5 minutes. The moving speed is about 0.2 m/s.

Table 4.8 Test conditions of experiment 3

Load	Abrasive	Abrasive Size	Charging Time	Velocity	Duration
19.6 N	Si C	8 micron	5 min	0.2 m/s	1.5 hours

Table 4-9 briefly reports the betterment in the flatness of the upper plate and down plate in the matched piece lapping of the AL 6063- T6 in about 90 minutes. Due to Table 4-9

Initial flatness of upper plate is 64 micron and final flatness is 14 micrometers where the initial flatness of down plate is 59 microns it has improved to 12 microns. A more detailed procedure is shown in Figure 4-19 the flatness is measured each 15 minutes with dial indicator and it has been seen that the flatness is gradually declined to about 14 micrometers for upper plate and 12 micrometers for down plate. In Figure 4-20 a graphical demonstration of initial and final forms of plates are given to compare the result of matched piece lapping process on aluminum plates.

Table 4.9 Initial and final flatness of two convex aluminum

Flatness	Initial Flatness [μm]	Final Flatness [μm]
Upper Plate	64	14
Down Plate	59	12

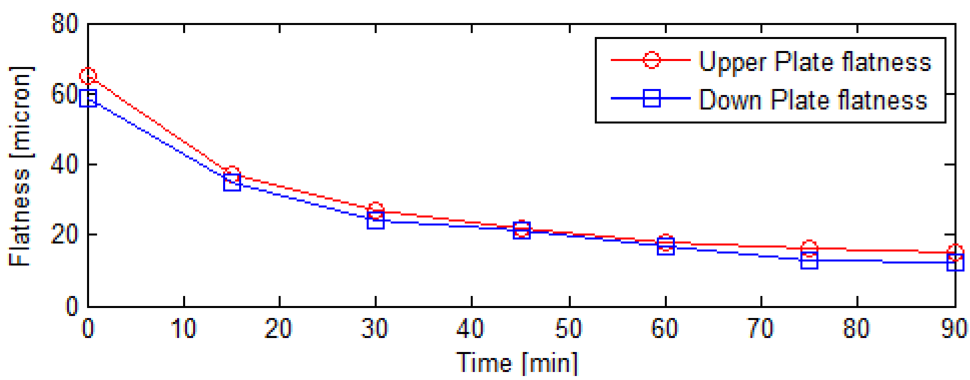

Figure 4.19 Aluminum Convex Flatness Progress

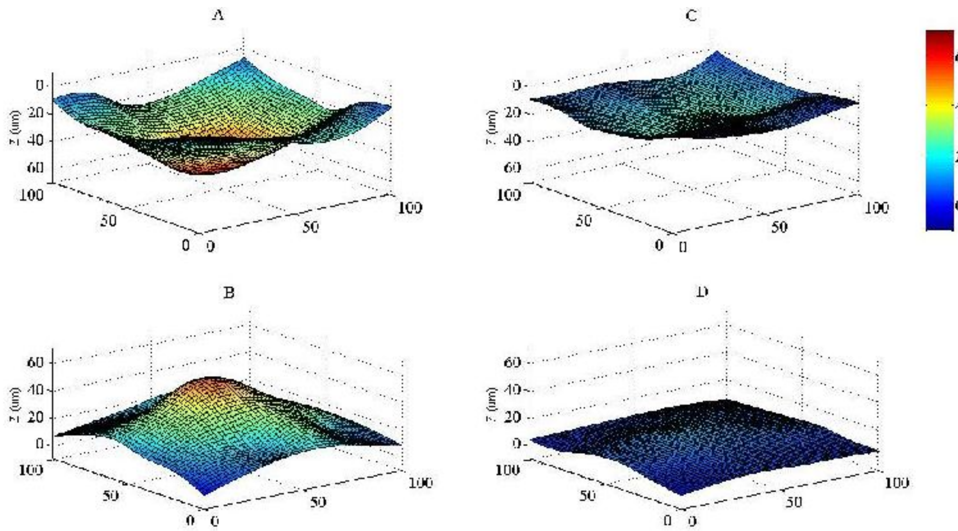

Figure 4.20 Two Aluminum convex plates; a) Initial form of Upper plate b) Initial form of Down plate c) Final form of Upper plate d) Final form of Down plate

4.4.4. Experiment-4; Two Aluminum Concave Plates

In order to see the effect of the matched piece lapping process on the concave surfaces of aluminum, two plates with concave form prepared and lapped together. The material properties and working conditions are as same as the two aluminum convex plates (Table 4-7 andTable 4-8). Table 4-10 includes initial and final flatness of workpiece briefly. Just like the previous test, abrasive used in this experiment is Silicon carbide grit 400, completing the process with abrasive grit 600, 800 and diamond paste, to achieve best surface finish.

Table 4.10 Initial and final flatness of two concave aluminum

Flatness	Initial Flatness [μm]	Final Flatness [μm]
Upper Plate	70	11
Down Plate	67	14

The flatness improvement is shown in Figure 4-21. The flatness is gradually reduces and converges to about 11 and 14 micrometers at the end of the process. Again every 15 minutes of lapping the flatness is measured via dial indicator. The whole process took about one and half hour in addition to a finishing process to obtain a good surface finish with diamond paste.

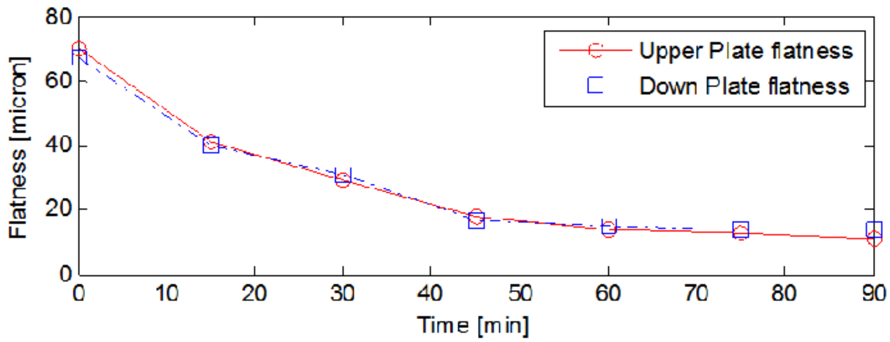

Figure 4.21 Aluminum Concave Flatness Progress

In Figure 4-22 a mathematical demonstration of the initial workpiece before lapping and final work after lapping is shown from a to d. The color bar at right side of the figure displays the height of the initial and final status of workpiece.

