Optimization of Process Parameters In Lapping of Stainless Steel

M. R. Pratheesh Kumar
Assistant Professor,
Department Of Production Engineering,
P.S.G. College Of Technology, Coimbatore, Tamil Nadu, 641004.

B. S. Arun
Department Of Production Engineering,
P.S.G. College Of Technology, Coimbatore, Tamil Nadu, 641004.

R. Aravind Babu
Department Of Production Engineering,
P.S.G. College Of Technology, Coimbatore, Tamil Nadu, 641004.

Abstract

Lapping is a finishing process in which the material removal takes place due to relative motion between the work material, loose abrasive grains, and the lapping plate. This process is used in achieving finer surfaces and closer fits, correction of minor imperfections, and maintaining close tolerances. Although a significant underlying science – base exists with regards to physics, mechanics, and thermal effects, lapping has been considered as an art, rather than a science. Hence exploring lapping at a fundamental level will help improve its application. This study discusses the effects of the various process parameters influencing the material removal rate and surface finish. This is done by conducting a series of experiments by varying the process parameters and calculating the material removal rate and surface roughness. Then the final step is to find out the optimum combination of process parameters to determine the material removal rate and the surface finish.

Keywords: *Lapping, Taguchi, optimization.*

1. Introduction

An investigation is conducted to determine the effect of the various controllable input parameters on material removal rate and the type of surface generated using flat lapping. Lapping, commonly used as a finishing operation, has been used for achieving ultra-high finishes and close tolerances between mating pieces. This process is characterized by its low speed, low pressure, and low material removal. The lapping process is carried out by applying loose abrasive grains between two surfaces and causing a relative motion between the two surfaces resulting in a good surface finish.

In general one of the two surfaces is the surface to be machined which is called as the work surface and the other is the lap surface. The lap surface is softer than the work surface, whereas the abrasive grains are comparatively harder than the lap surface and the work surface. The reason for this is that the hard abrasive grains get embedded in the softer lap plate (lap) thus forming fixed cutting edges similar to a grinding wheel. Lapping is also useful in the machining of ceramics, because lapping ceramic surfaces increases the adhesion strength of deposited film, improves chipping and cracking characteristics, releases trapped gasses and other contaminants.

Several factors need to be considered during the process of lapping. This includes factors such as condition of the lap plate surface, speed of the lap plate, type of abrasive, type of carrier fluid, slurry concentration, slurry flow rate, size and shape of abrasive, material of the lap plate, rigidity of the lap plate, applied force on the work material, time of operation and duration between the two consecutive instances of application of fresh abrasive slurry. In addition to the above aspects, there are some application-specific factors such as, the skill of an individual lapper, environmental conditions, vibrations caused due to external sources, batch of abrasives, condition of the machine, and inherent variability within the work material. As a result, comprehensive models are difficult to create. Every individual lapper, based on his or her experience and skills must tweak the variables until the desired result is achieved. This may cost the company in large sums of consumables and lost time. Hence, this project focus on creating some methodology for scientific inquiry while studying important variables in lapping.

Flat surface lapping or flat lapping is the most extensively used type of lapping process. Flat lapping is predominantly used where extremely high flatness of the work material and/or close parallelism of double-lapped faces are required. The other applications of flat lapping include removal of damaged surface and sub-surface layers and, enhancement of the surface finish on the work materials. Lapping is a critical technology that is used in a number of precision manufacturing applications such as optical mirrors and lenses, ceramics, hard disk drive, semi conductor wafers, ball bearings, and many more parts. Surprisingly, even with the extensive use in the industry, the research in the field of lapping has not progressed on pace with other machining operations.

Previous research has focussed primarily on mechanisms of material removal and the effects of Input variables on material removal rate (MRR). The behaviour of MRR when the standard input variables (like work material pressure, lapping speed, time of operation, and abrasive size) are carefully controlled, has not been extensively explored. Exploration of this controlled-condition situation is important because of its prevalence in the production environments.

