# On-Line Optimisation And Experimental Design Analysis For The Investigations On The Surface Roughness Produced By Roller Burnishing

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To

Komaraiah Koorapati

with greatest gratitude

# ABSTRACT

This thesis describes the improvement of the Surface finish of metals by a cold working, non-metal removal and plastic deformation process called roller burnishing. Roller burnishing is a popular finishing process. Surface finish has a positive and prolonged effect on the functioning of the machined parts. In this work roller burnishing is used to get a high quality surface finish on different materials like aluminum, copper, mild steel and brass. A roller burnishing tool was designed and fabricated for the project.

A test rig was set up on a center lathe to conduct experiments. The angle of approach and radius of the roller burnishing tool were checked for optimisation. Number of passes of the tool was also one of the factors under study for the optimisation. The surface finish of the roller burnished cylindrical surfaces was examined for the soft materials like Aluminum and Copper and also for the hard materials like Mild Steel and Copper. The optimum values of feed, speed and depth of penetration were suggested by conducting a number of experiments varying one factor-at-a-time holding the rest constant.

Since all the factors are interdependent, varying one-factor-at-a-time and keeping the rest constant method of experimental optimisation technique will not give accurate results either for the main effects or any interactions present. At same time it is not possible to vary more than one factor at a time experimentally.

Hence a theoretical approach focused on the computer based, process parameters and surface quality data acquisition from the shop floor was suggested. The collected data was then analysed by Design of Experiments method, an advanced statistical quality analysis method, to determine the significant process parameters influencing the surface finish. The basic design and analysis of the process was carried out by full factorial and ANOVA for the two level three factor ( $2^3$) experimental design.

More experiments for roller burnishing process were conducted for collection of data using experiments designed by the Central Composite Design (CCD) method. These experiments were used to determine the interactions among the factors. The analysis was carried out by the Response Surface Methodology (RSM) to find the optimum values of the more significant process parameters. The final surface finish for mildsteel was found to be 0.32μm with a feed

of 85μm/rev and depth of penetration of 70μm. The results of both experimental and theory were compared.

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# *Chapter 1*

# *Introduction*

## 1.1 Surface finish obtainable in various processes

With the advent of New Technology and increased demand, the necessity for accurate and quality components has increased. The quality of the components and the assembly can be improved considerably if they are finished better.

The functional performance of a machine component such as load bearing capacity, fatigue strength, resistance to wear, resistance to corrosion depend to a large extent on surface finish of components. Some of the factors that influence the surface characteristics are geometrical features of the surface, hardness and the residual stresses induced.

These machining processes can be divided into three groups.

1. Primary machining processes
2. Finishing processes
3. Fine finishing processes

The primary machining processes include turning, milling, drilling, boring, disc grinding and hand grinding etc. The surface finish in this process varies from 0.32 to 25 microns (μm). The actual value obtained depends up on the machining parameters such as the cutting speed, feed, and depth of cut, application of coolant, rigidity of work-tool-fixture and machine tool system. In the case of disc and hand grinding operations the grain size plays an important part.

In these finishing processes surface grinding, cylindrical grinding and reaming are included. The roughness obtainable in these processes varies between 0.06 to 5μm.The grinding operation, though superior to reaming with regard to roughness, the residual stresses existing on the ground surface are reported to be tensile in nature. The tensile residual stresses will reduce the fatigue life of the components. The situation is better in this regard with reaming.

The fine finishing process are grouped into two categories, one involving with removal of asperities through micro chipping and the other by causing gross plastic flow of the material at the surface. In the honing, lapping, polishing and super finishing operations very fine abrasives are used for improving the surface finish. The abrasives used may be in the form paste or a stick. The finish obtainable in this category of processes is between 0.01 to 0.4μm. In the second category of fine finish processes, there is no removal of material but only plastic flow of asperities at the work piece surface. This is caused by the use of a burnishing tool or by pushing a ball through the hole. The surface roughness obtainable in burnishing is between 0.04 to 0.8μm. The major advantage of these processes is the existence of a residual compressive stress field on the finished surface of the work-piece. Considerable strain hardening of work-piece surface also takes place resulting in better wear resistance and fatigue life. The sizing of the component is also found to be better.

## 1.2 Burnishing Process

It is basically a cold working processes in which the Machined surface undergoes a plastic deformation by the application of the pressure through a hard roller. As the surface pressure increases the metal from the crests (peaks) displace plastically to fill the troughs (valleys) of the surface irregularities. This results in reduction in height of the micro irregularities of the surface roughness. Burnishing causes work hardening and creation of beneficial compressive stresses in the surface layers [Azarevich G. M (1972)]. During burnishing operation, there will be a continuous plastic deformation of the work material and accordingly the surface finish changes.

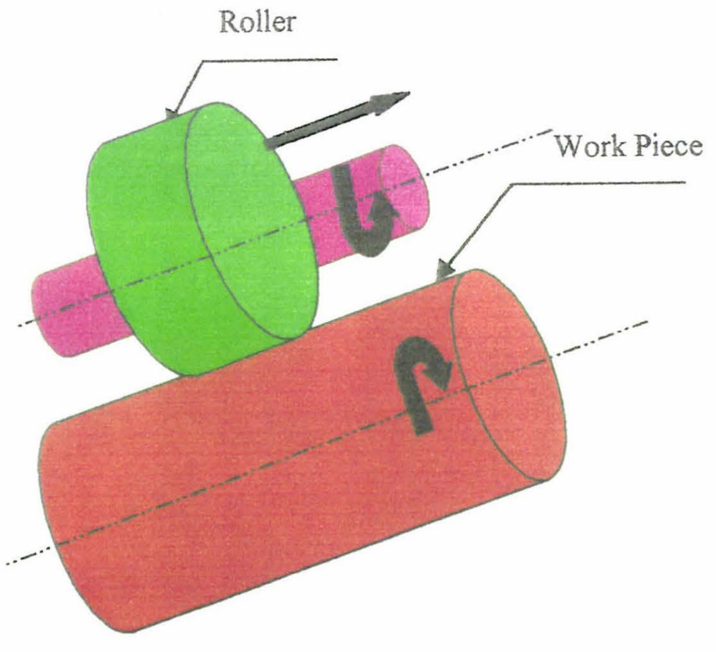



Figure 1.1 Principle of roller burnishing process

Due to the unevenness of the initial surface and high specific pressure, the smoothing out process is extremely intensive in the beginning even with comparatively low burnishing forces but later on it becomes less intensive due to work hardening effect [Adel M.H and Al-Basharat A. S (1996)] in surface layers.

More than ninety five percent of total machining work is done by metal cutting processes like turning, milling, drilling etc. These initial machining operations give the required shape and size to the components and to improve the surface characteristics of the components, the components are subjected to a metal finishing process. The finishing process, apart from improving the functional performance of the component, also improves the life of the component and gives a better appearance.

The dimensional accuracy, form deviations and surface smoothness can be achieved by properly selecting the finishing process. Table 1.1 indicates the surface roughness expected from various manufacturing processes.

It is understood that when compared to other finishing processes, the burnishing process offer certain specific advantages like work hardening of the surface layers, higher wear resistance, higher fatigue strength, precision sizing [Koti V. C and Ronanki L. M (1990)] of the component etc. Burnishing is an important member in the family of surface finishing processes.

## 1.3 Classification of burnishing process

The burnishing process is classified as the following and it is classified based on the process and shape of the tool.

### *1.3.1 Shape of the deforming tool*

The burnishing tools are designed to have the deforming element either in the form of a ball or a roller. Thus the process is named as ball burnishing or roller burnishing as per the shape of the deforming element. The comparative features of various finishing processes are in Table1.1.

Primary Machining Processes:

| S.No | Manufacturing Process | Surface finish in Microns |
|---|---|---|
| 2 | Drilling | 1.6 --- 20.0 |
| 3 | Boring | 0.4 ----6.3 |
| 1 | Turning and Milling | 0.32 –25.0 |
| 4 | Disc Grinding | 1.6 ----25.0 |
| 5 | Hand Grinding | 6.3 ----25.0 |

Finishing Processes:

| | | |
|---|---|---|
| 1 | Cylindrical grinding | 0.63 -----5.0 |
| 2 | Reaming | 0.4 -------3.2 |

Micro chip removal processes:

| | | |
|---|---|---|
| 1 | Honing | 0.025 --0.4 |
| 2 | Lapping | 0.012 --0.16 |
| 3 | Polishing | 0.04 -- 0.16 |
| 4 | Super finishing | 0.016 --0.32 |

Chipless process:

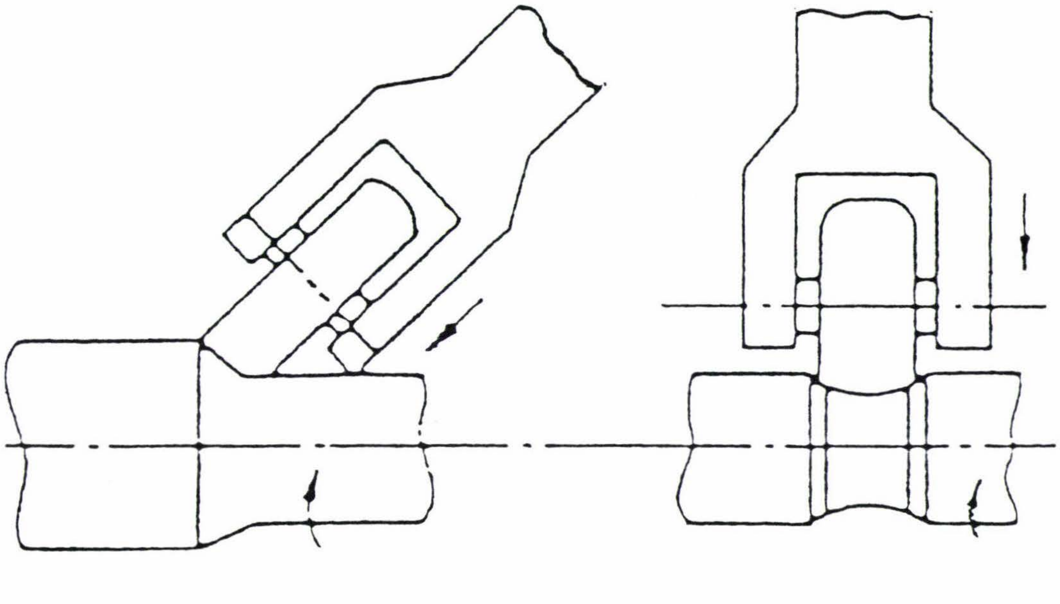
| | | |
|---|---|---|
| 1 | Burnishing | 0.04 --0.8 |

Table 1.1 Surface finish obtainable in various manufacturing processes

### *1.3.2 Number of deforming elements*

To get more productivity, multi ball or multi roller burnishing tool with two or more balls or rollers working on the surface of the job is employed. The number of deforming elements depends on the diameter of the work piece apart from the type of production.

Surfaces that can be burnished include external and internal cylindrical and tapered surfaces, spherical surfaces and flat surfaces. Gear tooth forms can also be burnished by using finger type burnishing tool [Loh N.H and Tam S.C (1989)].



a. External burnishing

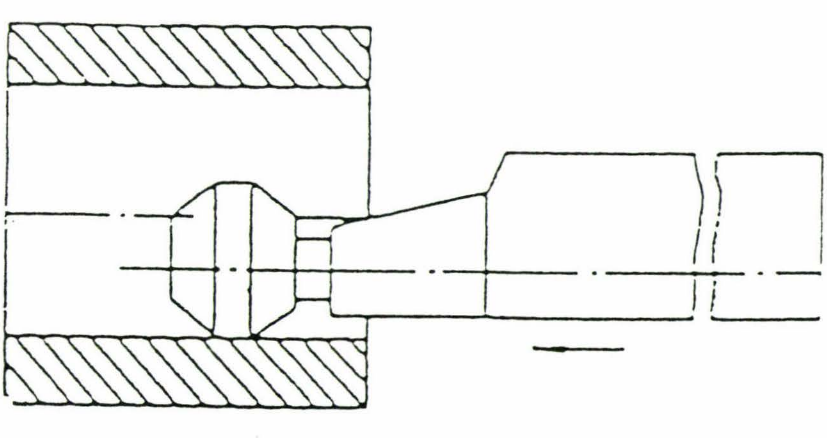


Figure 1.2 Types of burnishing

### *1.3.3 Motion of the tool*

Depending on the relative motion of the tool at the contact zone on the surface there are three types of burnishing processes. In 'impact Burnishing', hardened rollers rotating around bearing on cams rise and fall rapidly delivering as many as 20,000 blows per minute. The metal surfaces are treated and finished by combined action of rolling and peening

## 1.4 Work requirements

All the ductile materials can be easily burnished. The quality of surface finish in burnishing depends on the hardness of the work piece and its ductility. For best results and maximum tool life the work piece hardness should not exceed 40 $R_C$. Materials with a tensile strength up to 1400 $N/mm^2$ and ductility of at least 5-8% may be burnished [Lee S. G and Loh N.H (1996)].

Surface finish of the work piece prior to burnishing plays a dominant role in determining the final surface finish. Ductile materials like brass, aluminum and annealed steels can have rough machined surfaces prior to burnishing. Materials like cast iron, steels above 35 $R_C$ should have smoother machined surfaces and lesser stock allowance (i.e. the amount of material to be removed) [Lee S. G, Tam S.C and Loh N. H (1993)]. The ideal surface for burnishing is uniform peak and valleys pattern generated by a single point tool. By burnishing, the material flows from peaks to valleys and a fine surface finish is obtained.

While burnishing hollow work pieces, the wall thickness of the work piece should be strong enough to withstand the pressure of the burnishing tool. While burnishing thin walled work pieces there should be supporting fixtures to hold the job.

Parts with keyways and other interruptions or cutouts, which do not exceed 10% of circumference, can be burnished to obtain a good surface finish. Large cut outs tend to relieve the burnishing pressure of the tool. As a result, areas opposite to them may have a slightly rough surface finish.