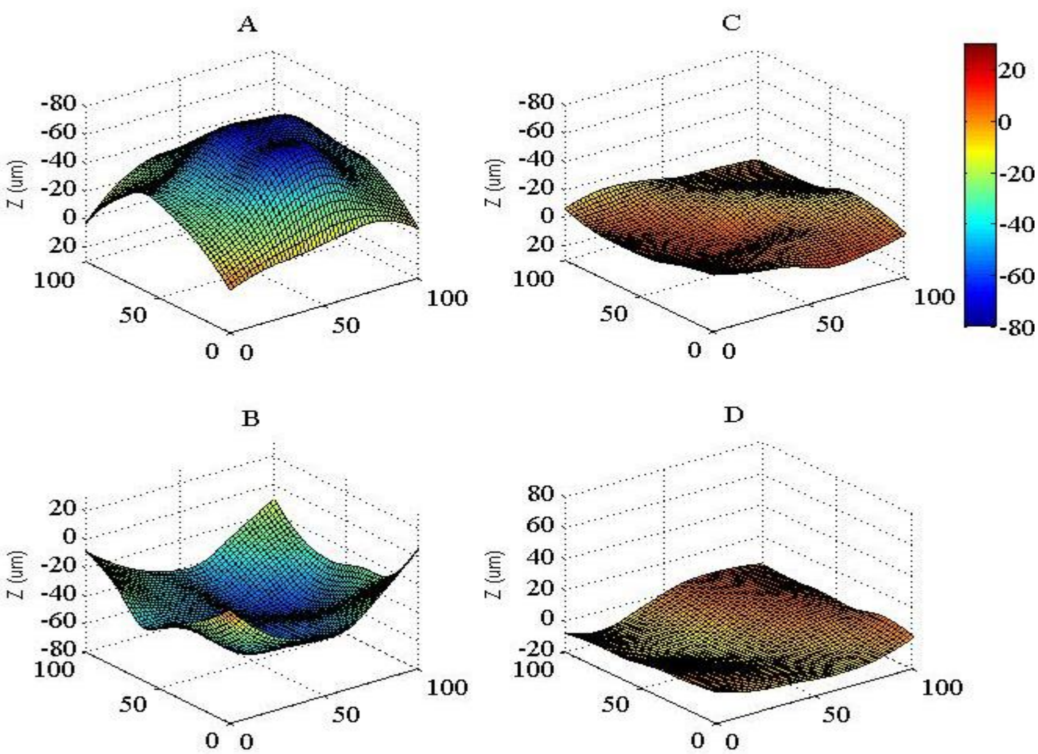

Figure 4.22 Two Aluminum concave plates; a) Initial form of Upper plate b) Initial form of Down plate c) Final form of Upper plate d) Final form of Down plate

4.4.5. Experiment-5; Two AISI 1040 Convex Plates

AISI carbon steel is inexpensive well known material with good physical properties like strength and hardness after hardening and heat treatment operations followed by tempering and quenching. Table 4-11 includes the material properties of quenched AISI 1040. As before, two square works are prepared with sandpaper to form it as it is needed in shape of convex and concave forms.

Table 4.11 Material properties of quenched AISI 1040

Material	Elastic Modulus	Poisson's Ratio	Density	Hardness
AISI 1040	200 G Pa	0.27- 0.3	7845 kg/m^3	149 Brinell

In Table 4-12, working conditions of Matched piece lapping of quenched AISI 1040 are presented. 3 kilogram force is applied to the upper workpiece to lap each other with SiC abrasive among. The abrasive slurry is changed each 10 minutes and during the 3.5 hours of the process, the flatness is measured in each 30 minutes.

Table 4.12 Working Conditions of Matched Piece Lapping of quenched AISI 1040

Load	Abrasive	Abrasive Size	Charging Time	Velocity	Duration
29.4	Si C	23 micron	10 min	0.3 m/s	3.5 hours

60 micrometers is the flatness of both upper and down plates of workpiece before lapping which after lapping a very good flatness of about 10 micrometer is obtained (Table 4-13). The flatness progress for AISI 1040 convex workpiece plates are show in Figure 4-23.

Table 4.13 Initial and Final Flatness of Two Convex Plates of quenched AISI 1040

Flatness	Initial Flatness [μm]	Final Flatness [μm]
Upper Plate	60	11
Down Plate	60	9

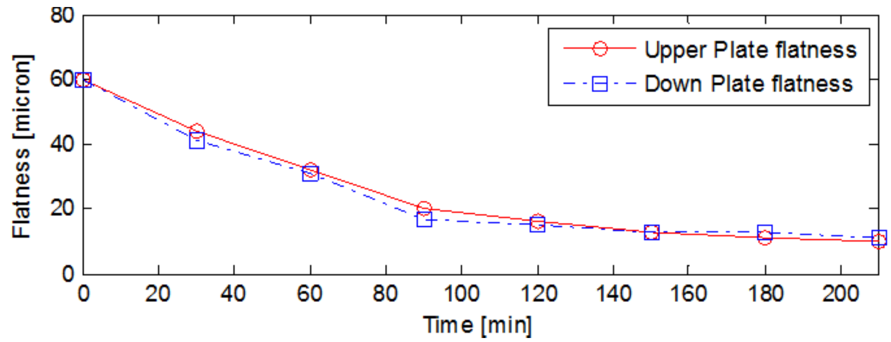

Figure 4.23 AISI 1040 Concave Flatness Progress

4.4.6. Experiment-6; Two AISI 1040 Concave Plates

With the same operating conditions of section 4-4-5, given in Table 4-11 and Table 4-12 and with preparing two concave workpiece with flatness of 55 micro meters the test has done to obtain a better flatness. In Table 4-13 and Table 4-14 initial and final conditions of workpiece is presented.

Table 4.14 Initial and Final Flatness of Two Concave Plates of quenched AISI 1040

Flatness	Initial Flatness [μm]	Final Flatness [μm]
Upper Plate	55	10
Down Plate	55	14

In Figure 4-24 a flatness convergence to 10 micrometers is seen that reduces from 55 micrometers. In this experiment measurements are done each 30 minutes and

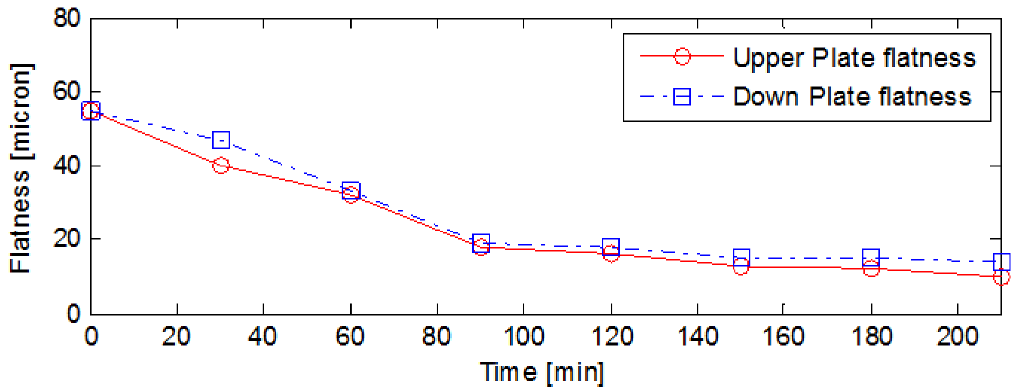

Figure 4.24 Flatness progress of concave AISI 1040 lapping

4.5. Individual Experiments

Abrasives as undefined edge cutting tools are playing an important role in matched-piece lapping process. During the experiments very important effect of abrasives on the procedure was obviously feeling. In the process two kind of abrasives were used; *Silicon Carbide* and *Aluminum Oxide.* Before lapping of granite as a brittle material it was tried to lap aluminum as a ductile material. Ductile materials are open to have superficial plastic flow under loads applied from edges of abrasives above. Matched-piece lapping of aluminum with *Alumina (Aluminum Oxide),* gives severe results in surface roughness of aluminum workpiece. Also it affects the process negatively because large amounts lateral forces during lapping so that two workpiece behaves as match of two welded-like parts! However when using *Silicium Carbide* there is no problem in sticking of plates and the process goes well. In case of using *alumina,* when the operator tries to separate the workpiece plates with lateral forces it will scratch the surface severely. This experiment was repeated with different medium lubricants such as:

- Water
- Water and soap
- Motor oil
- Liquid grease

But the result is the same. The problem seems to because of shape of abrasives. *Alumina* Particles are plate like abrasives and embed to the soft surface of the aluminum workpiece; as the other surface is also aluminum, so the other free edge of *alumina* tries to embed to the surface of other workpiece and the procedure results in pinning of two surfaces. Using *Silicium Carbide* supports the claim because the shapes of *Silicium Carbide* abrasives are more rounded than *alumina* abrasives. So they can easily roll under the applied load via moving the upper plate however by applying more forces, it tends to be embed and do the same of *alumina* abrasives.