2. Literature survey

Evans et al, 2000 stated that "the physical state of material removal process in lapping is such that it is difficult (practically impossible) to observe them directly. Much of what we know about the fundamental mechanisms involved in the process has been derived either by correlating macroscopic measurements of the process outputs with models or by extrapolation from experiments at scales which can conveniently be observed."

Imanaka et al, 2007 used glass as the work material and investigated it with respect to the roughness of lapped surface. With prior research being conducted in this area considering a single abrasive grain, Imanaka studied the micro-fracturing of glass by single abrasive grain from the viewpoint of the lapping process as the aggregation of each single grain. A theoretical equation for the roughness of lapped glass surface was developed.

Bulsara et al, 2002 studied the heat generated during lapping and polishing. A moving heat source model was developed to estimate the maximum and average temperature rise of abrasive work material contacts in the polishing of steels, glasses, and ceramics. Calculation of temperature from the developed equations, estimated the temperature to be less than 200°C. The lapped structure showed little evidence of structural changes commonly associated with localized high temperatures as found in grinding, phase transformations or burns.

Cai et al, 2006, revealed that, the pressure distribution of lapping and polishing is not even. The pressure goes up significantly near the edge of the work material. Not much relevant literature was identified in the area of friction modelling and the chip formation modelling in lapping which are some of the very important parameters governing any material removal process.

Letner and Snyder, and Chandrasekar et al, 2005 have developed predictive models for the process of grinding and have implemented them to predict the results from grinding with good success. However, the models have failed to achieve similar agreement when the same equations were implemented to predict the results from the lapping process. One of the reasons is that lapping is a free abrasive machining process as opposed to grinding which is a bonded abrasive machining process. Also, the associated speeds in lapping operations are very low when compared to grinding.

S.Chandrasekar et.al, (2002) observed that the material removal rate in lapping is about 1/5000 that in grinding. According to Archard and Tylczak, abrasive wear is directly proportional to applied load and sliding distance, but inversely proportional to the hardness of the work material. One of the comprehensive studies in developing a model for predicting the material removal in lapping was conducted by Chang. It was found that, MRR is directly proportional to applied pressure and relative velocity of the work material.

As seen from the above literature review, the important problem that is faced in today's industries is to determine the material removal rate and surface finish. The MRR and surface finish are dependent on a number of parameters like rotary speed, time taken, abrasive concentration, load applied, and type of work material. Hence these parameters are to be optimized in such a way to obtain the maximum result. So, a systematic approach has to be developed in order to obtain the required results.

3. Methodology

The various input process parameters which influence the output process parameters are to be identified. The required orthogonal arrays are designed. The experiments are to be carried on stainless steel component, according to the design of experiments. The surface roughness value and the material removal rate are measured. The design of experiments is done using Taguchi method for conducting the experiments. The correlations between the independent and dependent variables are established using "Statistica" software. The optimization of parameters is done using "Minitab" software. The various process parameters to be optimized are abrasive concentration, time taken and load applied.

4. Experimental details

The experiments are conducted on Stainless Steel (SS316), which is identified as most commonly used materials in the manufacturing of relief valve seats and thus selected for the experiments. Prior to lapping, the surface grinding operation is carried out on the work piece. The thickness of the specimen is 20mm with diameter of 30mm. The available loads are 5kg, 6kg and 7 kg. The three levels of time for lapping is taken as 5, 10, 15 minutes. The abrasives are mixed in the ratio of 1:4, 1:5, and 1:6. (Ex: The ratio1:4 denote, one part of abrasive mixed with four parts of oil by weight).

4.1. Abrasive materials

The most commonly used abrasive material for lapping is Aluminium Oxide. The rough lapping is carried out using Aluminium Oxide (220) and the finish lapping is done using Aluminium Oxide (400). It is the objective of this project to obtain sufficient data by lapping with a range of abrasive concentration to determine the material removal rate and surface finish. The slurry was prepared by mixing the abrasive with SAE 20W40 oil in the appropriate ratio.