## 1.5 Advantages of burnishing process

In the burnishing process the pressure of the roller causes, projections of the micro irregularities of the surface are to be plastically deformed, the roughness of the surface is reduced, its hardness is increased and residual compressive stresses in the surface layer rise, preventing the growth of cracks.

- Net improvements in the surface finish. In a burnished surface, there are no cracks, pits, burns, voids and gaps
- Improvement in the surface hardness to a considerable depth
- Improvement in dimensional accuracy. The geometrical tolerances like straightness and cylindricality can be maintained by reducing the out of roundness
- Increase in fatigue strength
- Induction of residual compressive stresses
- Improvement in wear resistance, friction resistance and anti corrosiveness
- short machining times and hence high productivity
- No need of coolants as the temperature involved in the burnishing process is low
- Longer tool life
- improvement in the percentage ratio of contact area

**1.6 Applications of burnishing process**

Burnishing can be used for:

- Finishing bores of hydraulic and automobile cylinders. Honing can be replaced by burnishing
- Finishing outer surfaces of pistons of hydraulic machinery

- Increasing contact area of valve seating in Internal Combustion (I.C) Engines
- Increasing the wear resistance &fatigue strength of rail axles
- Improving the quality and reducing the friction of main journals and crank pins of crank shafts and cam shaft journals of motor vehicles.
- Hardening the surfaces of tooth flanks of gears and plastic components

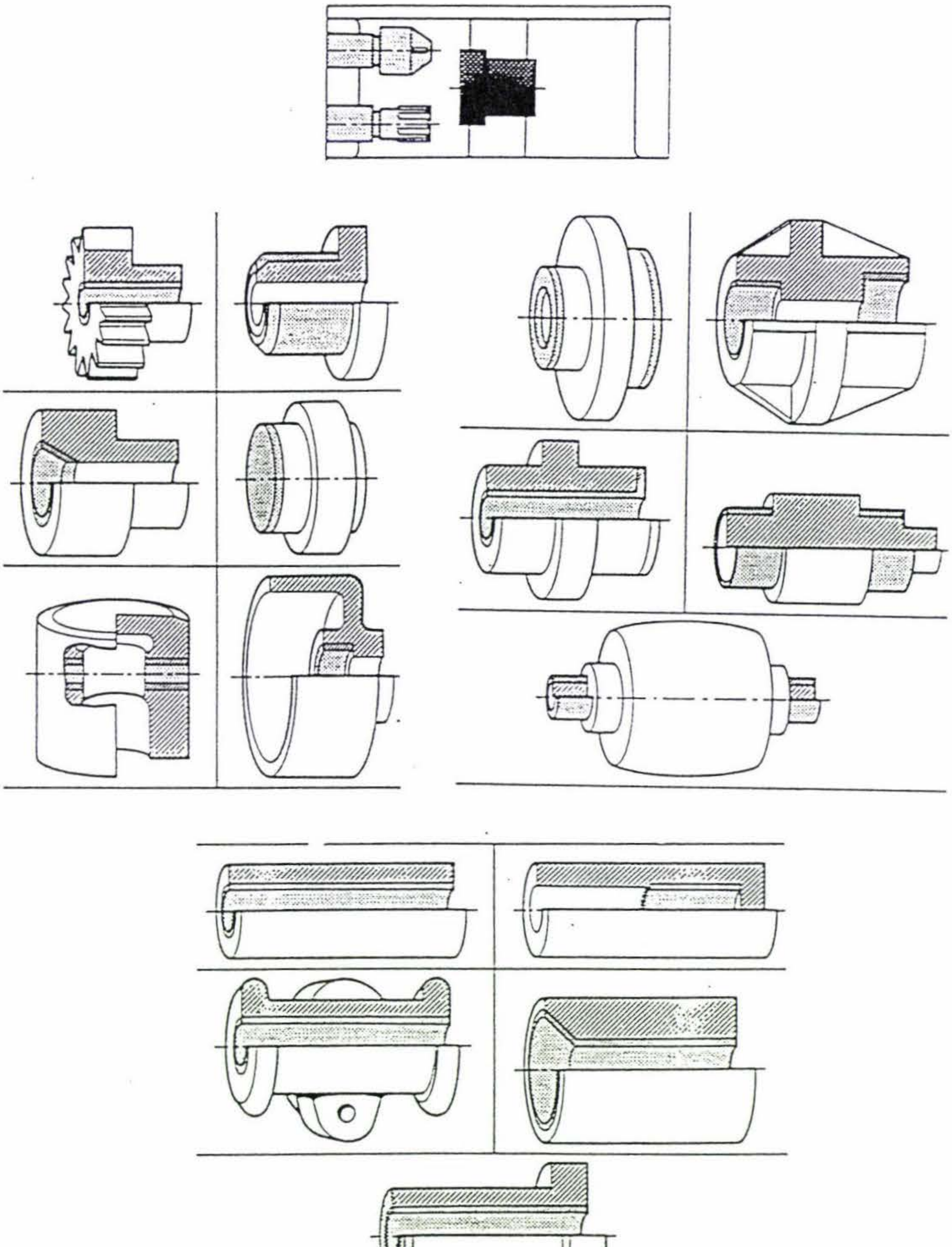


Figure 1.3 Applications of burnishing process

More applications are in the appendix-1.

### *1.6.1 Surface roughness and dimensional tolerances*

Surface roughness is closely tied to the tolerance of a machine component (Table 1.1). A close tolerance dimension requires a very fine finish, and the finishing of a component to a very low roughness value may require multiple machining operations. For example a 3.2μm surface roughness can be produced by milling or turning, while a very fine (low roughness value) surface would require grinding or additional subsequent operations, such as honing, super finishing, abrasive flow or burnishing. Therefore specifying very fine finishes will normally result in increased costs.

The importance of surface integrity is further heightened when high stresses occur in presence of extreme environments. Heat resistant, corrosion resistant and high strength alloys are used in a wide variety of such applications. Typical alloys used in these applications include alloy steels with hardness of 50 to over 60 HRC and heat treated alloys with strength levels as high as 2070 MPa. Additional materials include stainless steels titanium alloys, and high temperature Nickel-based alloys developed for high temperature and corrosion-resistant applications [Gambin W (1996)].

Unfortunately the alloys suitable for high strength applications are frequently difficult to machine. The hard steels and high temperature alloys, for example, must be turned and milled at low speeds, which tend to produce a built up edge and poor surface finish. The machining of these alloys tends to produce undesirable metallurgical surface alterations, which have been found to reduce fatigue strength.

The typical problems in surface finish include:

- Grinding burns in high straight steel air craft landing gear components
- Grinding cracks in the root sections of cast nickel base gas turbine buckets
- Lowering of fatigue strength of parts processed by Electric Discharge Machine
- Distortion of thin components
- Residual stress induced

### *1.6.2 Surface alterations*

The types of surface alterations associated with metal finishing operations are:

Mechanical: Hardness alterations, plastic deformations, cracks (microscopic and macroscopic), and residual stress distribution in surface layer

Metallurgical: Transformation of phases, grain size and distribution, precipitate and distribution, twinning, recrystallisation and resolutioning or austenite reversion

Chemical: Intergranular attack, intergranular corrosion, intergranular oxidation, contamination, embrittlement by the chemical absorption of elements such as hydrogen and chlorine, pits or selective etch and corrosion

Thermal: Heat effected zone, recast or re-deposited material, re-solidified material and splattered particles or re-melted metal deposited on surface

Electrical: Conductivity change, magnetic change and over heating

### *1.6.3 Sizing consideration may overweigh finish*

Sizing and surface improvement are usually considered separately in applications of roller burnishing. The rolling action does change size and this effect is exploited in several ways.

- To control quality of press fits

Suppose a part made on a turret lathe or automatic is to be reamed to size for a press fit preferably with a reamer ground to produce a proper peak to valley pattern. In the course of time the tolerance will drift as the tool wears. Obviously, at assembly the tighter part will give a different degree of press fit, and this change may prove to be undesirable [Bokov M and Markas L. I (1972)].

The burnishing action compacts the metal, produces a greater degree of contact with the mating part and achieves the desired uniformity in hole size, net result is a gain in the quality of the press fit.

- Sizing of sleeve bearings for proper fit with shafts

End bells for a certain_electric motor require that a bronze bushing 1 in. long be pressed into support a ¾ in. shaft. During the pressing operation the bushing closes in 0.001 in. instead of reaming or broaching, the bore is roller burnished at a rate of 300 pc per hour on a drill press. The bushing inner diameter (ID) is rolled to 0.0005in. above nominal size and the sizing operation locks the part in the bore.

### *1.6.4 Metallic Seals*

Metallic Seals are of three general types reciprocating, rotating and stationary production of high quality finishes on sealing surfaces usually under (10micro inch.) is essential if seals are to control leakage of air, oil, grease or water.

The customary method of producing this class of finish on a sealing surface is to use grinding, often followed by honing. These operations require more time and expense than roller burnishing. There is always a chance that embedded abrasive will be present to wear out the mating sealing element.

- Sealing surfaces

Sealing surfaces in or on production parts can be of many kinds: face seals, angular or taper seals or seats, ID or outer diameter (OD) seals, recessed seals, under cut seals and combinations of these general types.

- Sealing Elements

The sealing element that contacts the sealing surface may be soft (O-ring leather or plastic) or hard (graphite, graphite impregnated bronze, Stellite, steel or ceramic). Usually these are purchased parts for the assembly and are often renewable. The sealing surface in the product is the one that will be machined, and very often it can't be salvaged if incorrectly made or worn beyond service limits.

- Poor Seals increase costs

An automobile manufacturer found that many transmissions leaked while the vehicles were still under warranty. Cause: worn out O-rings. After a switch to roller burnishing the bores, large sums were saved.

- Valve Seats

The valve industry ranks first as a producer of seats. Most of these seats are tapered, some are flat, and they are used in valves for water, oils, gas, and air. Metal-to-metal seats are likewise used in pipefittings. In any case excellent geometry and finish are required for a seat to prevent leakage [Konalov E.G (1970)]. The finish should range from 8 to 12 micro- inches.

- Checking plug bodies

In checking plug bodies, they are blued to 80% contact, and the tolerances on the seat must be held to 0.00075in. for the entire length of the taper. Taper length can be two to three times the diameter.

This relationship magnifies roller burnishing problems (as compared to valve seats as a whole). Metal displacement becomes more difficult, the tapered surface is hard to generate, and the taper reaming as the prior machining step does not produce a suitable surface.

In burnishing a taper, the wall thickness surrounding the burnished surface should be uniform to avoid creating an egg shape.

- Burnishing Hydraulic cylinders

In many applications hydraulic cylinders are fitted with O-rings and a good finish is therefore required. The maximum allowable roughness is 15 micro inches. Sometimes the cylinders are fitted with glands and the seal faces are found only in those glands. In other instances the finish on the rod is very important (as in lift cylinders for form equipment and construction machinery)

- Long cylinders

In long cylinders waviness can't be corrected by honing, but such a condition is probably not important any way. There are two ways to hone (1) to size (2) to finish. In the first instance a lot of stock is removed by honing. A cheaper way to do this work is to pack bore to size, then burnish. The pack-boring tool is faster and can be made to produce the desired peak to valley distance for a good burnishing job.

In heavy-wall tubing is required, it can be produced by forging or trepanning, but the next problem is to find a shop with equipment capable of honing the part.

- Telescoping cylinders

In various hydraulic lifts the designer uses telescoping cylinders. Here the OD finish is also important. Much of this work has been done by turning to size and then finishing by cylindrical or belt-grinding [Pavlov V.A (1975)]. The newer technique is to turn and then immediately burnish in the same machine using a hollow burnishing tool that follows behind the turning tool. Any length of tubing can be processed.

- Small cylinders

Commercial air and hydraulic cylinders require two finishing operations: (1) Burnish the ID to 5-10 micro inches, and (2) Burnish the end piece or end cap to a good finish.

It is cheaper to ream and burnish an end cap in an automatic than it is to hone on a separate machine.

In respect to the cylinder's ID the cost of burnishing will probably be less than the cost of honing stones. The burnishing rolls have a long life.

## 1.7 Scope of the present work

The present work aims at studying the influence of roller burnishing process on the response factor surface finish. Experiments on the roller burnishing process were conducted under varying conditions of process parameters on different work materials like Aluminum, Brass, Copper and Mild Steel. These experiments were conducted to study the influence of main and interaction effects and also to get the optimum values of various process parameters such as burnishing force, feed, speed and depth of penetration for the best results of response factor i.e. surface finish. Other factors such as number of passes and tool approach angle were also under study for the experimental optimisation for the best results of the response factor.

The experimental optimisation was carried out for the burnishing process parameters feed, speed and depth of penetration by one-factor-at-a-time technique. The geometry of the tool was also optimised experimentally for its tool approach angle and radius. The number of passes had also got significant effect on the surface finish. The work materials selected for the experimentation were mild steel, copper, brass and alluminum. The experimental technique of changing one-factor-at-a-time optimisation might not give satisfactory results, because all the factors were inter-dependent. It was not possible to calculate interaction effects among them. Hence the experimental results were analysed theoretically for the optimum values of the process parameters by the 'Statistical Design Analysis' technique.

For the purpose of this project one of the materials most commonly used one, mild steel was selected, to determine the optimum input parameters for minimising the surface roughness the method used was 'Design of Experiments'. The 'Full factorial two level three factors Design' ($2^3$) was chosen as an initial screening method to select key input parameters which have significant effects on the 'Surface Roughness'. But it was observed that there was a curvature present. Computer print out with all details also enclosed in appendix-2. Then the design was changed to 'Central Composite Design' (CCD) with 3 factors full factorial design. For analysis of the main and interaction effects of the most significant factors ‘Response Surface Methodology’ (RSM) was used. Then the significant factors optimum values were found by using regression by drawing Response Surface (RS) plots.