The second experience was about the effect of applied load on the abrasive wear out. The force above the abrasives makes them to embed to the surface and plastically deforms the surface of workpiece. Abrasives are harder than the workpiece however; if the force exceeds a certain amount it will crash the abrasive also; no doubt that at this condition the work is also deformed plastically. In case of lapping aluminum via *Silicium Carbide*, if the load exceeds a certain amount but still remains less than embedding abrasives to the work plate, after just few minutes lateral forces decrease and continuing will be Ineffective. It is said in the literature that is because of blunting of edges. Blunt edges are not doing the cutting effect as well as sharp ones and so it will result in decrease in material removal rate.

4.6. Closure

In this chapter, an experiment is designed to study the effect of initial form of workpiece plates on the final form result. In order to perform the experiment, an apparatus is needed to perform the matched piece lapping with random movements and under constant load. The best design is approved from three design concepts and manufactured. Then the experiments are done on three different materials: Granite stone, aluminum and quenched AISI 1040. The strategy is the same with the modeling section. Two convex plates and two concave plates are studied. In all studies, betterments in flatness are attained in both upper and down plates.

CHAPTER 5

CONCLUSIONS AND FUTURE WORKS

5.1. Conclusions

In this thesis, in spite of what has been done practically in the past, which consider the operation of lapping as an art instead of a science, it has been tried to study the affective parameters on the result of lapping scientifically. First the literature is searched to understand the mechanism of wear process and study the similar material removal processes such as grinding, scrapping, machine lapping and polishing. Several modeling and experiments are available in the literature that, studies material removal rate and affecting parameters like applied load, speed of process, abrasives sizes, abrasive hardness, abrasive sharpness, material properties such as hardness, brittleness, toughness, ductility of material and other properties. The main focus area of the literature is on effect of parameters on material removal rate and flatness of final product is rarely considered.

The main goal of this document is to see the effect of parameters on final geometric and dimensioning tolerances. Flatness is studied as a study case here and effects of initial form is studied. First of a wear model is designed for the process of lapping in one and two dimensional case. Lots of initial forms such as two convex matched-piece lapping plate, two concave matched-piece lapping plates, two convex-concave matched-piece lapping plate, and combined large wavy surfaces under lapping with normal convex or concave surface are studied. Except for the case of convex-concave combination of plates in other cases of studies, betterments have been seen in flatness firstly in the modeling and finally improved with experiments.

In order to study the effect of several parameters on the final geometry an experiment designed and implemented with an precision apparatus, designed and manufactured during the studies to be able of controlling the applied load on the plates and desired degree of freedoms. The experiment was based on the random movement of human operator performed on the workpiece plates. The random movements cause homogeneous distribution of contacts between abrasives and the surface of workpieces. Workpieces are prepared and formed manually in convex and concave forms and the lapped to obtain the results of randomly lapping of match of pieces. Experiments proved the modeling results in case of final shape and form. However a vast area is opened for scientists to study the other affective parameters on geometry tolerances which are crucial in precision engineering design and manufacturing.

5.2. Future Works

As a huge gap is in the literature in the case of precision manufacturing methods and ways, lots of trends are open to study and examine. May be this trend can be categorized in two case: modeling and experiments. As the modeling and simulation of the processes is almost the cheapest way of studying it is better to start with modeling in this highly expensive precision case studies. For example in the modeling subject, different matched piece size of workpieces can be studied. Also studying the moving paths and contact density of peaks of surfaces might be important because if the contact density in a specific area would be high that area will be more exposed to wear; in addition, it might prevents the other areas of surface from having distributed contact density. The other bunch of modeling might be modeling of matched-piece lapping of V-shape and cylindrical profiles which are very common in the industry of high precision and ultra-high precision machine manufacturing. In experimental workings, manufacturing an automatic apparatus device to continue experiments with numerically controlled machines might be a case of study. Also matched piece lapping of cylindrical and V shape rails would have great scientific outcomes. At the end, combination of simulations and experiments and forwarding both of them in parallel will speed up the studying process to have better and better products with more precise machines.