4.2. Machine details

The operation was carried on a lapping machine. The parts of the machine includes a heavy duty steel fabricated housing, abrasive distribution system with pump, tank with infinitely variable flow control, cast alloy lap plate which is radially serrated, three adjustable conditioning rings with yoke and bearing assemblies.

Figure 1. Lapping machine

There is an automatic lapping cycle timer, drive unit with 0.37kw motor and gear box, three pressure plates with lifting eye bolts and three felt pads. The specification of the machine is given in table 1.

Table 1. Lapping machine specifications

S.NO	DESCRIPTION	VALUE
1	Lap plate OD	300 mm
2	Conditioning ring	107 mm
3	Maximum length	800 mm
4	Maximum width	675 mm
5	Height	610 mm
6	Lap plate speed	48 rpm
7	Main motor	0.37 KW/ 0.5 HP
8	Pump motor	0.11 KW/ 0.15 HP
9	Timer range	0 – 30 minutes
10	No. Of conditioning rings	3
11	Standard power supply	415 V / 3 phase / 50 Hz
12	Manufacturer	Guindy Machine Tools Limited, Chennai.
13	Model	06 / 01
14	Year	2010

4.3. Mitutoyo surface roughness tester

The surface roughness of the specimen is measured by Mitutoyo surface roughness tester. The device is powered by electrical supply. The device has a sensitive probe in it, which makes contact with the surface to be examined and reveals the “Ra” value.

Figure 2. Mitutoyo surface roughness tester

The “Ra” value is displayed in the digital meter of the device. First the device is tested in the standard specimen to check for the errors before measuring the specimen. Then the surface roughness of the components is measured.

5. Experimental procedure

The experiments are conducted according to the appropriate procedure. The time of lapping is first set in the machine according to the requirements. The lapping abrasive of the required concentration is taken. The specimens are placed in the fixture which is kept on the lapping plate. The machine is turned on and the abrasive flow is maintained properly. Initially all the samples were rough lapped using aluminium oxide grade 220 abrasive for a period of 10 minutes. This process ensured that the uneven surface generated by the machining of the components was removed and a new smooth and flat surface is generated. The other advantage is that any burrs left on the edges were also removed. The initial weight of the components was noted down. After rough lapping is done, finish lapping was carried out. The experiment is conducted for different parameters. The final weight of the components was measured and the difference between both the initial and final weights gives the material removal rate. Then the surface roughness of the components is measured using the surface roughness tester.

6. Design of experiments

The design of experiments process is divided into three main phases which consists of all experimental approaches. The three main phases are

6.1. Planning

The planning phase is the most important phase as proper planning of the experiment provides the best results. Also, the correct selection of factors and levels is more important.

6.2. Experimentation

The second most important phase is the conducting phase, where the test results are actually collected. If the experiments are well planned and conducted, the analysis is actually much easier and more liked to yield positive information about factors and levels.

6.3. Analysis

The analysis phase involves the analysis of the experimental data and is however more statistical in nature when compared to other phases.

6.4. Steps in design of experiments

The following steps are followed in the design of experiments.

a) State the problems or areas of concern.
b) State the objectives of the experiment.
c) Select the quality characteristics and measurement systems.
d) Select the factors that influence the selected quality characteristics.
e) Select the levels for the factors and the appropriate orthogonal arrays.
f) Assign factors to OA and locate interactions.
g) Conduct tests described by trials in OA.
h) Analyze the results of the experimental trials.

6.5. Rough lapping

The process parameter for rough lapping of all the samples is given in table 2.

Table 2. Rough lapping parameters

Abrasive concentration	Time (min)	Load (Kg)
1:5	10	5

6.6. Design of experiments for finish lapping

The design of experiments for finish lapping is given in table 3.