# *Chapter 2*

# *Subject over view*

## 2.1 Background and motivation

The technique of applying a roller under pressure to a machined surface in order to harden the metal and improve the finish has been known and applied in the engineering industry, usually referred to as burnishing. The actual procedures varied according to the application, but they were for the most part of an empirical nature. The results were often unpredictable and adverse effects such as flaking of the surface were sometimes encountered. On account of lack of understanding the factors governing success, the only remedial steps which could be taken comprised trial and error tests. Such tests sometimes involved the scraping of many components, and in general, little information was gained which would be applied in connection with the treatment of other work pieces. Against the background of limited and rather speculative success, the process never gained more than specialized acceptance.

Within the last fifteen years an appreciation of the wider commercial possibilities, based on the results obtained in the relatively few really successful applications, has led to a revival of interest. In consequence, serious investigations have been undertaken principally on the continent, in an effort to understand the basic principles, and thus place the process on a scientific and predictable basis. Much of the research has been undertaken in Germany and Russia, [Bokov M and Markas L. I (1972)] where the modern form of the technique appears to be gaining wide acceptance in industry as a fully developed process with well established commercial and technical merits. A growing number of applications are reported in other countries, and several firms in the United Kingdom, for example, are applying what is now generally referred to as roller finishing in preference to other alternative procedures, in the volume production of high grade components.

Surface roughness is generally defined as the irregularities that are inherent in the production process left by the machining tool. Some factors causing the roughness are: the marks left by the tool, the finer structure due to the tearing of the material during machining, the debris of a built-up edge and small irregularities in the shape of the tool tip.

Owing to the inherent irregularities in the machining process, grinding, polishing, lapping and honing are commonly employed to improve the surface finish. However in recent years attention has been paid to operations, which improve surface characteristics such as the friction and wear properties, fatigue strength and surface hardness etc. by plastic deformation. Such operations sometimes referred to as plastic surface deformation. Burnishing falls into this category and is becoming more widely employed. The design of new tools and fixtures enables the plastic surface deformation process to be extended to more complicated machines and instrument components. It also enables the process to be automated and production rate to increase.

## 2.2 State of the art

Various researchers have investigated the burnishing process in different ways to find out the effect of different process parameters on lathes and milling machines for a wide range of materials [Loh N. H and Tam S. C (1988)], [Loh N. H and Tam S. C (1989)]. Work can also be carried out on grinding and shaping machines and machining centers. The experimental and theoretical investigations carried out by different researchers till now were explained in detail under four categories such as metal burnishing methods, shapes of burnishing tools, investigations on metal characteristics and surface finish measuring techniques [Hingle T and Rakes J. H (1983)].

### *2.2.1 Metal burnishing methods*

Azarevich G. M (1972) reported that when multi roller deforming devices are used for surface plastic deformation treatment it increases the wear resistance, the hardness, the depth of strengthening, and the magnitude of the residual stresses. He further reported that the residual stresses depend both on force of deformation and number of elasto-plastic cycles of deformation. The number of elasto-plastic cycles depends on the speed of the work piece, the number of deforming rollers and the duration of the process. He concluded that the state and the quality of the treated surface depend more on the deformation force than on the number of deformation cycles. But Bokov E. M and Markus L. I (1972) investigated on the same process using diamond burnishing tool and found that the use of diamond burnishing as a final treatment for the rolling tracks of bearing instead of polishing. They said that diamond burnishing simplifies the manufacturing process replacing the multi rollers, increases the surface hardness, wear resistance and creates a favorable nature of distribution of residual stresses in the surface layers.

Later Anatharam and Krishnamurthy (1978) have conducted burnishing tests using two kinds of burnishing tools such as ball burnishing tool and roller burnishing tool. They made the machine set-ups for both the processes to investigate the influence of important burnishing parameters such as speed, feed and depth of burnishing. They concluded that there is an optimum value for each of the parameter at which the best surface finish could be obtained. They also reported that there is a considerable increase in wear resistance of burnished work piece compared to ground ones. They did not verify the results by any optimization technique. The experimental investigation of above scientists is only one-factor-at-a-time technique. This will not give accuracy, as all the factors are interdependent. Hence it should be verified theoretically using existing optimization techniques.

### *2.2.2 Shapes of burnishing tools*

Some researchers changed the shape of the burnishing tool to work on different machined parts like gears, tapered grooves and holes and also any irregular shapes for better surface finish.

Konolov E. G. (1970) et al reported on the test results of burnishing of spherical surfaces stating that there is an optimum burnishing force which gives minimum surface roughness. According to him the number of passes have little effect on the surface finish. In the first pass itself a surface finish of class 8-9 limit was achieved. He concentrated only on the surfaces and modified the tool to be a spherical one to test on spherical surfaces.

Pavlov V. A (1975) developed a finger type-burnishing tool and tested the same for burnishing of large module gear tooth profiles to increase the surface hardness and at the same time to improve the surface finish. The tool was mounted on a gear hobbing machine. The test results indicated that the profile errors were reduced by 10-12%; contact spot area was increased by 10-15%; surface finish of the teeth raised from class 4- 5 to class 8-9. The surface hardness of the teeth was increased by 30-60% with a hardening depth of upto 1.65mm. Residual compressive stresses were set up in the surface layer. The fatigue strength of the teeth, the wear resistance and life of the transmission was improved.

The tool designed by Pavlov will come under roller burnishing with tool modification. He concentrated only on the gear tooth surface. He did not test different material surfaces. Later Tokio M (1992) also designed a special tool for ball burnishing to be mounted on a lathe. It is, a carbide ball elastically supported by a spring and rotated by the drive of the work piece. He examined the influence of the burnishing force, tool feed, burnishing speed, tool size, lubricants, number of passes of the tool. He recommended that burnishing process could be carried out at speeds of up to 400 m/min. The roughness of the machined surface of about Rmax = 8 μm reduced to Rmax 1μm when burnished with one pass of the tool and it reduced further to Rmax 0.1μm when burnished with repeated passes of the tool to the maximum of three passes. He further carried out the work just allowing rotation of the ball-burnishing tool to study the effect of lubricant fluid on the burnishing process. The ball-burnishing tool is rotated by the drive of the work piece mounted on the lathe. The effects of lubricants and mineral oils on the burnishing process of a medium carbon steel bar were investigated. The burnishing process was conducted on cemented carbide, bearing steel, silicon nitride, silicon carbide, and alumina ceramic ball tools. He grouped the effect of roughness of the burnished surface into three classes.

- For the cemented carbide ball tool every lubricant had a good effect
- The mineral oil containing the tricresyl phosphate had an excellent effect for each lubricant.
- Using silicon carbide and alumina ceramic ball tools no lubricant produced a beneficial effect

He worked on the ball material and concluded that straight mineral oil and mineral oil containing tricresyl phosphate has a good effect for silicon nitride ceramic and bearing steel ball tools. According to his conclusion the quality of the surface depends on the ball material and also the lubricant fluid. Most of the investigations to-date are on ball burnishing and these are only on experimental analysis. No one used theoretical or empirical analysis for optimising the results.

### *2.2.3 Investigations on material characteristics*

A.Shturman and A.N. Berlin worked on the roller burnishing process but on only for plastic materials. They investigated on the surface hardness improvement of plastic components only.

While investigating the surface hardness of plastic components by roller burnishing they found that roller pressure and speed of burnishing have some effect on the micro irregularities whilst the number of passes has plastically no effect on the class of finish. They reported that the strength of the specimens machined by roller burnishing when compared to the strength of the un-machined cast plastic specimens was found to be greater. They as shown in table 2.1 furnished this data in the form of coefficients of increase of strength.

| Property | Direction of peaks | Class of finish | | | |
|---|---|---|---|---|---|
| | Micro-irregularities | 5 | 6 | 7 | 8 |
| Tensile-Strength | longitudinal | 3.8 | 14.2 | 16.5 | 16.8 |
| | transverse | 11.2 | 11.6 | 11.5 | 10.0 |
| Impact Strength | longitudinal | 27.0 | 27.8 | 37.6 | 37.2 |
| | transverse | 18.0 | 17.5 | 22.2 | 21.5 |
| Bending Strength | longitudinal | - | - | 1.5 | 2.5 |
| | transverse | - | - | - | 3.4 |

Table 2.1 Coefficients of increase of strength

Their conclusion that the number of passes has no effect on the surface finish appears to be wrong. Loh N. H found that number of passes of the burnishing proved tool has an effect on the surface finish.

Tokio M suggested that the coolant to be used has an effect but later Bashkov G. P and Karpov N. F (1973) carried out tests to determine the effect of viscosity of coolant on burnishing process. They reported that with increasing viscosity the friction coefficient declines reaching a minimum when high viscosity mineral oil is used.

Neema M. L and Pandey P. C (1980) have conducted tests to evaluate the effects of ball burnishing parameters like speed, feed, ball diameter and force on the induced surface hardness. The results showed that very low (10ms/min.) or very high (40ms/min.) speed gives better surface finish. They reported that the increase of feed causes surface roughness to increase. However, at very low feeds the surface roughness has increased. The optimum feed was found to be 0.1mm/rev.

They also reported that the increase in burnishing force beyond the optimum level leads to reduction in surface finish and micro hardness of the surface layer. He used regression analysis for the empirical analysis of the results. His work is mainly on the ball burnishing process and the effect of coolant.

Later Tokio M et al (1993) investigated the effect of lubricant fluid on the burnishing process. They performed a burnishing experiment by forcing a cemented carbide ball or a steel ball through a slightly undersized machined hole, which is called ballizing. It is found that the viscosity of the fluid has most marked influence on the burnishing process. In the present work the authors have shown that the viscosity of the applied fluid has a great influence on the working force, plastic metal flow in the surface layer and finished surface roughness. These effects are greater than the effects produced by the addition of an "oiliness" agent to the lubricating fluid in the case of ballizing of steel.

Tokio M suggested that burnishing materially increase the hardness of the material at the surface and in the sub surface. He suggested that in particular the burnishing force has the greatest influence on work hardening the surface and sub surface to a depth of more than 200μm. He further inspected the tool surface and the retainer surface was examined using an electron probe micro-analyzer to identify the particles that scratch the tool surface. But this work was confined to only internal ball burnishing (ballizing) and the effects of the lubricant fluid.

Loh N. H et al conducted experimental work to establish the effects of various ball-burnishing parameters: depth of cut, feed, ball material, burnishing speed and lubricant on the surface roughness of specimens. He found that the surface roughness parameter first decreases and then increases with increasing depth of penetration and also the effect of feed and burnishing force showed a similar trend. The effect of speed depends on the type of lubricant used. They suggested grease is a better lubricant than cutting oil for the speed range of 450mm/min to 1200mm/min. With appropriate selection of the process parameters they obtained a surface finish of 0.7μm. from a pre machined surface roughness of about 4μm.

Later Loh N. H et al (1988) conducted experimental work using a machining center to establish the effects of various ball burnishing parameters on the surface finish of high carbon-high chrome steel including burnishing speed, ball material, lubricant, burnishing force and feed. Within the parameters explored they suggested that burnishing speed has the greatest effect on the surface finish. In his experiments he proved that grease is the better lubricant than any other cutting oil.

Loh N. H and Tam S. C (1989) further studied the effects of ball burnishing parameters on surface roughness using factorial design. They conducted experimental work based on $3^4$ factorial design on a machining center to establish the effects of the ball burnishing parameters on the surface roughness of AISI 1045 specimens. Analysis of the results by the analysis of variance technique and the F- test show that the ball material, the lubricant, the feed and the depth of penetration, have significant effects on the surface roughness. A pre machined surface roughness of 4.0μm ($R_{tm}$) can be finished to about 0.772μm. They reported that the use of factorial design showed that the effects of ball material, lubricant, feed and depth of penetration on the surface roughness were highly significant.

Loh N. H with Miyazawa investigated the use of response surface methodology to optimise the finish in ball burnishing. A second order mathematical model correlating two predominant process parameters namely depth of penetration and feed with surface roughness parameter was obtained. It predicts an optimum surface roughness value for a tungsten carbide ball. The empirical and experimental results agree reasonably well, deviating by about 2.8%. They have suggested the optimum depth of penetration and feed for best surface finish for each set of burnishing conditions. The model used by them shows that there is an interaction effect between the two parameters depth of penetration and feed.

Loh N. H et al reported on the application of experimental design in ball burnishing. They used Response Surface Methodology to establish mathematical models correlating the process parameters. They have studied burnishing speed in addition to feed and depth of penetration. They discussed the experimental design and method of analysis for fitting polynomials of the first and second order designs. Loh N.H and others worked on only ball burnishing. They did not consider the roller burnishing process.

Mohamed R and Abdellatef A. K investigated the effect of surface finish on fatigue strength. The work they carried out correlates the various surface finish parameters with the endurance fatigue strength of a commercial aluminum alloy. The fatigue initiation life as interpreted from the generated flow curves is correlated with the surface finish parameters. Results indicate a great effect for all surfaces finish parameters. They used regression analysis for exponential correlation between the parameters.

Koti V. C and Ronanki L. M (1990) investigated ball and roller burnishing processes. They made an attempt to determine the depth of plastically deformed layer both analytically and experimentally. Expressions were derived based on the theory of elasticity. Experiments were conducted on mild steel, copper, brass, and lead. The scribed lines originally straight will deform in the region of plastic deformation caused by the load applied. Under toolmakers microscope it is observed before and after loading that the surface lines underwent permanent deformation.

They concluded that the depth of plastically deformed layer increases linearly with the load. But later Skalski K et al made an analysis of contact elastic plastic strains during the process of burnishing. They developed a new mathematical model using Finite Element Method (FEM). They have considered the stick-slip friction between the tool and the machined object. The method of finite elements is an effective research tool in the analysis of contact strains as per their investigation. They proved FEM is the best method for the plastic layer deformation but not the theory of elasticity as suggested by Koti V. C and others. After Skalski K an investigation was carried out by Nicoltti N et al on residual strains induced by the burnishing process using Finite Element Analysis. Their paper describes two finite element models, which give information about the distribution of strains for an annular plate, which was burnished at a constant radius, and compares the calculations with experimental results obtained with strain gauges.

Some researchers proved that FEM could also be used to investigate elastic-plastic strains during burnishing. But it was not applied to investigate other properties of the material.