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APPENDIX A

ENGINEERING DRAWINGS

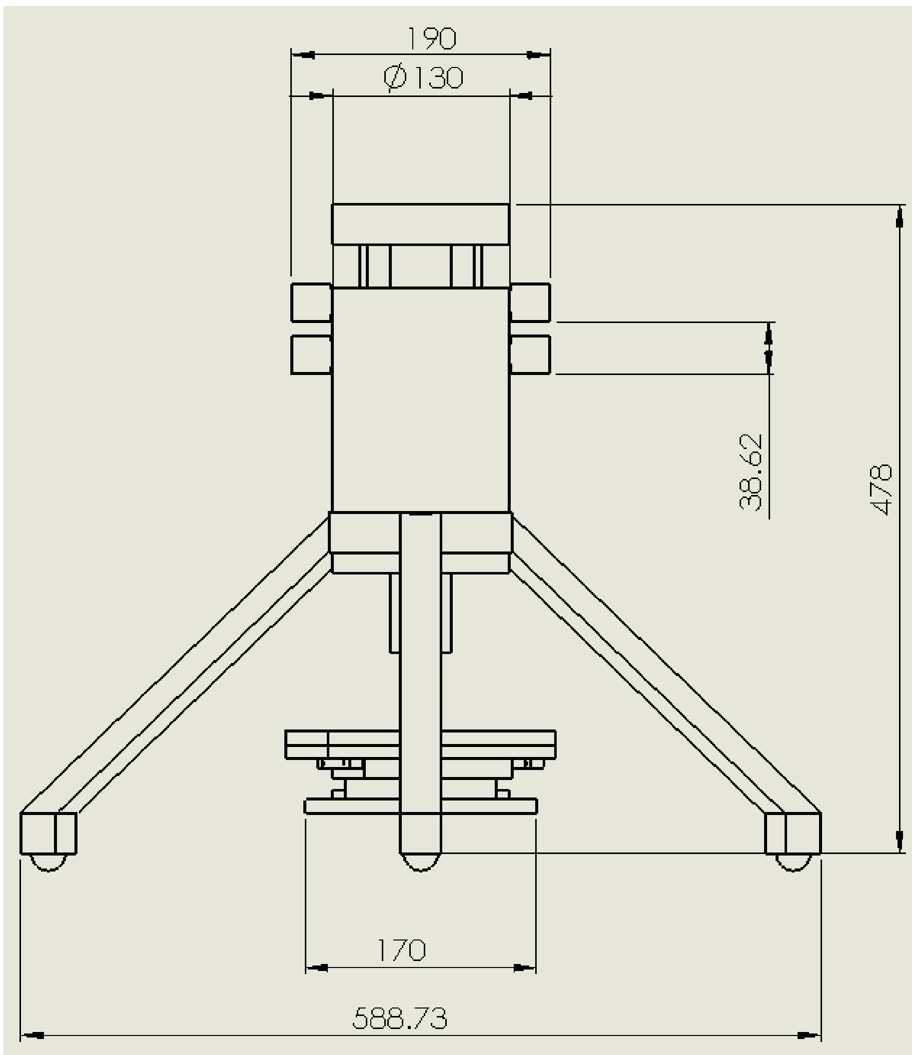

Figure A-1 Main assembly

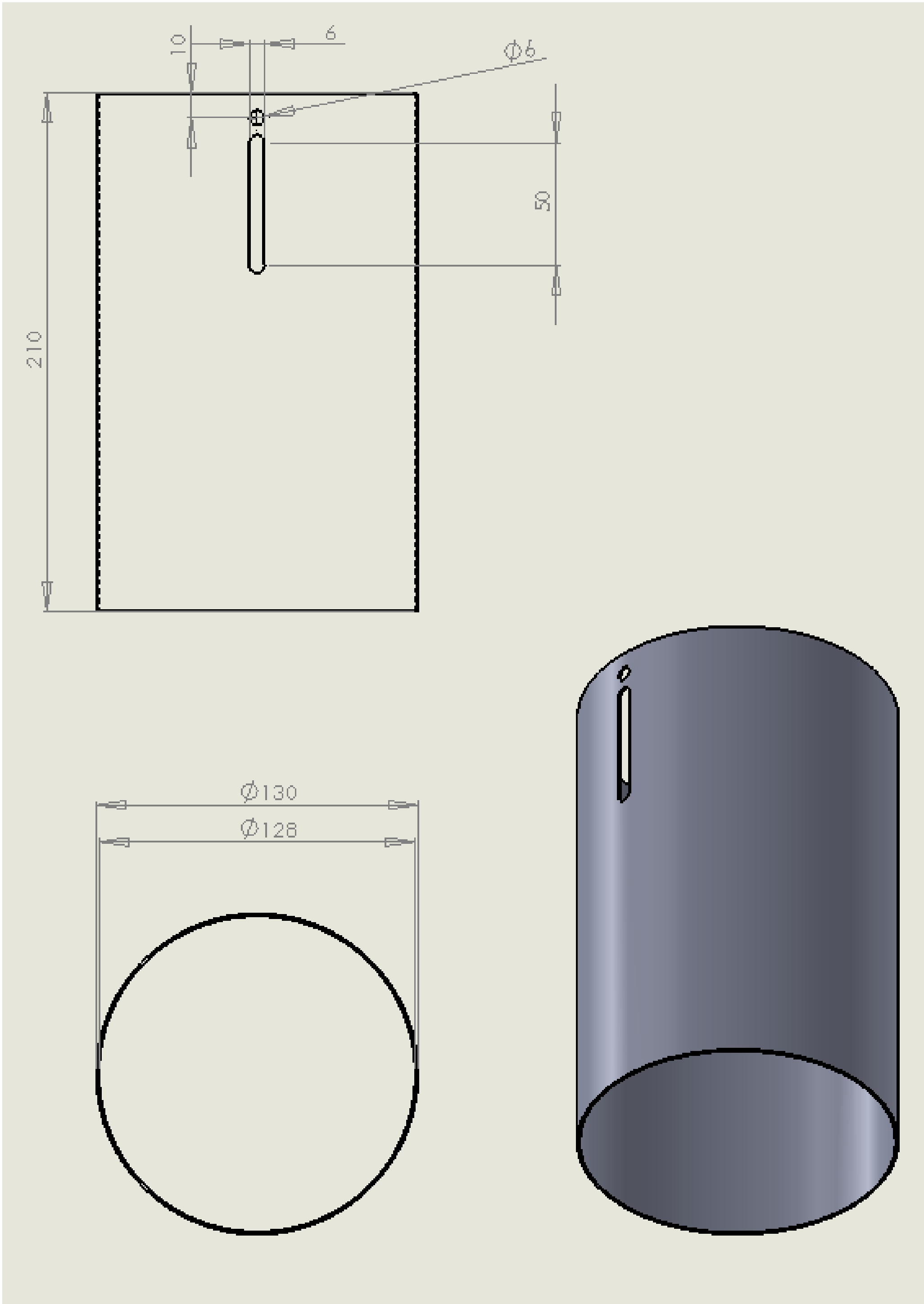

Figure A-2 Main body

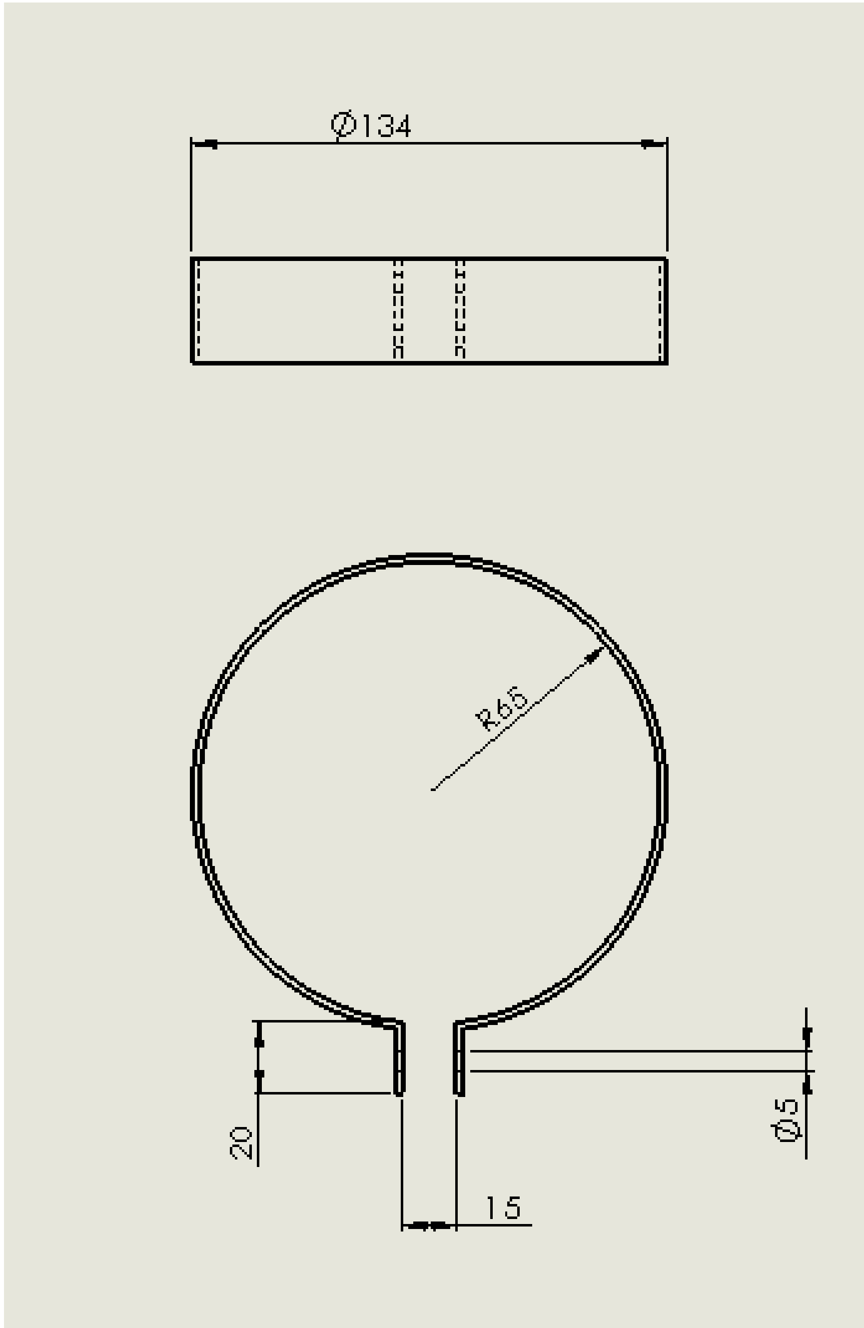

Figure A-3 Body holder

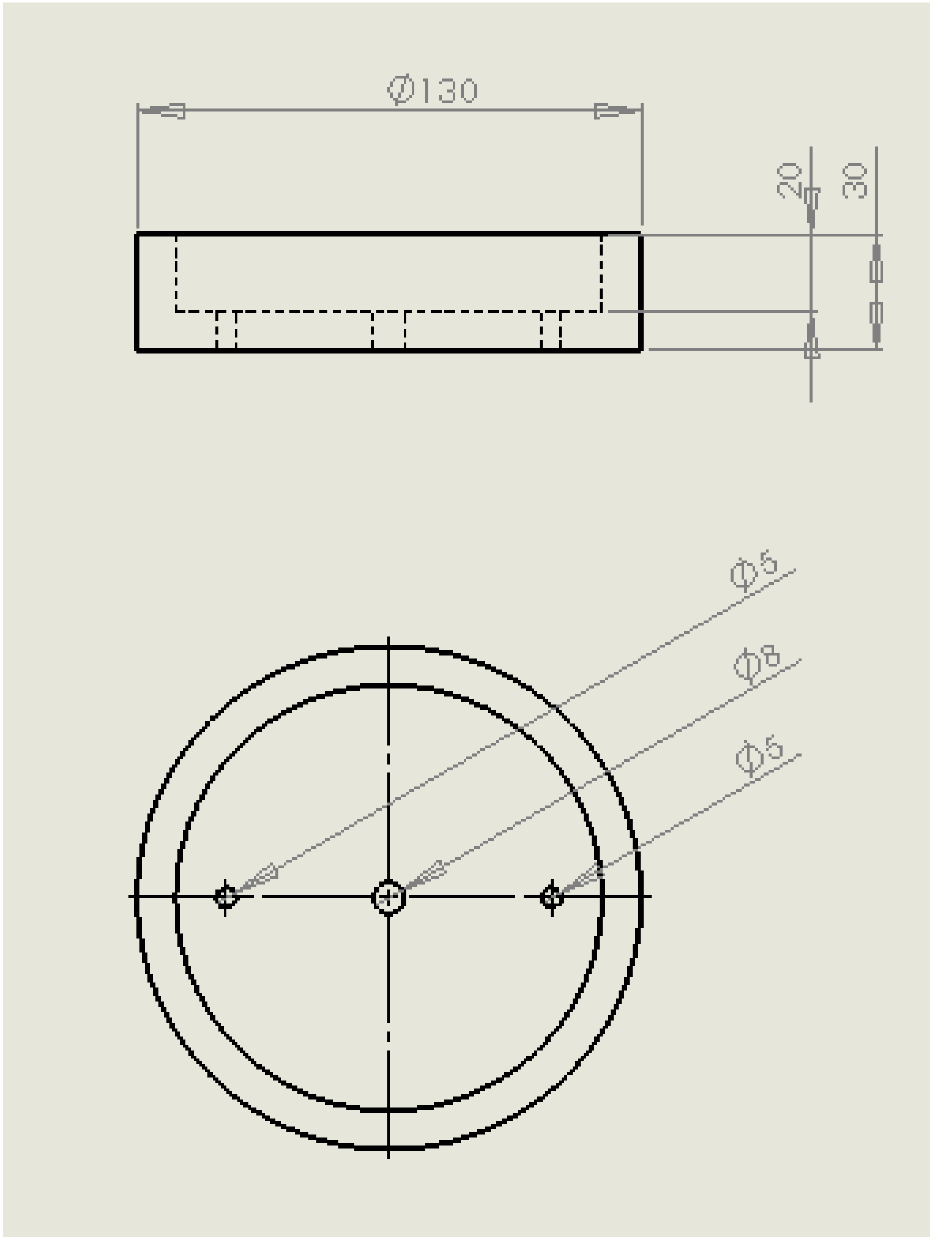

Figure A-4 Weight plate

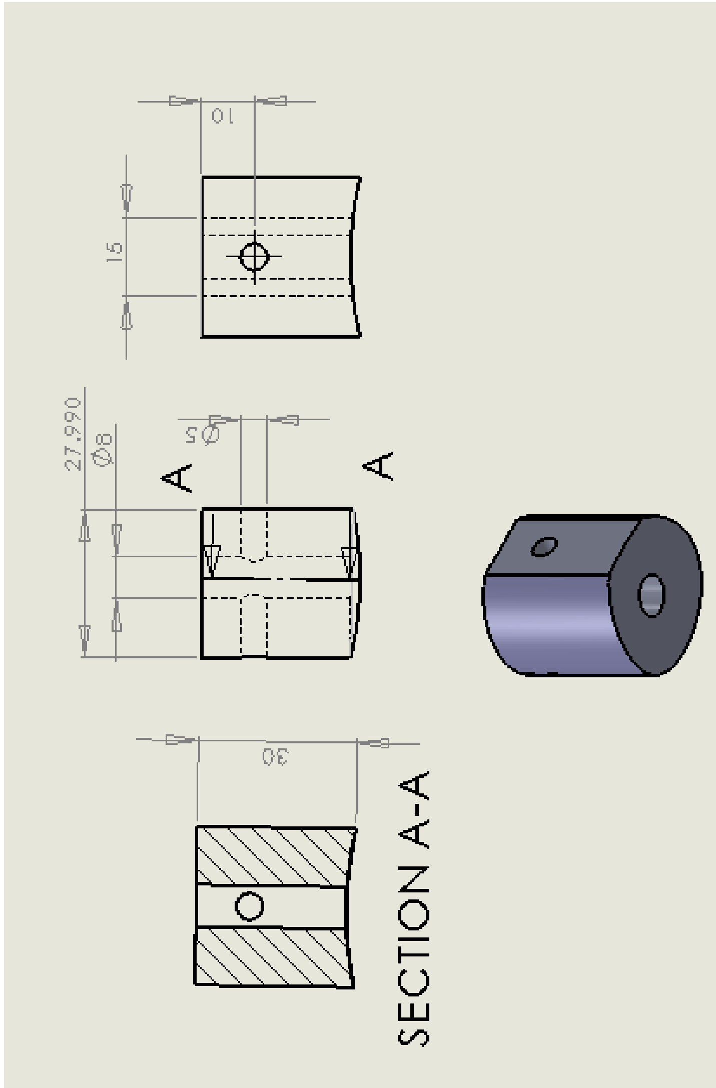

Figure A-5 Elevator part

APPENDIX B

MATLAB CODES

Main Codes:

```
clear variables
close all
clc
m = 10; n = 10;
m3=10;   n3=10;
UpperLimit = 4;      DownLimit = -4;
ResMinVal=-5;        ResMaxVal=ResMinVal;
Moment_limit=5;
FL=51;      Endtime= 400;
up_wear_coeff=0.3;      down_wear_coeff=0.3;
gama=pi/16;
t=zeros(1,Endtime); tt=0;    du=1;   dv=.6; dt=1;
V=1;
% set bottom surface parameter
[x,y]=meshgrid(-m:m,-n:n);
z0 = 0;
surf_z = (1*cos((x + y)/7))+1*cos((y-x)/7); % .2*cos((x -
y)/5))
z = (1)*(z0 + surf_z);
x_old=x; y_old=y; z_old=z;
% set top surface parameter, initially
[u,v]=meshgrid(-m3:m3,-n3:n3);
w0 = 0;
surf_w = -(1*cos((u+v)/7)+1*cos((v-u)/7));
w = 1*(w0 + surf_w);
u_old=u; v_old=v;w_old=w;
w;
% [u,v,w]=HTM (u,v,w,0,0,0,1,1,0);
ZERO=zeros (2*m+1,2*m+1);
idx=0;
while tt< Endtime
    tt=tt+dt;
    idx=idx+1;
```

```
    if      u(m3+1,m3+1)>UpperLimit
        du=-rand(1,1);
        dv=sign(dv)*(V.^2-du.^2).^.5;
        uu=u(m3+1,m3+1); vv=v(m3+1,m3+1);
        [u,v,w] = HTM(u,v,w,0,0,0, -u(m3+1,m3+1) , -
v(m3+1,m3+1) , 0 );