Table 3. Design of experiments for Finish lapping

Test run	Abrasive concentration	Time (min)	Load (Kg)
1	1:4	5	5
2	1:4	10	6
3	1:4	15	7
4	1:5	10	5
5	1:6	15	5
6	1:5	5	7
7	1:5	15	6
8	1:6	5	6
9	1:6	10	7

7. Experimental analysis

The experimental result for finish lapping is given in table 4.

Table 4. Experimental results

Test run	Abrasive concentration	time (min)	Load (Kg)	Initial weight (Grams)	Final wt. (Grams)	MRR (g/min)	Surface roughness (Microns)
1	1:4	5	5	112.564	112.540	0.0048	0.0675
2	1:4	10	6	112.411	112.261	0.015	0.0575
3	1:4	15	7	112.359	111.975	0.0232	0.0725
4	1:5	10	5	112.321	112.140	0.0181	0.0425
5	1:6	15	5	111.602	111.480	0.0081	0.057
6	1:5	5	7	112.640	112.578	0.014	0.07
7	1:5	15	6	112.368	112.056	0.0208	0.0575
8	1:6	5	6	113.044	113.032	0.0024	0.07
9	1:6	10	7	112.276	112.225	0.0051	0.085

7.1. Canonical correlation

The canonical correlation is a way of establishing the relationship between the dependent and independent variables. In our project, the independent variables are abrasive concentration, time and load applied. The dependent variables are material removal rate and surface finish. Using the 'Statistica' software, the canonical correlation is established between the dependent and independent process parameters, which are given in table 5.

Table 5. Canonical correlation

	Abrasive concentration	Time	Load	Material removal rate	Surface roughness
Abrasive concentration	1	7.4015E-18	1.4803E-16	-0.5223747	0.17146461
Time	7.4015E-18	1	-7.772E-17	0.58910137	-0.2424155
Load	1.4803E-16	-7.772E-17	1	0.21543189	0.7154213
Material removal rate	-0.5223747	0.58910137	0.21543189	1	-0.40906
Surface roughness	0.17146461	-0.2424155	0.7154213	-0.40906	1

By processing the above data by using "Statistica" software, the canonical R is found.

Canonical R = 0.9751.

The value of 'R=0.9751', denotes that there is a good dependency between the input and output variables.

7.2. Scatter plot for canonical correlation

The figure 3 shows the scatter plot for the dependent and independent variables.

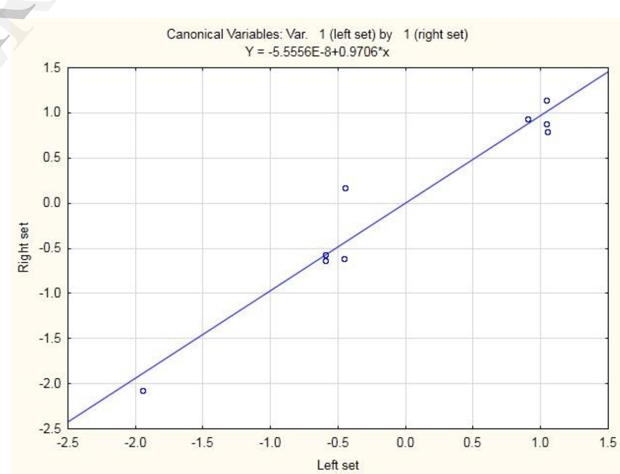

Figure 3. Scatter plot

In Figure 3, the points in the plot cluster around the regression line and does not indicate any non-linear trend (e.g., by forming a U or S around the regression line). Therefore, it is evident that there are no major deviations between the input and output process parameters.