Gambin W investigated the Seizing effect in the roller burnishing process. He reported that micro graphs of metal surface layers after the roller burnishing process show that while about 90% of the surface layer thickness is displaced forwards of the roller motion. A thin contact zone undergoes a backward displacement.

Adel Mahmood Hassan et al discussed the surface hardness produced by the ball burnishing process. They studied the influence of the main burnishing parameters speed, feed, number of tool passes and ball diameter on the surface roughness and hardness of two different non-ferrous materials. Further, subsurface hardness and microstructure under specific conditions were also studied. They found that feed and force are the more significant parameters, which alter the work piece surface during the burnishing process.

They concluded that the surface roughness decreases with increase in feed rate, burnishing speed, force and number of passes, to a certain limit and then it starts to increase with each of the above parameters. The surface hardness decreases with an increase in feed rate and burnishing speed, while the hardness increases with the burnishing force and number of tool passes.

Lee S. S. G and Loh N.H started investigations on surface finishing of plastic injection mould cavity plastics by ball burnishing Table 2.2 - 2.5. They studied computer integrated ball burnishing of a plastic injection mould cavity. A CAD model of the cavity insert was first created and the associated NC tool path is down loaded to a CNC vertical-machining center in which the milling and burnishing were undertaken. They presented a procedure for creating a solid model of the mould cavity. Pilot milling and burnishing operations were performed on flat specimens, in order to ascertain suitable speeds, feeds and depths of cut. They suggested a depth of penetration of 10μm and a feed of 0.1mm could achieve the best surface finish of 0.03μm.

| | Milling (mm) | Burnishing single pass |
|---|---|---|
| Tool | HSS ball -end | HSS ball end |
| Table speed | 100 mm-1 | 300mm-1 |
| Machining Tolerance | 0.001 | 0.001 |
| Feed | 0.1 | 0.1 |

Table 2.2 Parameters used in trial milling and burnishing of mould cavity insert

| | | | |
|---|---|---|---|
| Depth of penetration in microns | 10 | 25 | 50 |
| Surface roughness | 0.93 | 0.62 | 1.20 |

Table 2.3 Surface Roughness of mould cavity insert for different depths of penetration

| | | | | |
|---|---|---|---|---|
| Depth of penetration | 25 | 10/15 | 10/15 | Milled surface |
| Surface roughness | 0.89 | 1.11 | 1.14 | 3.68 |

Table 2.4 Surface roughness of the mould cavity for different depths of penetration

| | Milling surface finish | Burnishing surface finish | Percentage(%) Improvement |
|---|---|---|---|
| Flat specimen | 2.34 | 0.30 | 87.2 |
| Curved surfaces | 3.68 | 0.98 | 75.8 |

Table 2.5 Comparisons of the burnished surface quality of flat and curved surfaces

They discussed the variation of surface roughness with depth of penetration as well as single and double passes of the burnishing process. They showed that if the depth of penetration were not large double pass burnishing would not produce a better surface quality than single pass.

### 2.2.4 Surface finish-measuring techniques

There are different types of surface finish measuring techniques. Very few of the researchers worked on measuring techniques.

Hingle H. T and Rakes J. H investigated on Diffraction Technique to assess surface finish. They concluded that conventional stylus techniques are not always suitable for measuring surface finish due to the physical shape of the stylus and also because of possible damage of the surface due to tracking the stylus across the surface. Hence they suggested an alternate non-contact technique. One of the possibilities is diffraction technique. They investigated the validity of this technique in a working environment. Brodmann G et al (1984) studied on an optical instrument for measuring the surface roughness in production control. The measuring instrument is based on the light scattering method. Different theoretical models of stray light reflection are addressed. An optical parameter will be calculated from the stray light distribution, and its relationship to the surface roughness was proved in practical applications. They also proved that optical techniques would be increasingly used for testing the surface quality.

D. J. Whitehouse compared Stylus and Optical methods for measuring surfaces. He proposed that optical methods have taken off in one direction and mechanical methods have taken off in a complementary direction but neither by themselves is as yet capable of fully integrated measurement as well as providing an in process measurement capability. Ideally therefore, a technique in which the two trends of the past are vectorially added is to be expected in the future. Whitehouse D. J further investigated on the same methods and explained two important points through his study on surface topography and its quality, one instrumental and other theoretical. The instrumental advances were digitizing the outputs of stylus instruments and using relocation methods. The theoretical advance has been the use of random process theory, which enables the most suitable parameters for a given function to be identified. It would allow the designer to be able to look up the functionality of components based on the achieved surface finish. Ramesh and Ramamoorthy also worked on an optical diffraction technique for the measurement of surface finish. They investigated the validity of the non-contact optical type of diffraction technique in the evaluation of the surface finish. They demonstrated the diffraction technique was better than the stylus method.

## 2.3 Objectives of the research work

From the literature survey it is clear that most of the work has been carried out in four different areas of the burnishing as explained. Loh N. H and others investigated ball burnishing theoretically using experimental design. Tam S. C and Loh N. H did experimental verification.

Azarevich G. M and Pavlov V. A and Anantharam et al worked individually on finger type burnishing, gear tooth profile burnishing and conventional roller burnishing and suggested optimum process parameters experimentally. But no research was found which investigated the roller burnishing process parameters theoretically for its optimum values. Most experimental results were based on the one-factor-at-a-time technique. That means one can't change more than one factor at a time on the machine. This will not give much accuracy, as all the process parameters are interdependent factors. In this process of experimentation interaction effects cannot be measured. That's why it is less accurate. I have suggested an optimisation technique with which these interaction effects will be taken into consideration and give much more accurate results.

This research work considered the roller-burnishing process to investigate the surface finish, which can be achieved with both soft and hard materials. The work was carried out experimentally for the materials like aluminum, copper, brass and mild steel. The theoretical analysis was for mild steel. The empirical optimisation technique used in this research work was Experimental Design Technique. The preliminary tests were conducted using $2^3$ Full Factorial Designs and the analysis was done by ANOVA. But this preliminary design and analysis was not helpful in finding the interactions, as there was a lack of fit present. However, it was possible to identify the significant factors. Then the Central Composite Design (CCD) was used and the analysis was carried out by the Response Surface Methodology (RSM). The significant factors found by RSM were further analysed by regression to find their optimum values.

# *Chapter 3*

# *Roller burnishing tool Design and Fabrication*

*Page no.*

## 3.1 Design of roller burnishing tool

The design of roller burnishing tool for external cylindrical surfaces was based on the following guidelines:

- Selection of the roller material and its dimensions based on the diameter of the work to burnish and the stiffness of the tool.

- Selection of the material for the shank and pin and its dimensions based on the stiffness criteria, roller size and availability.

- Determination of the size of the each part of the burnishing tool based on the machine on which it is being used as an attachment.

- Finally the aesthetic aspect of the roller burnishing tool.

The roller burnishing tool is designed in such a manner that it can be mounted on the Centre Lathe tool post. In the design more emphasis is given to streamlining the overall dimensions.

### *3.1.1 Selection of roller*

The most widely used profiles of rollers, used for burnishing are shown in Figure 3.1. The use of cylindrical roller 'b' (land) will increase the surface smoothness of burnished surfaces and the longer the cylindrical land the larger can be the burnishing feeds. However the larger land requires the application of higher radial loads. This is possible only with stiffer burnishing fixtures. For small and medium sized components the length of the cylindrical land is normally 1mm to 5mm and for heavy components it is 5 mm to 15 mm. The tool approach angle was selected in the order of $6^0$ - $12^0$ for the optimisation of the tool angle. The roller used has a 4mm land and $8^0$ tool approach angle.

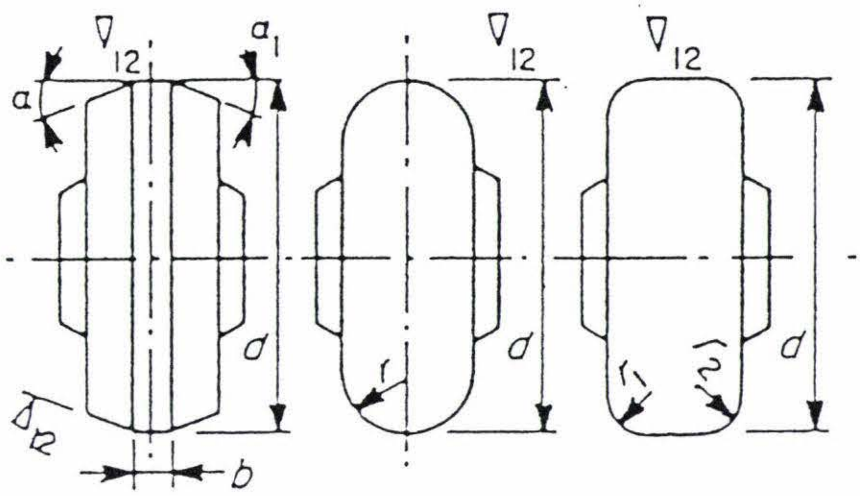


Figure 3.1 Different types of rollers

### *3.1.2 Shank selection*

Mild steel is selected for the shank portion of the tool. All the dimensions were fixed based on the roller size and the tool post size of the lathe.

## 3.2 Fabrication of the roller burnishing tool

The shank of the tool was machined to the correct dimensions on a milling machine using end mills. For this purpose a square block of mild steel of size 300mm × 75mm × 75mm was cut.

### 3.2.1 Sequence of operations

1. Sizing of the block to 70 × 40mm in cross section
2. Machining of the surfaces using 25mm end mill

3. Machining of 30mm width slot using 25mm end mill.

4. Holes of 32.4mm and 25.4mm diameter were drilled in the two ends of the front portion.

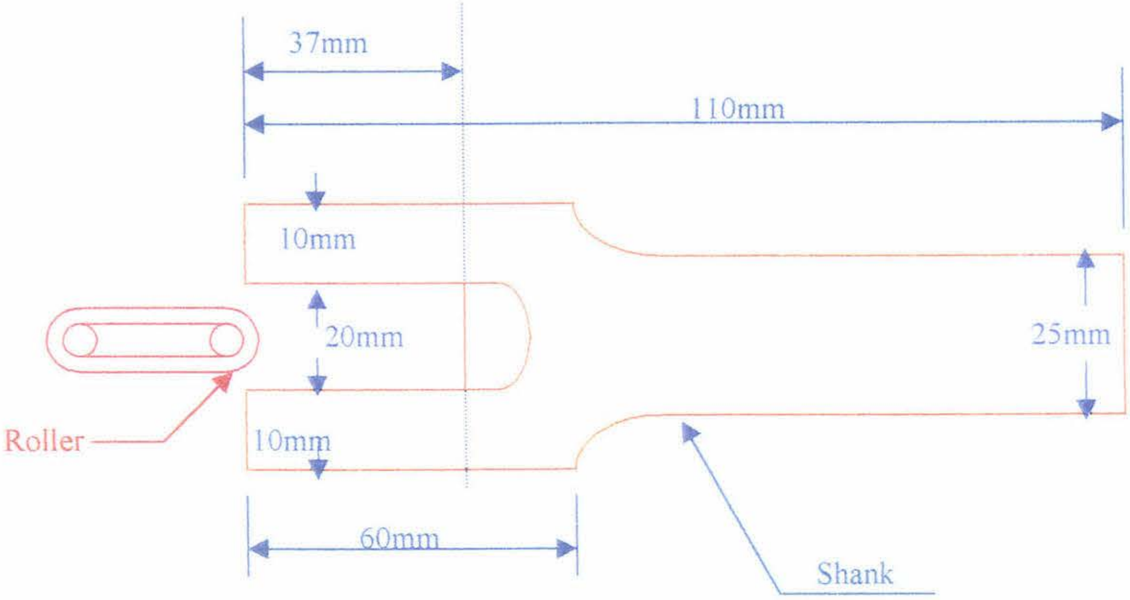
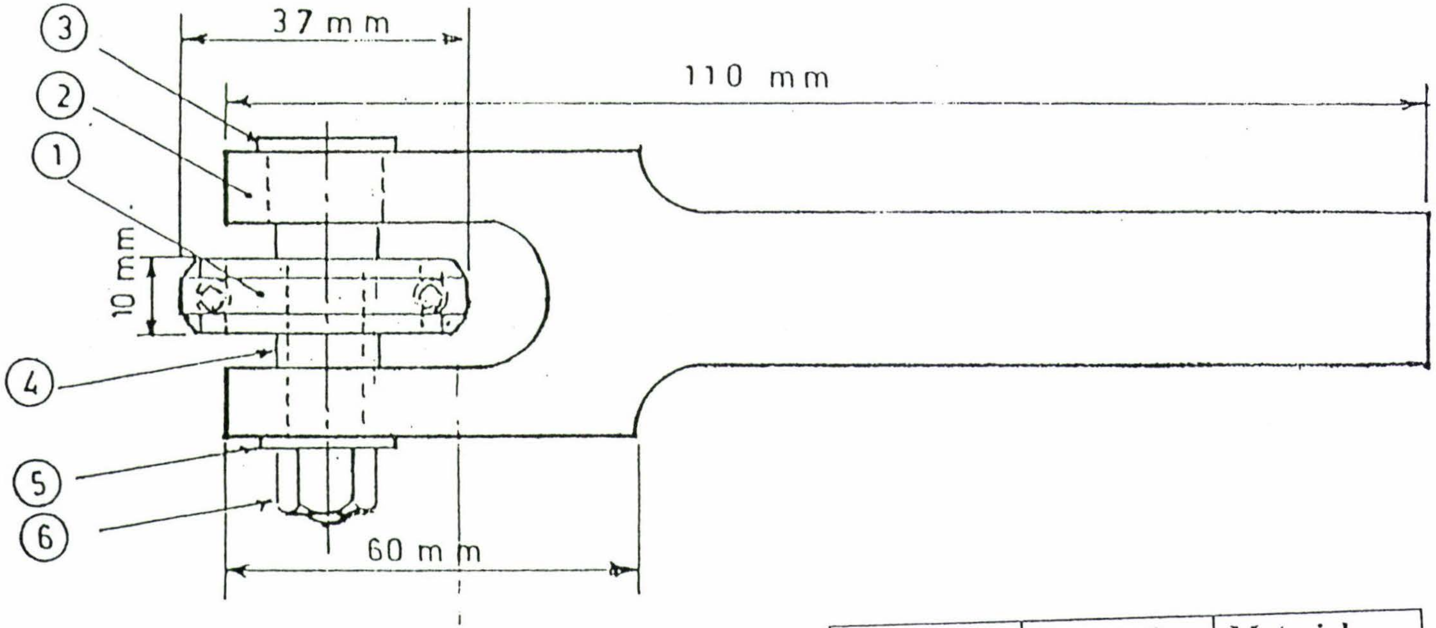



Figure 3.2 Shank of the burnishing tool

After preparation of the shank the pin for positioning the roller into the shank was made on a lathe from a mild steel rod of size diameter 50mm and 150mm long Figure 3.2.