        [u,v,w] = HTM(u,v,w,0,0,gama, 0,0,0);
        [u,v,w] = HTM(u,v,w,0,0,0, uu,vv,0);
    elseif u(m3+1,m3+1)<DownLimit
        du=rand(1,1);
        dv=sign(dv)*(V.^2-du.^2).^.5;
        uu=u(m3+1,m3+1); vv=v(m3+1,m3+1);
        [u,v,w] = HTM(u,v,w,0,0,0, -u(m3+1,m3+1) , -
v(m3+1,m3+1) , 0 );
        [u,v,w] = HTM(u,v,w,0,0,gama, 0,0,0);
        [u,v,w] = HTM(u,v,w,0,0,0, uu,vv,0);
    else
    end
    if v(m3+1,m3+1)>UpperLimit
        dv=-rand(1,1);
        du=sign(du)*(V.^2-dv.^2).^.5;
        uu=u(m3+1,m3+1); vv=v(m3+1,m3+1);
        [u,v,w] = HTM(u,v,w,0,0,0, -uu , -vv , 0 );
        [u,v,w] = HTM(u,v,w,0,0,gama, 0,0,0);
        [u,v,w] = HTM(u,v,w,0,0,0, uu,vv,0);
    elseif v(m3+1,m3+1)<= DownLimit
        dv=rand(1,1);
        du=sign(du)*(V.^2-dv.^2).^.5;
        uu=u(m3+1,m3+1); vv=v(m3+1,m3+1);
        [u,v,w] = HTM(u,v,w,0,0,0, -u(m3+1,m3+1) , -
v(m3+1,m3+1) , 0 );
        [u,v,w] = HTM(u,v,w,0,0,gama, 0,0,0);
        [u,v,w] = HTM(u,v,w,0,0,0, uu,vv,0);
    else
    end
    %   MOVEMENT
    [u,v,w]=HTM(u,v,w,0,0,0, du*dt,dv*dt,0);
    [x,y,z,u,v,w]=Seat( x, y, z, u, v, w+1,
FL,m,n,m3,n3,Moment_limit);
    cla
    mesh(u,v,w); hold on; mesh(x,y,z); hold on ; %mesh
(u,v,dist -1);
    axis([-15 15 -15 15 -5 5])
    pause(.01)
    % WEAR Mechanism
    % Projection of upper plate on the down plate
    projw2xy=griddata(u,v,w,x,y);
    projw2xy=SubstituteNaN(projw2xy,ZERO);
    dist_xy=z-projw2xy;
```

```