7.2.1. Regression equation. The regression equation is found using the Microsoft Excel software.

Material Removal Rate = -9.737 X + 0.0005 Y – 0.00031 Z + 0.449
Surface Roughness = 11.0057 X + 0.00036 Y + 0.0153 Z – 0.53136
Where,
X = Abrasive concentration
Y = Time
Z = Load

To obtain the optimal set of parameters, using the Minitab software the graphs were plotted which represents the effects of various parameters (abrasive concentration, time taken and load) on the material removal rate and surface finish of the work piece.

7.3. Main effect plot for means

The main effect plot for means is plotted between the lapping process parameters and the means of material removal rates, shown in figure 4.

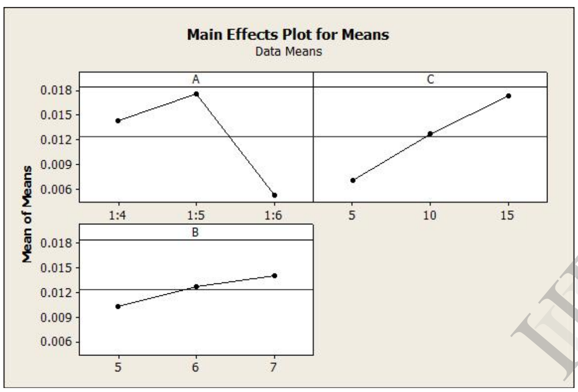

Figure 4. Main effect plot for means of material removal rate

Again, the main effect plot for means is plotted between the lapping process parameters and the means of surface roughness values.

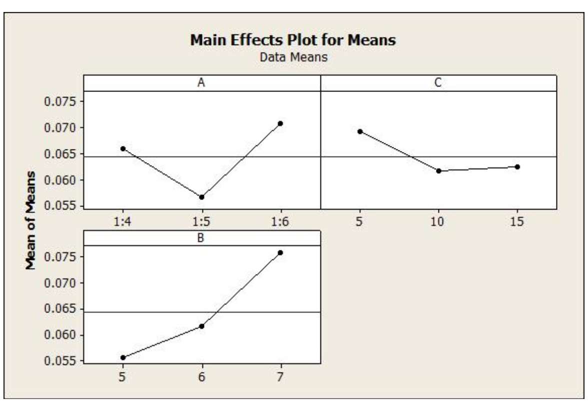

Figure 5. Main effect plot for means of Surface roughness

7.4. Evaluation of S/N ratios

Taguchi suggests the transformation of the repetition data in a trial into a consolidated single value called the S/N ratio. Here, the term 'signal' represents the desirable value (mean) and the 'noise' represents the undesirable value (standard deviation). Depending upon the objective of quality characteristics, there can be various types of S/N ratios.

7.5. Main effect plot for S/N ratios

The taguchi method uses the signal-to-noise (S/N) ratio in order to interpret the trial results data into values for the evaluation characteristics in the optimum setting analysis. This is because the S/N ratio can reflect both the average and the variations of the quality characteristics.

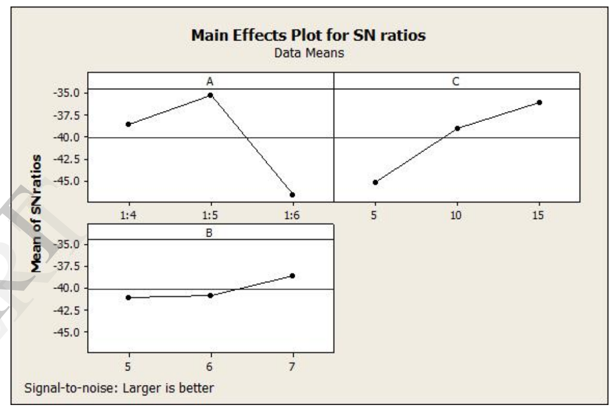

Figure 6. Main effect plot for SN ratios of Material removal rate

The Figure 7 shows the Main effect plot for S/N ratios of surface roughness values.