The final shape with dimensions of the roller burnishing tool is shown in the Figure 3.3.




| Part No. | Description | Material |
|---|---|---|
| 1 | Roller | Nickel Alloy |
| 2 | Shank | Mild Steel |
| 3 | Pin | Mild Steel |
| 4 | Bush | Mild Steel |
| 5 | Washer | Mild Steel |
| 6 | Nut | Mild Steel |

Figure 3.3 Roller burnishing tool

# *Chapter 4*

# *Experimental set up*

## 4.1 Experimental set-up

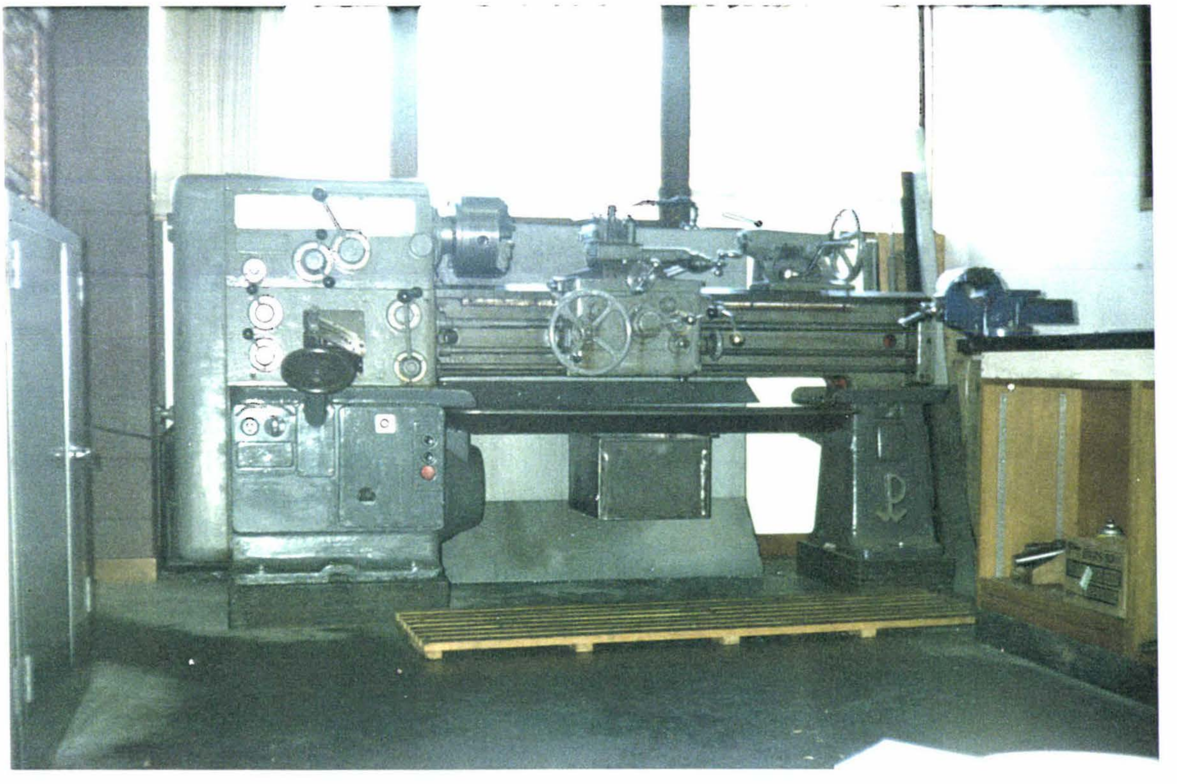
The experimental investigations for roller burnishing requires an experimental set up consisting of the following:

- The lathe machine on which the burnishing tool post is mounted in the tool post
- Work pieces of different materials
- Lathe tool dynamometer for measuring the burnishing forces
- Surface finish measuring equipment
- Hardness testing equipment

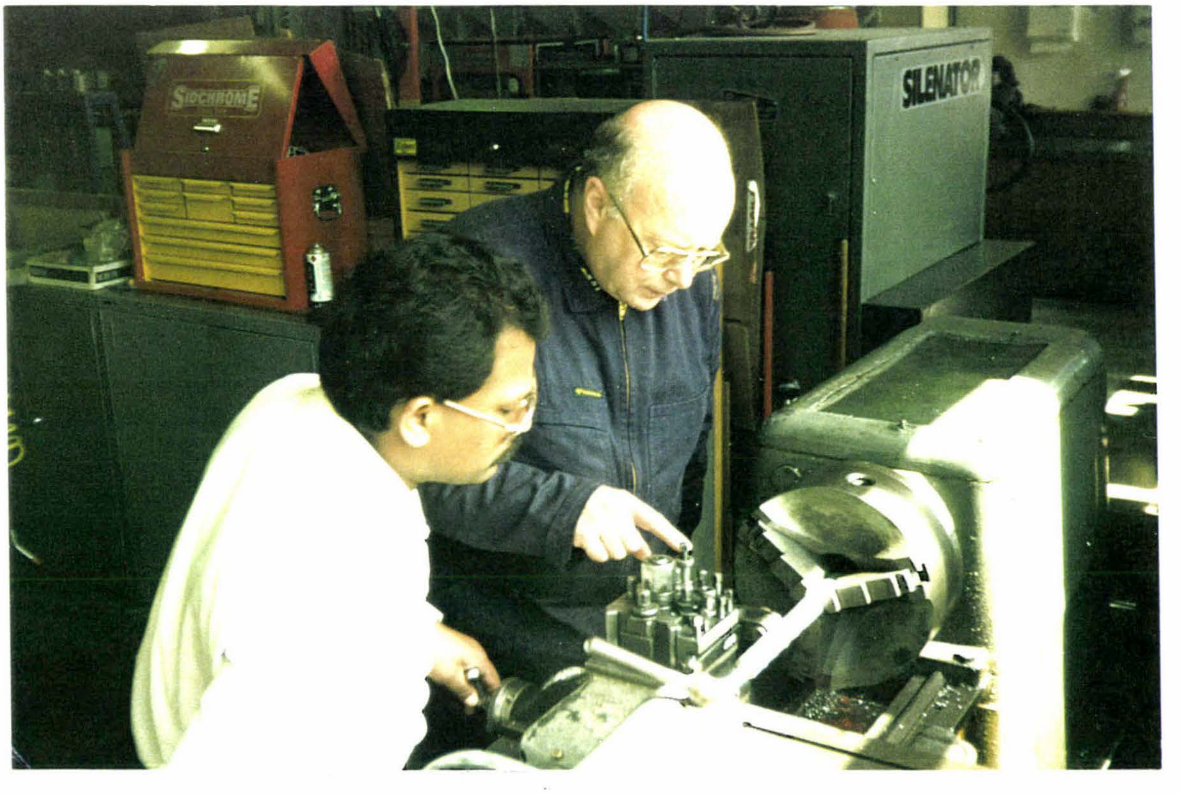
The experiments of roller burnishing were carried out on a centre lathe. The Figure 4.1a shows the overall picture of the lathe and Figure 4.1b shows the setup of the burnishing tool. The specifications of the centre lathe were given in the Table 4.1.

| | |
|---|---|
| Maximum distance between centres | 1000mm |
| Height of centres | 200mm |
| Swing over bed (diameter) | 420mm |
| Swing over cross slide (diameter) | 220mm |
| Width of gap (diameter) | 155mm |
| Head stock spindle nose | 42- 6" type |
| Spindle bore (diameter) | 53mm |
| Spindle socket taper | Metric 60 |
| Spindle speed | 32 to 1200rpm |
| Number of speeds | 8 |
| Number of feeds | 18 |
| Pitch of lead screw | 6mm |

Table 4.1 Specifications of the centre lathe



4.1 a. Centre Lathe




4.1 b. Working on centre lathe

*4.1.1 The principle of burnishing process*

Burnishing process is a relatively simple and can be easily performed on most machine tools. The principle of the roller burnishing process is shown in Figure 4.2. The roller axis AA is slightly skewed with respect to the work axis and the feed direction. The work revolves at a constant speed and the roller rotates as a result of the frictional engagement to the work piece. As each portion of the surface of the work is traversed, metal from the protrusions is displaced plastically and will fill the depressions [Loh N. H and Tam S. C (1989)].

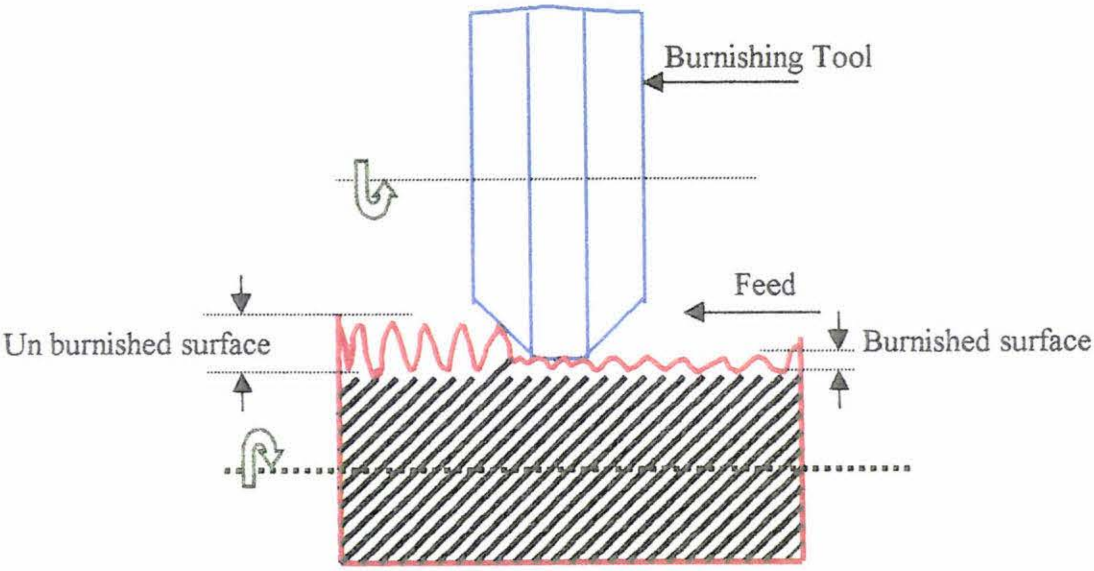



Figure 4.2 Roller burnishing process

As observed in the process of experimentation the roller burnishing process is a plastic deformation process and the deformation zones are shown in Figure 4.3. There is rotary motion between the roller and the work piece [Neema M. L and Pandey P. C (1980)]. Due to this rotary motion there is some intermittent loss of contact. This loss of contact does not effect the result. Hence it is neglected.

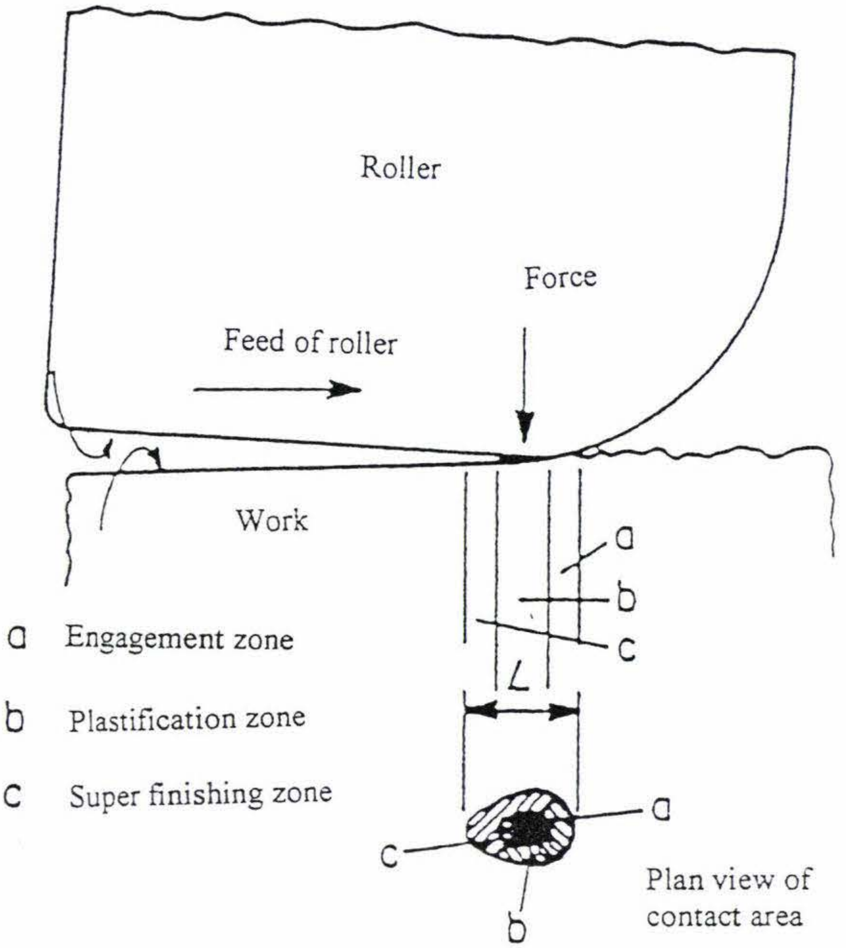



Figure 4.3 Contact zones in roller burnishing process

Disregarding the intermittent loss of contact, the surface metal is first compressed, then plasticised and finally wiped to a super finish as the contact is progressively diminished and the stresses are gradually dissipated. Among the three zones, engagement zone, plastification zone and super finishing zone of deformation as shown in Figure 4.3. The principal action takes place in the central plasticisation zone, where the metal in both the peaks and valley becomes plastic. Flow is induced along the lines of least resistance down both flanks of the peaks with the valleys filling as two opposed flow streams meet at the bottom. As the metal is neither lost nor gained during the deformation, the final diameter is roughly the mean of initial protrusion and depression diameter [Morawski et al (1995)].