    dist_xy(dist_xy<0)=0;
    % Projection of the Down plate on the upper plate
    projz2uv = griddata( x,y,z,u,v);
    projz2uv = SubstituteNaN(projz2uv,ZERO);
    dist_uv =   projz2uv - w    ;
    dist_uv(dist_uv<0)=0;
    % In this part we can contribute different wear
mechanisms
    % By the way for now, we just use the simple method
    % Wear of the upper plate and down plate
    F_uv = find (dist_uv);
    w(F_uv)= w(F_uv ) + up_wear_coeff * dist_uv (F_uv);
    F_xy = find(z-dist_xy);
    z(F_xy) = z(F_xy) - down_wear_coeff * dist_xy(F_xy) ;
    % Flatness Requirements for upper WP
    [W]=Reed( x, y, 0*z, u-u(m3+1,m3+1),v-v(m3+1,m3+1) ,
w+1, FL,m,n,m3,n3,Moment_limit);
    %      [XX,YY,ZZ,U,V,W]=Reed( x,y, 0*z, UU, VV, W+.1,
FL,m,n);
    up_flatness(idx)=max(max(W))-min(min(W));
    down_flatness(idx)=max(max(z))-min(min(z));
end

f=figure('Name','Flatness of workpieces');
subplot(2,1,1)
plot(up_flatness);
title('Flatness of Upper workpiece');
xlabel('Time  x10 [s]')
ylabel('Flatness x10 [\mum]')
subplot(2,1,2)
plot(down_flatness);
title('Flatness of Down workpiece');
xlabel('Time  x10 [s]')
ylabel('Flatness x10 [\mum]')
figure, surf(x,y,(1/3)*(z0 + surf_z))
figure, surf(x,y,z)
figure, surf(u,v,w)
figure, surf(u,v,surf_w)
[W]=Reed( x, y, 0*z, u-u(m3+1,m3+1),v-v(m3+1,m3+1) , w+1,
FL,m,n,m3,n3,Moment_limit);
DrawSimulationResult(x_old,y_old,z_old,u_old,v_old,w_old,
x,y,z,u-u(m3+1,m3+1),v-v(m3+1,m3+1),W,-5,5)
```