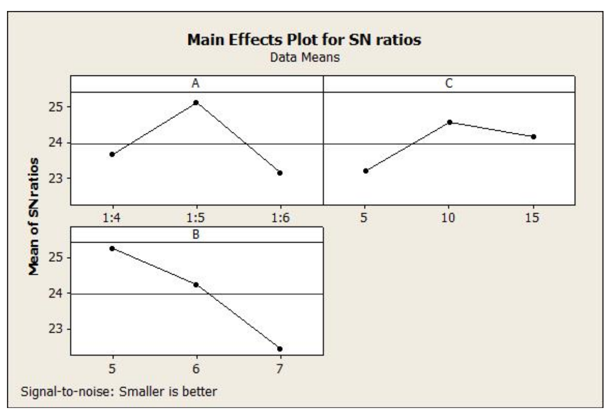

Figure 7. Main effect plot for SN ratios of surface roughness

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8. Results and discussions

8.1. Material removal rate

From the experiments it is understood that there is a slight increase in the material removal rate when the abrasive concentration is decreased but there is a rapid fall in the material removal rate when the abrasive concentration is decreased further. This is because of increase in the amount of oil which decreases the amount of abrasive grains per unit area, when applied on the lapping plate. As studied from the literature, the material removal rate increases with increase in time. Again, when the pressure applied increases, the material removal rate also increases, but this happens up to a certain extent only. When the load increases beyond a certain limit, the relative motion between the work piece and the abrasive slurry will decrease, this in turn reduces the material removal rate.

In order to obtain the maximum material removal rate, larger the better quality characteristic is used. In some applications, despite the surface finish, where the job has to be processed quicker, the material removal rate should be high. Hence, the optimal combination of process parameters suiting the condition is given in table 6.

Table 6. Optimum set of process parameters for better material removal rate

Process parameter	Value
Abrasive concentration	1:5
Time	15 minutes
Load	7 kilograms

8.2. Surface roughness

From the experiment it is seen that the surface roughness decreases when the abrasive concentration decreases, resulting in a good surface finish. But, further decrease in the abrasive concentration results in increase in surface roughness. This may be due to insufficient amount of abrasive grains in the slurry that should have caused the increase in surface roughness. Also, it can be understood that the surface roughness decreases with increase in lapping time.

It is also shown that the surface roughness increases with increase in load applied. This is because when the load is increased, there would be less space available for the loose abrasive grains to move. This causes more abrasive grains to come in contact between the work piece and hence the surface roughness increases.

In order to obtain the maximum surface finish, smaller the better quality characteristic is used. In some applications, despite the material removal rate, where the job should have a very high surface finish, the optimal combination of process parameters suiting the condition is given in table 7.

Table 7. Optimum set of process parameters for better surface finish.

Process parameter	Value
Abrasive concentration	1:5
Time	10 minutes
Load	5 kilograms

9. Conclusion

The surface finish produced on the component depends on the number of factors like abrasive concentration, time of lapping, etc. So, these factors have to be controlled efficiently for a good surface finish. Maintaining all these parameters within a limit is not going to be so easy. The flow of abrasive slurry should be continuous in order to have the desired surface finish. Surface finish is an important factor when dealing with issues such as friction, lubrication and wear. It also has a major impact on applications involving thermal or electrical resistance, noise and vibration control, dimensional tolerance, etc. The surface finish obtained from lapping is a function of the material removal rate. Normally, the surface roughness tends to increase as the MRR increases. In this project, the concepts of material removal rate as well as the parameters that influence the surface roughness are presented.

The surface finish obtained also depends upon the grain size of the abrasives being used. The fine grains take away very less material and provide a good surface finish. Also, fine grains generate less heat. Though each grain cuts less, there are more grains per unit area which helps in removing more amount of material. Coarse grains are good for higher material removal rate as the depth of cut increases. Considering all these factors and the experimental results obtained, it is found that the good combination of input parameters helps in obtaining a good surface finish in the lapping process.

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