### *4.1.2 Work pieces*

The work piece materials used for the present investigation work are indicated in Table 4.2

| S. No | Materials | Quantity (Nos.) |
|---|---|---|
| 1 | Mild Steel | 5 |
| 2 | Braas | 2 |
| 3 | Aluminum | 3 |
| 4 | Copper | 2 |

Table 4.2 Work pieces used for roller burnishing

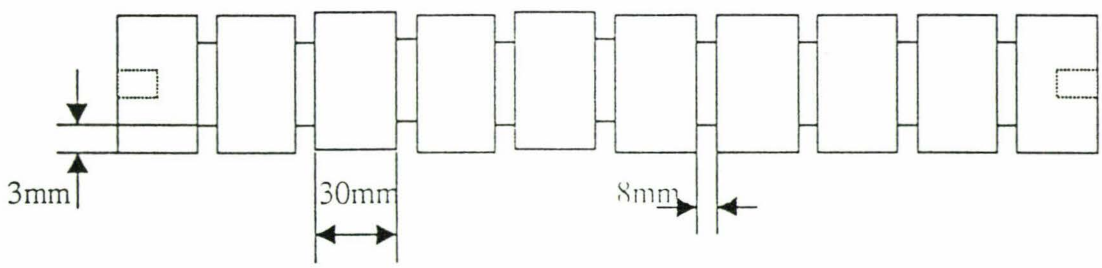



Figure 4.4 Work piece with grooves

The rods were turned carefully to give the most general finish obtainable in turning operations. The length of the rod was divided into a number of stations of length 30mm each separated by a groove of 8mm width and 3mm deep. Each station on the job is utilised to study the effect of a particular parameter Figure 4.4. Both the ends of the job, centre holes were made so that job could be held between the two centres to have a better supporting grip. The tail stock centre support also helps in avoiding the overhanging of the job and also in preventing deflection under the action of the burnishing forces. The set up on the lathe machine is shown in Figure 4.5. On the work piece all the sharp edges are chamfered off so that no metal particles come in between the roller and the work piece while the burnishing process is in progress.

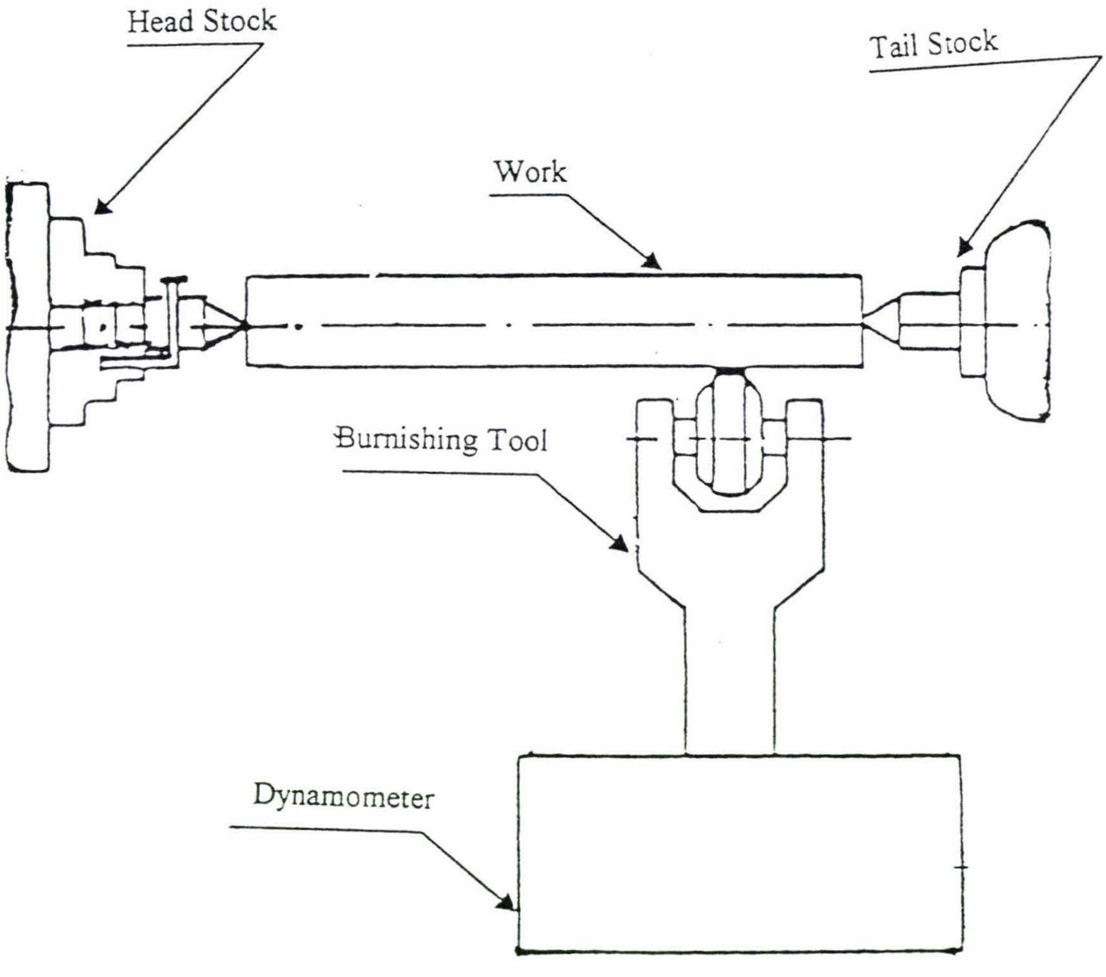



Figure 4.5 Experimental setup for Roller Burnishing

### *4.1.3 Mechanism of burnishing*

In burnishing the metal flows from the peaks to fill the valleys of the surface irregularities. This results in reduction of peak to valley height of surface roughness. This idea of plastic flow did not seem to be realistic at first thought. To check only this mechanism of burnishing two types of experiments were conducted. In the first, burnishing tool was given a depth of penetration of 200microns without any cross feed engaged with the rotating work piece and then suddenly withdrawn. In the second, along with the depth of penetration a cross feed of 150 microns was also given, and then the tool is engaged with the rotating work piece.
Hence due to the burnishing mechanism the material is plastically displaced leading to the formation of grooves. These grooves will not get modified again due to metal plastic deformation in the succeeding revolution of the work piece. The style of the pattern observed on the surface of the work piece is represented graphically with the more accuracy in approximation as shown in the Figure 4.6. But a new surface roughness pattern is obtained which has a better finish when compared to un-burnished surface. Due to the pressure exerted by roller, the material will occupy the troughs of micro-irregularities deforms on either side of the roller thus forming into grooves. This is tested by engaging the roller burnishing tool with the work and withdrawn after one revolution, two revolutions and multiple revolutions of the work piece and the same pattern is shown in Figure 4.6 as an initial groove formation, second groove formation and a set of overlapped grooves respectively. The grooves are seen at the junction of burnished and un-burnished surface. Hence we can say that the improvement in surface finish during burnishing is due to combined effect of two processes, one is material flow from peaks into valleys and the other one is overlapping of grooves.

## 4.2 Description of experiments

Experiments were conducted on four different materials mild steel, brass, aluminum and copper. All these work pieces of different materials were turned for finish cut at high speed and low feed and low depth of cut on the centre lathe prior to the roller burnishing process. Turning was done with High Speed Steel (H.S.S) single point tool having rake angle $5^0$, included angle $52^0$ and clearance angle $6^0$. Grooves were made along the length of the work pieces to study the effect of changing various burnishing process parameters. Each section is tested for a different set of burnishing process parameters varying only one parameter at-a-time keeping the rest constant. The burnishing force was measured for each of the burnished sections with a tool dynamometer.

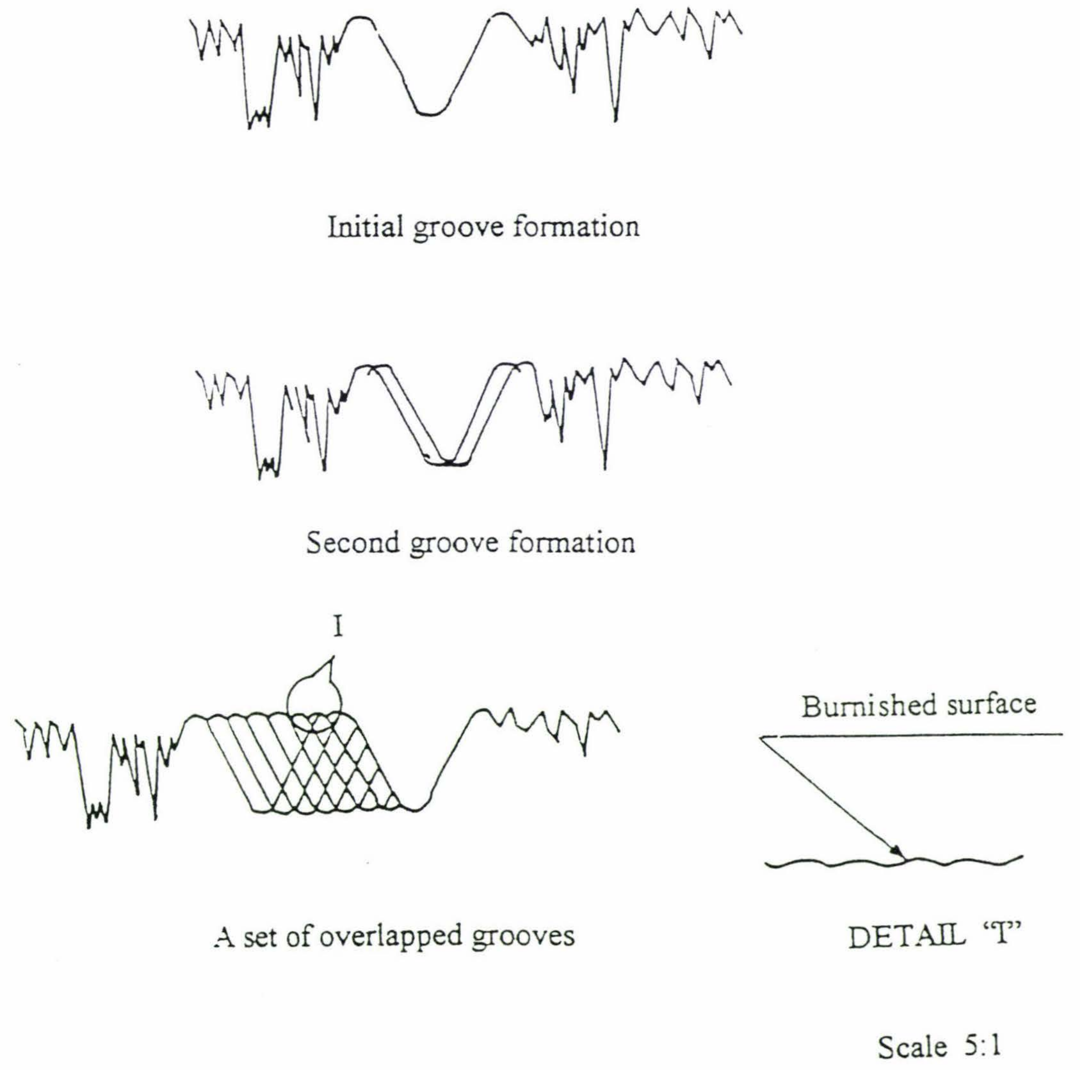


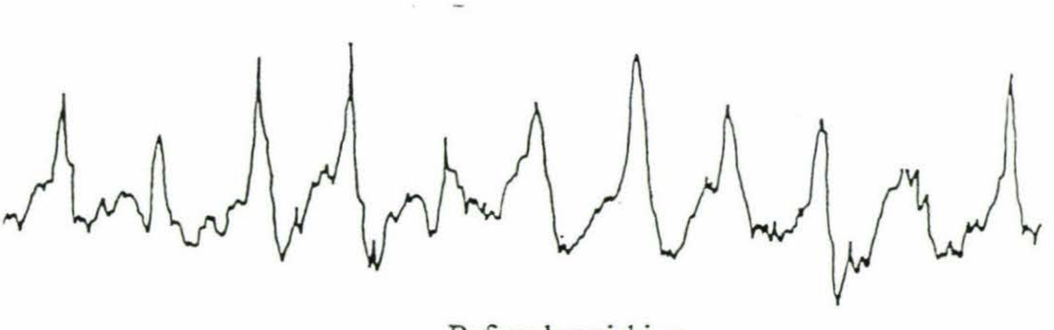

Figure 4.6 Mechanism of burnishing

### 4.3 Measurement of surface roughness

The present work deals with the effect of selected parameters of roller burnishing on the surface finish, of the burnished work piece. Any machined surface indicates a great number of both macro-geometrical and micro-geometrical deviations from the ideal geometrical surface figure 4.7

The macro geometrical deviations are known as waves and are caused due to inaccuracies of the machine tool such as lack of straightness of slide ways, vibrations, chatter, deflection of work piece during process etc.

The micro geometrical deviations refer to its surface roughness. The surface roughness is dependent on metal cutting process parameters and tool geometry. The micro irregularities are also caused by various factors such as work material properties, the chip formation process, condition of the tool, friction at the contact point between the tool and the work. These process parameters are generally considered as the predominant factors causing surface roughness. Mainly with the increase in feed, the phenomenon of capture and rupture of metal layers increases causing the surface finish to deteriorate.