Homogeneous Transformation Matrix Function:

```
function [ x_n, y_n, z_n ] = HTM( x, y, z, phi, theta,
psi, dx, dy, dz)
% This function generates homogenous transform for given
meshgrid data.
```

```
% phi, theta and psi represent rotation about X, Y and Z
axes in radian,
% respectively. dx, dy and dz represents translation
along X , Y and Z
% axes, respectively. Note that, number of rows and
columns  are identical
% for x, y and z.

th1=phi;
th2=theta;
th3=psi;

R=[ cos(th3)*cos(th2) cos(th3)*sin(th2)*sin(th1)-
sin(th3)*cos(th1)
cos(th3)*sin(th2)*cos(th1)+sin(th3)*sin(th1) dx; ...
    sin(th3)*cos(th2)
sin(th3)*sin(th2)*sin(th1)+cos(th3)*cos(th1)
sin(th3)*sin(th2)*cos(th1)-cos(th3)*sin(th1) dy; ...
    -sin(th2)          cos(th2)*sin(th1)
cos(th2)*cos(th1)                            dz; ...
    0                 0
0                                            1];

[r,c]=size(x);
NumberOfElement = r*c;
x_=reshape(x,1,NumberOfElement);
y_=reshape(y,1,NumberOfElement);
z_=reshape(z,1,NumberOfElement);
LastRow=ones(1,NumberOfElement);

T_ = R*[x_ ;y_ ;z_;LastRow];

x_n= reshape(T_(1,:),r,c);
y_n= reshape(T_(2,:),r,c);
z_n= reshape(T_(3,:),r,c);

end
```

Force and Momentum Function:

```
function [W] = Reed( x, y, z, u, v, w,
FL,m,n,m3,n3,Moment_limit)
% format('short')

ZERO=zeros (2*m3+1,2*n3+1);
Mux=ZERO;Muy=ZERO;
Ones=ones(2*m+1,2*n+1);
SMxTot = 0;
SMyTot = 0;
Ang_inc=pi/50000;
```

```
%%%%%  lowering of the surface to make contact
%       Calculation of summation of contact point
distances
%       in order to multiply to the spring constant

%       First find the contacted point
% ww = w;
Projw2xy=griddata(u,v,w,x,y,'linear');
Projw2xy= SubstituteNaN(Projw2xy, 100.*Ones);

% % % Projw2xy= SubstituteNaN(Projw2xy, ZERO);

if (isnan(Projw2xy))
    F
end
d = min(min(Projw2xy - z));
[u,v,w]=HTM (u,v,w,0,0,0,0,0,-d);
D=0;
F=FL*.3;    %initial tolerated force
d=.01;
stepp = 0;
while (F < FL)
    if (F>FL)
        F
    end
    [u,v,w]=HTM (u,v,w,0,0,0,0,0,-D);


    projz2uv= griddata(x,y,z,u,v,'linear');

    projz2uv= SubstituteNaN(projz2uv, ZERO);

    %       negative magnetiutes are not in contact

    dist=projz2uv-w;
    dist= SubstituteNaN(dist, -100.*Ones);
    dist(dist<0)=0;
    F=sum(sum(dist))*10;

    if (F>FL)
        F
    end

    %%%% Test of SMx

    [u,v,w]=HTM (u,v,w,0,0,0,0,0,0);
    SMx=10; SMy=SMx;
    if F>.7*FL
```

```
        while SMx>Moment_limit ||SMx<-Moment_limit ||
SMy>Moment_limit ||SMy<-Moment_limit

            for i=1:2*m3+1
                for j=1:2*n3+1
                    Mux(i,j)=dist(i,j)* (v(i,j)-
v(m3+1,m3+1));
                end
            end

            for i=1:2*m3+1
                for j=1:2*n3+1
                    Muy(i,j)=dist(i,j)* (u(i,j)-
u(m3+1,m3+1));
                end
            end

            SMx=sum(sum(Mux));
            SMy=sum(sum(Muy));

            [u,v,w]=HTM (u,v,w,0,0,0,-u(m3+1,n3+1),-
v(m3+1,n3+1),0);
            [u,v,w]=HTM (u,v,w,sign(SMx)*Ang_inc,-
sign(SMy)*Ang_inc,0,0,0,0);
            [u,v,w]=HTM
(u,v,w,0,0,0,u(m3+1,n3+1),v(m3+1,n3+1),0);

            % new line
            SMxTot = SMxTot + sign(SMx)*Ang_inc ;
            SMyTot = SMyTot + -sign(SMy)*Ang_inc;
            %
            if ((abs(SMxTot) > pi/4) || (abs(SMyTot) >
pi/4000) )
                F
            end
            dist=projz2uv-w;
            dist= SubstituteNaN(dist, -100.*Ones);
            dist(dist<0)=0;

        end
    end
    [u,v,w]=HTM (u,v,w,0,0,0,0,0,0);


    [u,v,w]=HTM (u,v,w,0,0,0,0,0,D);
    D=D-sign(F-FL)*d;

end
```

```
SMxTot
SMyTot

[u,v,w]=HTM (u,v,w,0,0,0,0,0,-D);

W=w;
```

Settling Function:

```
function [X,Y,Z,U,V,W] = Seat( x, y, z, u, v, w, 
FL,m,n,m3,n3,Moment_limit)
% format('short')

ZERO=zeros (2*m3+1,2*n3+1);
Mux=ZERO;Muy=ZERO;
Ones=ones(2*m+1,2*n+1);

SMxTot = 0;
SMyTot = 0;

Ang_inc=pi/50000;
%%%%%  lowering of the surface to make contact

%        Calculation of summation of contact point 
distances
%        in order to multiply to the spring constant

%        First find the contacted point
% ww = w;
Projw2xy=griddata(u,v,w,x,y,'linear');
Projw2xy= SubstituteNaN(Projw2xy, 100.*Ones);

% % % Projw2xy= SubstituteNaN(Projw2xy, ZERO);
%
% if (isnan(Projw2xy))
%      F
% end
d = min(min(Projw2xy - z));
[u,v,w]=HTM (u,v,w,0,0,0,0,0,-d);

D=0;
F=FL*.3;    %initial tolerated force
d=.01;
stepp = 0;

while (F < FL)
%      if (F>FL)
%          F
%      end
```

```
    [u,v,w]=HTM (u,v,w,0,0,0,0,0,-D);

    projz2uv= griddata(x,y,z,u,v,'linear');

    projz2uv= SubstituteNaN(projz2uv, ZERO);

    %       negative magnetiutes are not in contact
    dist=projz2uv-w;
    dist= SubstituteNaN(dist, -100.*Ones);
    dist(dist<0)=0;
    F=sum(sum(dist))*10;



    %%%% Test of SMx

    SMx=100; SMy=SMx;
    if F>.7*FL
        while SMx>Moment_limit ||SMx<-Moment_limit ||
SMy>Moment_limit ||SMy<-Moment_limit


            for i=1:2*m3+1
                for j=1:2*n3+1
                    Mux(i,j)=dist(i,j)* (v(i,j)-
v(m3+1,m3+1));
                end
            end

            for i=1:2*m3+1
                for j=1:2*n3+1
                    Muy(i,j)=dist(i,j)* (u(i,j)-
u(m3+1,m3+1));
                end
            end

            SMx=sum(sum(Mux));
            SMy=sum(sum(Muy));

%
            [u,v,w]=HTM (u,v,w,sign(SMx)*Ang_inc,-
sign(SMy)*Ang_inc,0,0,0,0);
%

            % new line
            SMxTot = SMxTot + sign(SMx)*Ang_inc ;
            SMyTot = SMyTot + -sign(SMy)*Ang_inc;
            %
```

```
%              if ((abs(SMxTot) > pi/4) || (abs(SMyTot) >
pi/4000) )
%                  F
%              end

             dist=projz2uv-w;
             dist= SubstituteNaN(dist, -100.*Ones);
             dist(dist<0)=0;

         end
     end
     [u,v,w]=HTM (u,v,w,0,0,0,0,0,0);


     [u,v,w]=HTM (u,v,w,0,0,0,0,0,D);
     D=D-sign(F-FL)*d;

end

SMxTot;
SMyTot;

[u,v,w]=HTM (u,v,w,0,0,0,0,0,-D);

X=x;
Y=y;
Z=z;
U=u;
V=v;
W=w;
```