Before burnishing

After burnishing

Figure 4.7 Surface roughness profiles

### *4.3.1 Measurement by mechanical methods*

The surface finish of the specimens was measured using a Taylor Hobson Talysurf Machine. This is a direct measuring instrument using stylus probe type of instruments. Talysurf is an electronic instrument working on carrier modulating principle. This instrument records the static displacement of the stylus and is a dynamic instrument like a profilometer but the measurement is obtained much more rapidly and accurately (Figure 4.8).

The measuring head of this instrument consists of a diamond stylus of about 0.002 mm tip radius and skid or shoe which is drawn across the surface by means of motorised driving unit (gear box), which provides three speeds suitable for obtaining an average reading. A neutral position in which the pickup can be transversed manually was also provided. The arm carrying the stylus forms an armature which pivots about the centre-piece in the form of an 'E'shaped stamping. The two coils present on the stamping along with the resistor form an oscillator. Any movement of the stylus causes the air gap between the stamping and the armature to vary and thus the magnitude of the current from mains (AC supply) is modulated which is further amplified and demodulated to give a measure of the vertical displacement of the stylus.

The demodulated output is fed to a pen recorder to produce a permanent record and a meter to give a numerical assessment directly. The recorder of this instrument has the marking medium, which is an electric discharge through a specially treated paper. The discharge blackens the paper.

Figure 4.8 Surface finish measurement with Taylor Hobson Talysurf Instrument

# *Chapter 5*

# *Experimental Results and discussion*

Roller burnishing experiments were conducted on aluminum, copper, brass, and mild steel to study the effect of burnishing process parameters on surface finish. The geometry of the tool is optimised for its radius and its approach angle. The number of passes of burnishing tool was also under consideration for optimising the response variable of surface roughness. During the process of roller burnishing the optimum geometry of the roller was also determined [Koorapati E. P et al (1996)]. The force applied during this process was also noted.

### 5.1 Effect of roller radius

The effect of roller radius on surface finish during roller burnishing was studied. The selected parameters for this study are speed of 33m/min, feed of 0.05mm/rev and depth of penetration of 0.01mm. The results are shown in Table 5.1 and the corresponding graph is in Figure 5.1. The optimum radius of the roller was found to be 10mm from the Figure 5.1. It was compared with the effect of nose radius of a single point cutting tool on surface finish in metal cutting to the roller radius during burnishing.

It is concluded that at a small radius the surface finish was made worse deteriorated. At higher radius the contact area being greater, the work material may not be fully yielding to the load exerted by the roller. Therefore, the material from the peaks of the surface was not deformed to fill up the valleys thus resulting in lack of improvement in surface finish of the work material.

### 5.2 Effect of tool approach angle

The effect of approach angle of the burnishing tool was investigated and the results are tabulated in the Table 5.2 and the graph in the Figure 5.2

The optimum approach angle was found to be $8^0$. It may be concluded that at higher approach angle the surface finish will not be good. But at lower angles the material at the peaks was fractured instead of being smoothly deformed to fill up the valleys. Therefore the roller approach angle with $8^0$ produced better results. Fracturing was observed at the lower approach angles.

### 5.3 Effect of number of passes

The experimental results obtained by varying the number of passes are as shown in the Table 5.3 and the graph in the Figure 5.3. It shows that after every pass up to three passes, there was an improvement in the surface finish and there after it started deteriorating.

The reason may be due to the material getting work hardened during every pass. Due to this effect, the material was becoming brittle and after third pass brittle fracture was taking place thus deteriorating the surface finish.

### 5.4 Effect of burnishing force

At lower values of the burnishing force the material from the peaks of the surface was not fully deformed to fill up the valleys thus resulting in rough surface.

At higher burnishing forces due to seizure failure the surface finish was deteriorated. Also at higher forces the material goes to a plastic state and is work hardened. Due to this work hardening effect the material loses its ductility and becomes brittle. The results of changing the burnishing force are shown in Tables 5.4 - 5.7, with the trend line graph shown in Figures 5.4 -5.7. From the graph it could be observed that the force also had a significant effect on the surface roughness. The optimum values of the force are found experimentally for the materials as follows. Mild steel 400 Newtons, aluminum 310 Newtons, copper 350 Newtons and brass 410 Newtons.

### 5.5 Effect of feed

An optimum feed was evident for each work material [Arshinov et al (1976)] found that the work hardening effect on the burnished surface is greater at lower feed and decreases with increase in feed. This is true with all the metals mild steel, copper, brass and aluminum. At lower feeds the surface is very rough because of the stick-slip phenomenon [Koti V. C and Ronanki L. M (1990)], [Morawski at al (1995)] in metal cutting and at higher feeds due to the onset of vibrations, the surface finish deteriorates. At feeds lesser than 0.05mm/rev the surface finish deteriorated due to stick slip motion. The results are given in the Tables 5.8 – 5.10. The trend line graphs are given in the Figures 5.8 – 5.10. The experimental optimum values of the feed for mild steel 105μm, aluminum and copper 120μm and for brass 110μm are observed from the Figures 5.8 - 5.10.

### 5.6 Effect of burnishing speed

During the experiments, the depth of cut and feed were kept constant and the speed was varied. The results are shown in the Table 5.11 and the corresponding graphs are shown in Figure 5.11 for aluminum and copper, Figure 5.12 for brass and 5.13 for mild steel.
Within the range of speed studied, the general trend is that the surface roughness ($R_a$) value first decreases as the speed increases, after attaining the optimum value then the reverse effect occurred. The trend of the graph is shown in the Figures 5.11, 5.12 and 5.13. The optimum speed for obtaining the better finish is observed to be 33m/min. The reasons for deteriorating the surface finish at speeds other than this speed is because of the volume of the material deformed will increase with increase in speed. This results in increase in burnishing force. At higher burnishing force the peaks are getting fractured instead of deforming smoothly into the troughs of the surface resulting in bad surface finish. At lower speeds, the burnishing force was insufficient to deform the crests into the troughs.

### 5.7 Effect of depth of penetration

The effect of depth of penetration on surface roughness has been studied. The test results revealed that at very low values of depth of penetration the surface finish obtained was too rough. This is due to insufficient burnishing force, resulting incomplete deformation. At higher values of depth of cut a heavy force of burnishing is comes onto the surface, causing excessive seizure failure. The optimum value of the depth of cut is 0.1mm. The test results are recorded in the Table 5.12. The graph in the Figure 5.14 for mild steel and brass and Figure 5.15 for aluminum and copper show that as the depth of penetration increases, the surface roughness decreases up to an optimum point, and increases beyond the optimum depth of penetration.

For each material under study there is a corresponding optimum depth of penetration, which gives the best surface finish. As the roller burnishing process is basically a plastic deformation process, the depth of penetration has to be sufficiently high to deform the work piece. Too shallow deformation may cause elastic deformation only. The graph shows the trend of changing surface finish with the change in depth of penetration. For the best surface finish the optimum value of depth of penetration was suggested experimentally for aluminum 120μm, copper 110μm, mild steel 100μm and brass 110μm. The same can be observed from the graphs shown in Figures 5.14 and 5.15.

| Roller radius mm | Surface roughness μm (microns) |
|---|---|
| 3 | 0.6 |
| 4 | 0.52 |
| 5 | 0.46 |
| 7 | 0.31 |
| 8 | 0.26 |
| 9.5 | 0.27 |
| 11 | 0.29 |
| 12 | 0.32 |
| 14 | 0.45 |
| 15.5 | 0.57 |

Table 5.1 Influence of roller radius on surface roughness

| Approach angle degrees | Surface roughness μm (microns) |
|---|---|
| 4.5° | 0.78 |
| 6° | 0.48 |
| 7° | 0.41 |
| 8° | 0.36 |
| 10° | 0.45 |
| 12° | 0.82 |