NaN Substitution Function:

```
function [ R ] = SubstituteNaN( A,B )
%SubstituteNaN Summary of this function goes here
% This function, firsltry find the Nan entries position
of the matrice
% A. Next, change the Nan entries values of the matrice A
with the values
% of the matrice B

%Find the NaN entries position
NaNEntries = find(isnan(A));

%Nanentries values changing
A(NaNEntries) = B(NaNEntries);

%Result
R = A;
```

```
end
```

Result Function:

```
function [  ] = DrawSimulationResult( X, Y, Z, U, V, W,
Xn, Yn, Zn, Un, Vn, Wn , MinVal, MaxVal)
%UNTÝTLED Summary of this function goes here
%   Detailed explanation goes here

%Finding maximum and minimum values of the concatenated
matrix Z and W
% MaxX = max(max(Z));
% MinX = min(min(Z));
% MaxW = max(max(W));
% MinW = min(min(W));
% if MaxX>MaxW
%     MaxVal = MaxX;
% else
%     MaxVal = MaxW;
% end
%
% if MinX<MinW
%     MinVal = MinX;
% else
%     MinVal = MinW;
% end

% RemMinVal =rem(MinVal,10);
% if (RemMinVal > -5)
%     MinVal = MinVal - RemMinVal - 10;
% else
%     MinVal = MinVal - RemMinVal - 20;
% end
%
% RemMaxVal =rem(MaxVal,10);
% if (RemMaxVal < 5)
%     MaxVal = MaxVal - RemMaxVal + 10;
% else
%     MaxVal = MaxVal - RemMaxVal + 20;
% end

minx=-10;
maxx=10;

fig1 = figure('Name','Simulation Result');

%plot first workpiece(WP) before lap. on the first column
sp1=subplot(4,4,1);
mesh(X,Y,Z);
set(gca,'Clim',[MinVal, MaxVal])
```

```
zlim([MinVal, MaxVal])
axis([minx maxx minx maxx MinVal MaxVal])
xlabel('X x10 [mm]'),ylabel('Y x10 [mm]'),zlabel('Z [x10
\mum]')


sp5=subplot(4,4,5);
contour(X,Y,Z,30)
set(gca,'Clim',[MinVal, MaxVal])
colorbar('location','EastOutside')
axis([minx maxx minx maxx ])
xlabel('X x10 [mm]'),ylabel('Y x10 [mm]')

sp9=subplot(4,4,9);
[ry,cy]=size(Y);
plot(Y(:,round(cy/2)),Z(:,round(cy/2)));
ylim([MinVal, MaxVal])
xlabel('Y'),ylabel('Z')
title('X Profile')
xlabel('Y x10 [mm]'),ylabel('Z x10 [\mum]')

sp13=subplot(4,4,13);
plot(X(round(ry/2),:),Z(round(ry/2),:));
ylim([MinVal, MaxVal])
xlabel('X'),ylabel('Z')
title('Y Profile')
xlabel('X x10 [mm]'),ylabel('Z x10 [\mum]')

%plot second WP bef. lap. on the second column
sp2=subplot(4,4,2);
mesh(U,V,W);
set(gca,'Clim',[MinVal, MaxVal])
zlim([MinVal, MaxVal])
axis([minx maxx minx maxx MinVal MaxVal])
xlabel('X x10 [mm]'),ylabel('Y x10 [mm]'),zlabel('Z x10
[\mum]')

sp6=subplot(4,4,6);
contour(U,V,W,30);
set(gca,'Clim',[MinVal, MaxVal])
colorbar('location','EastOutside')
axis([minx maxx minx maxx ])
xlabel('X [x10 mm]'),ylabel('Z x10 [\mum]')

sp10=subplot(4,4,10);
[rv,cv]=size(V);
plot(V(:,round(cv/2)),W(:,round(cv/2)));
ylim([MinVal, MaxVal])
title('X Profile')
```

```
xlabel('Y x10 [mm]'),ylabel('Z x10 [\mum]')

sp14=subplot(4,4,14);
plot(U(round(rv/2),:),W(round(rv/2),:));
ylim([MinVal, MaxVal])
title('Y Profile')
xlabel('X x10 [mm]'),ylabel('Z x10 [\mum]')

%plot first WP aft. lap. on the third column
sp3=subplot(4,4,3);
mesh(Xn,Yn,Zn);
set(gca,'Clim',[MinVal, MaxVal])
zlim([MinVal, MaxVal])
axis([minx maxx minx maxx MinVal MaxVal])
xlabel('X x10 [mm]'),ylabel('Y x10 [mm]'),zlabel('Z x10
[\mum]')

sp7=subplot(4,4,7);
contour(Xn,Yn,Zn,30);
set(gca,'Clim',[MinVal, MaxVal])
colorbar('location','EastOutside')
axis([minx maxx minx maxx ])
xlabel('X x10 [mm]'),ylabel('Y x10 [mm]')

sp11=subplot(4,4,11);
plot(Yn(:,round(cy/2)),Zn(:,round(cy/2)));
ylim([MinVal, MaxVal])
title('X Profile')
xlabel('Y x10 [mm]'),ylabel('Z x10 [\mum]')

sp15=subplot(4,4,15);
plot(Xn(round(ry/2),:),Zn(round(ry/2),:));
ylim([MinVal, MaxVal])
title('Y Profile')
xlabel('X x10 [mm]'),ylabel('Z x10 [\mum]')

%plot second WP aft. lap. on the forth column
sp4=subplot(4,4,4);
mesh(Un,Vn,Wn);
set(gca,'Clim',[MinVal, MaxVal])
zlim([MinVal, MaxVal])
axis([minx maxx minx maxx MinVal MaxVal])
xlabel('X x10 [mm]'),ylabel('Y x10 [mm]'),zlabel('Z x10
[\mum]')

sp8=subplot(4,4,8);
contour(Un,Vn,Wn,30);
set(gca,'Clim',[MinVal, MaxVal])
colorbar('location','EastOutside')
```

```
axis([minx maxx minx maxx ])
xlabel('X x10 [mm]'),ylabel('Y x10 [mm]')

sp12=subplot(4,4,12);
plot(Vn(:,round(cv/2)),Wn(:,round(cv/2)));
ylim([MinVal, MaxVal])
% legend('salar')
title('X Profile')
xlabel('Y x10 [mm]'),ylabel('Z x10 [\mum]')

sp16=subplot(4,4,16);
plot(Un(round(rv/2),:),Wn(round(rv/2),:));
ylim([MinVal, MaxVal])
title('Y Profile')
xlabel('X x10 [mm]'),ylabel('Z x10 [\mum]')


% suptitle('kireks')

end
```