Table 5.2 Influence of approach angle on surface roughness

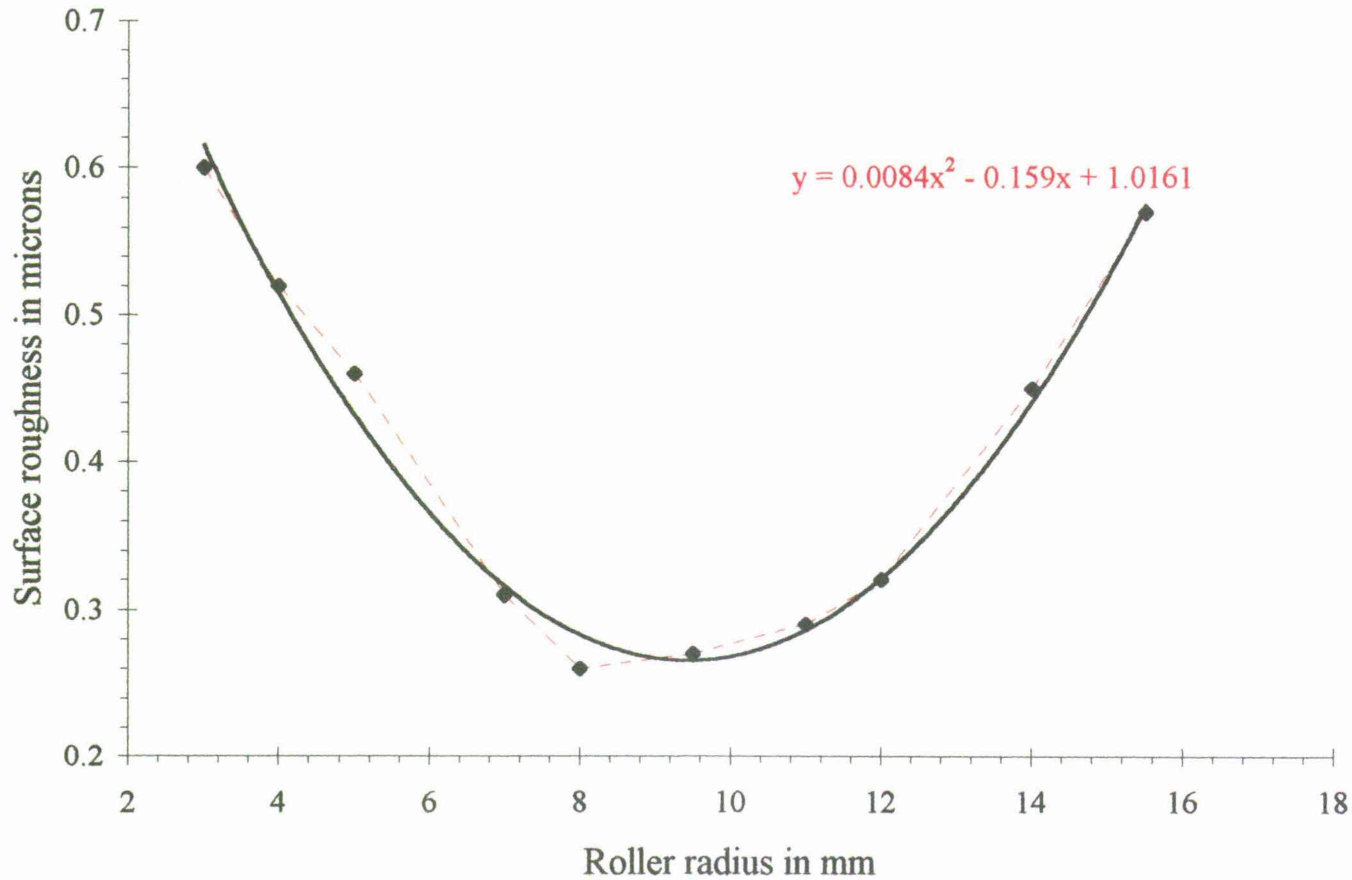



Figure 5.1 Effect of roller radius on surface roughness

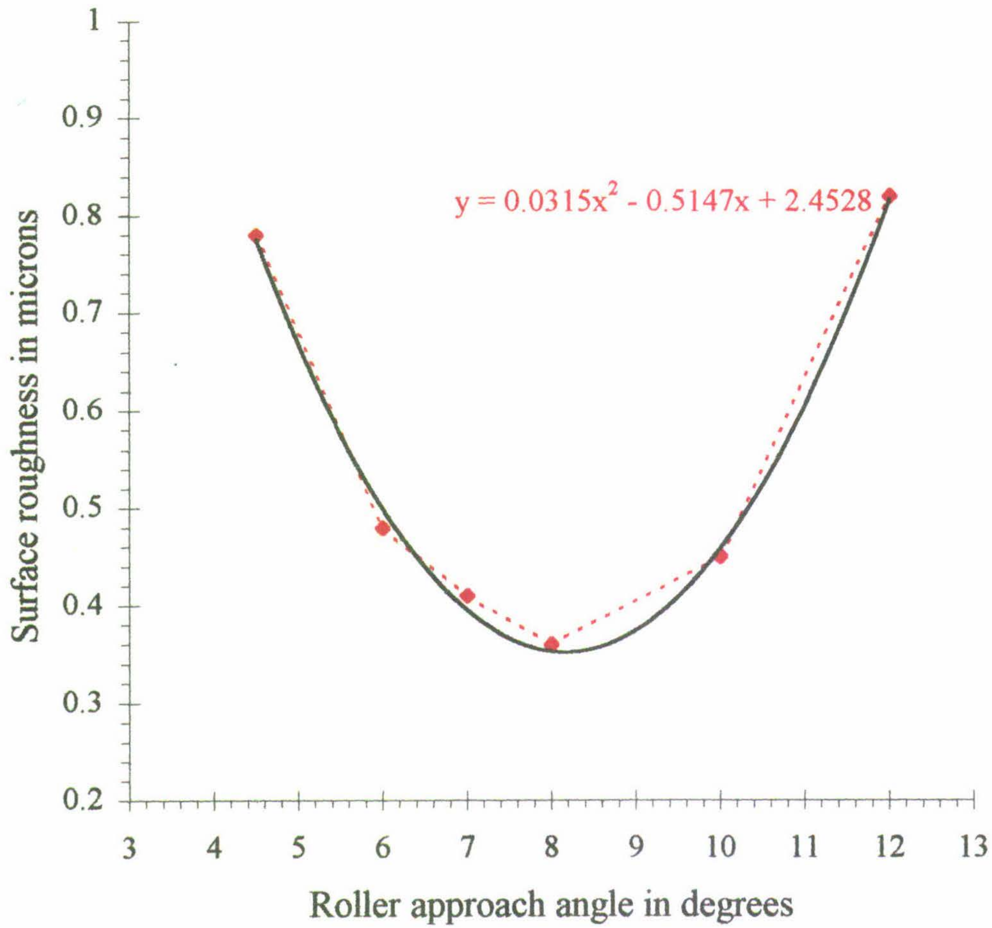



Figure 5.2 Effect of roller approach angle on surface roughness

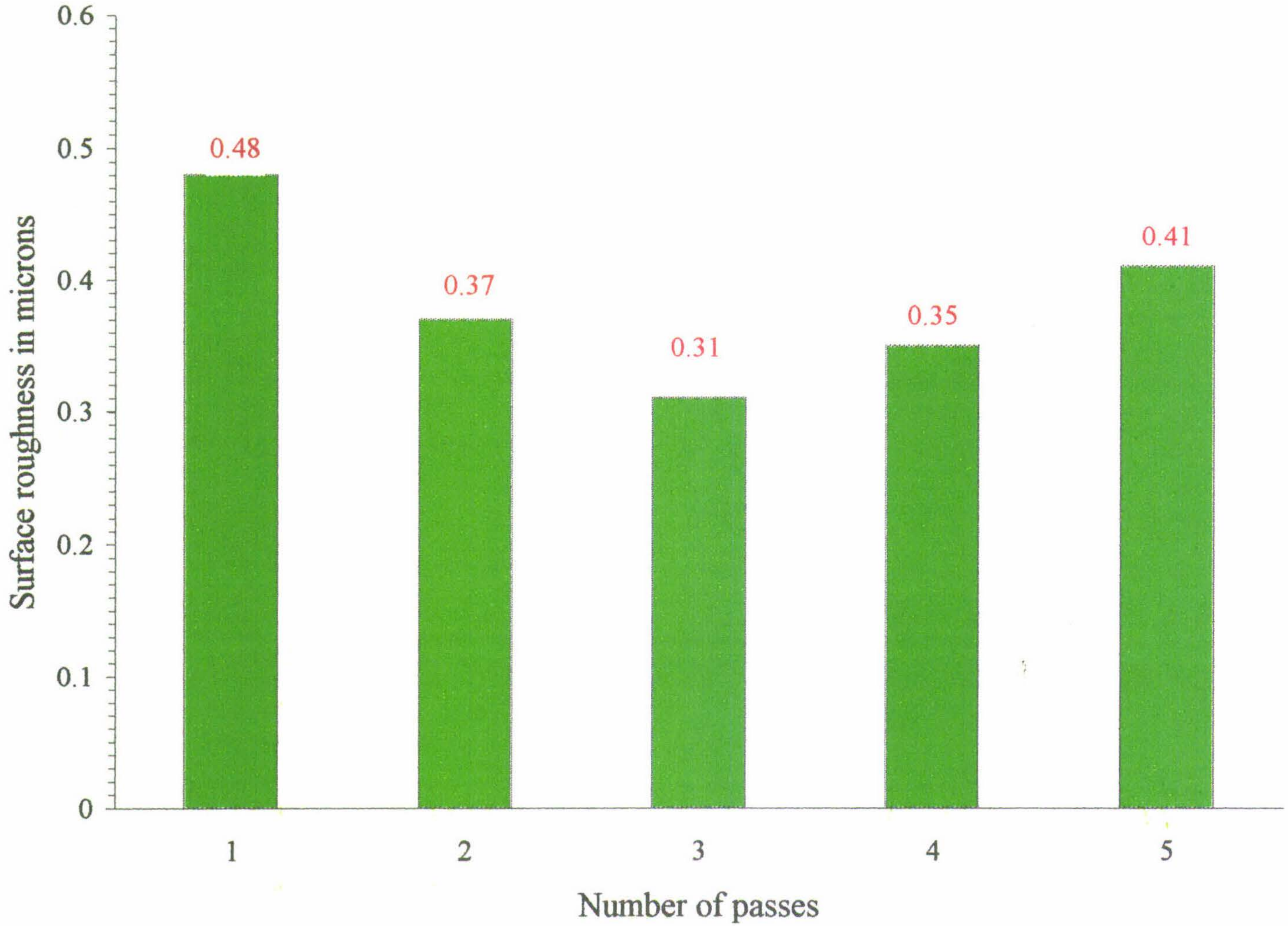



Figure 5.3 Effect of number of passes on surface finish

| Number of passes<br>Nos. | Surface roughness<br>microns |
|---|---|
| 1 | 0.48 |
| 2 | 0.37 |
| 3 | 0.31 |
| 4 | 0.35 |
| 5 | 0.41 |

Table 5.3 Influence number of passes on surface roughness

| S.No. | Force<br>Newtons | Surface roughness<br>Microns |
|---|---|---|
| 1 | 248 | 0.9 |
| 2 | 324 | 0.65 |
| 3 | 371 | 0.49 |
| 4 | 450 | 0.37 |
| 5 | 528 | 0.56 |
| 6 | 609 | 0.85 |
| 7 | 675 | 1.03 |
| 8 | 749 | 1.38 |
| Material : Mild Steel<br>Feed = 0.125mm/rev Speed = 28.4m/min | | |

Table 5.4 Effect of force on surface roughness

| S.NO | Force Newtons | Surface roughness Microns |
|---|---|---|
| 1 | 200 | 0.76 |
| 2 | 254 | 0.53 |
| 3 | 269 | 0.44 |
| 4 | 357 | 0.33 |
| 5 | 430 | 0.68 |
| 6 | 520 | 1.25 |
| Material: Aluminum<br>Feed = 0.125mm/rev; Speed = 20.29m/min | | |

Table 5.5 Effect of force on surface roughness for aluminium

| S.NO | Force Newtons | Surface roughness Microns |
|---|---|---|
| 1 | 220 | 0.96 |
| 2 | 284 | 0.7 |
| 3 | 362 | 0.48 |
| 4 | 418 | 0.35 |
| 5 | 427 | 0.44 |
| 6 | 447 | 0.56 |
| 7 | 473 | 0.69 |
| 8 | 524 | 0.99 |
| 9 | 560 | 1.2 |
| Material: Copper<br>Feed = 0.125mm/rev; Speed = 20.29m/min | | |

Table 5.6 Effect of force on surface roughness for copper

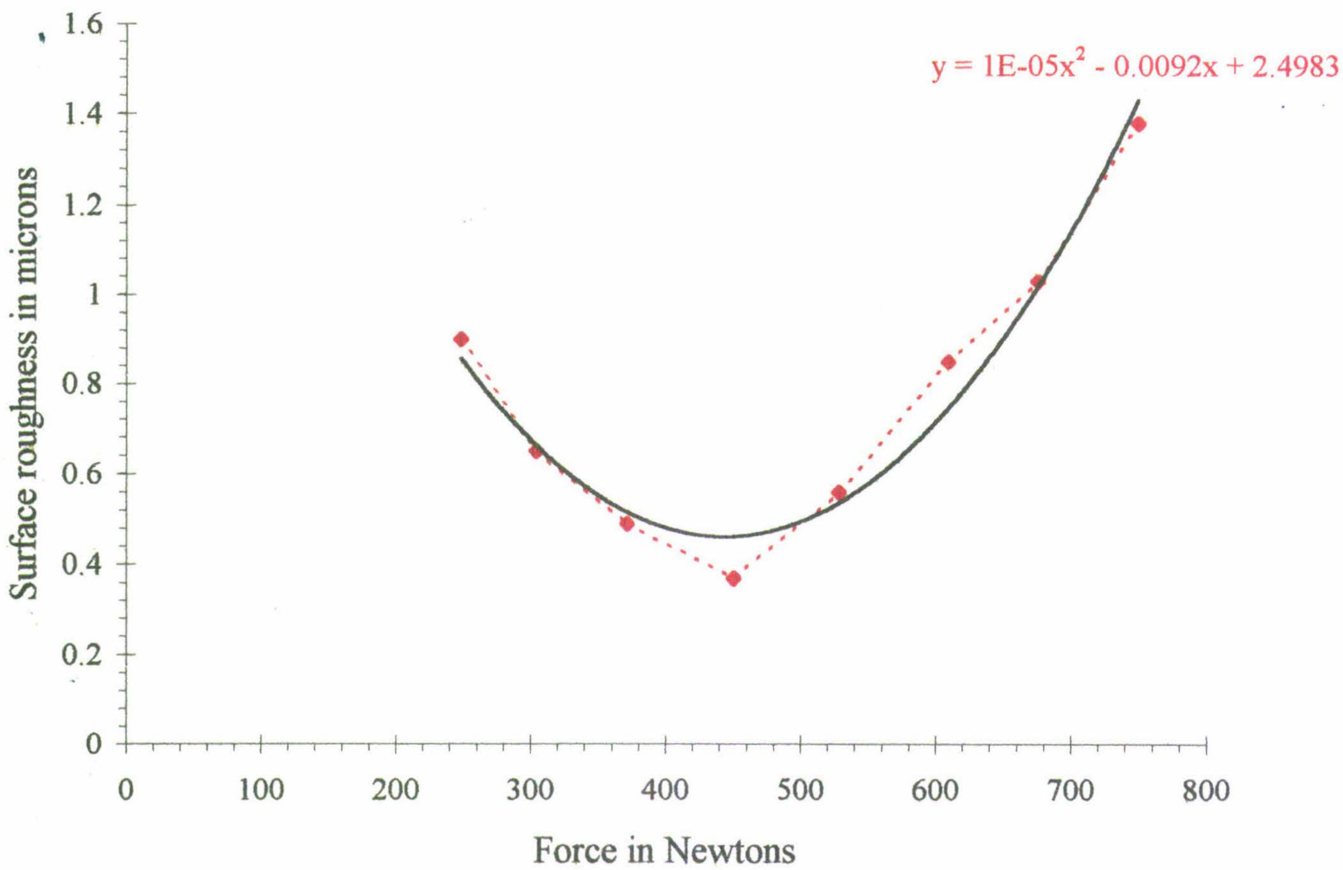



Figure 5.4 Effect force on surface roughness for mild steel

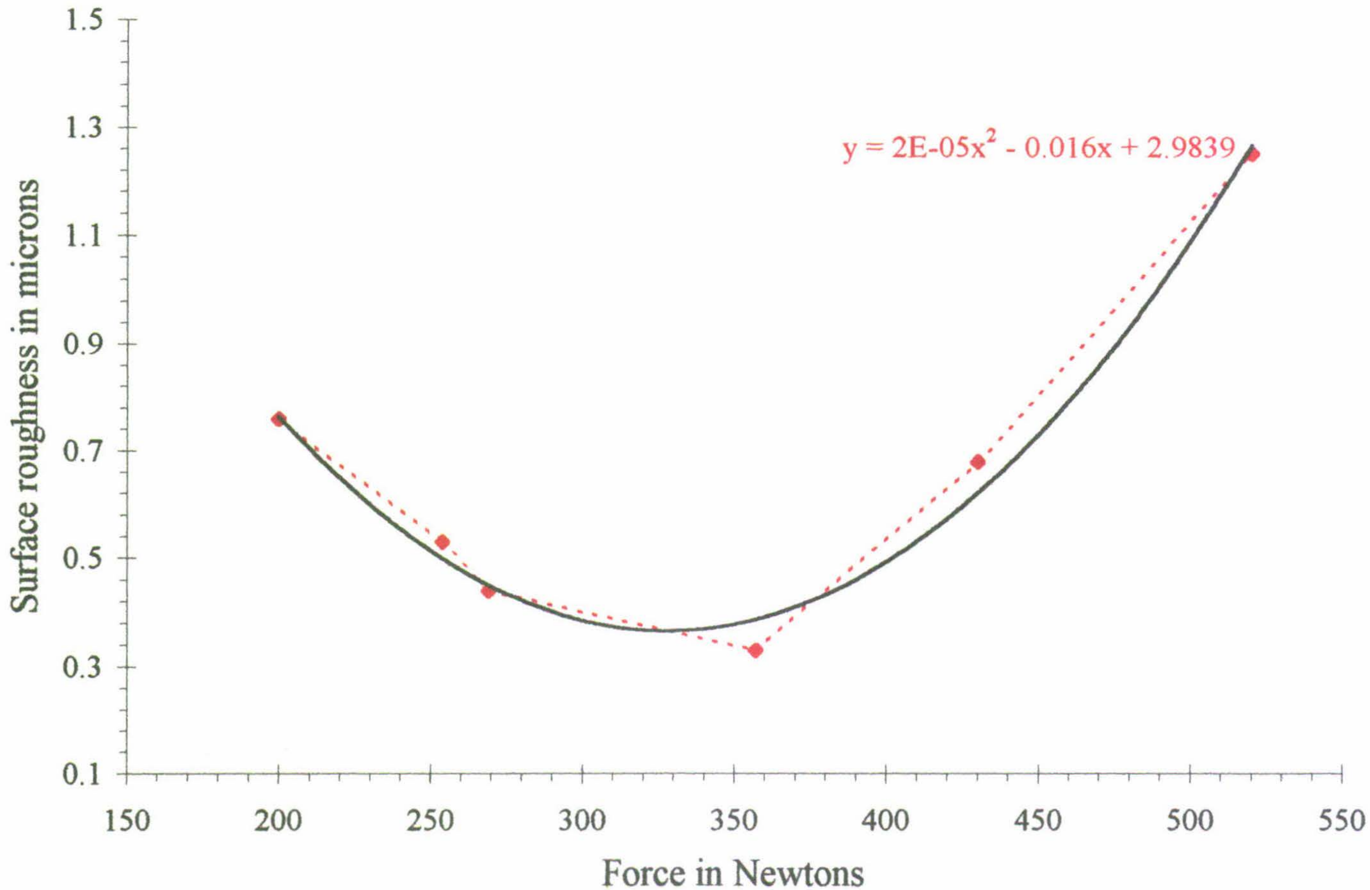



Figure 5.5 Effect of force on surface roughness for aluminium

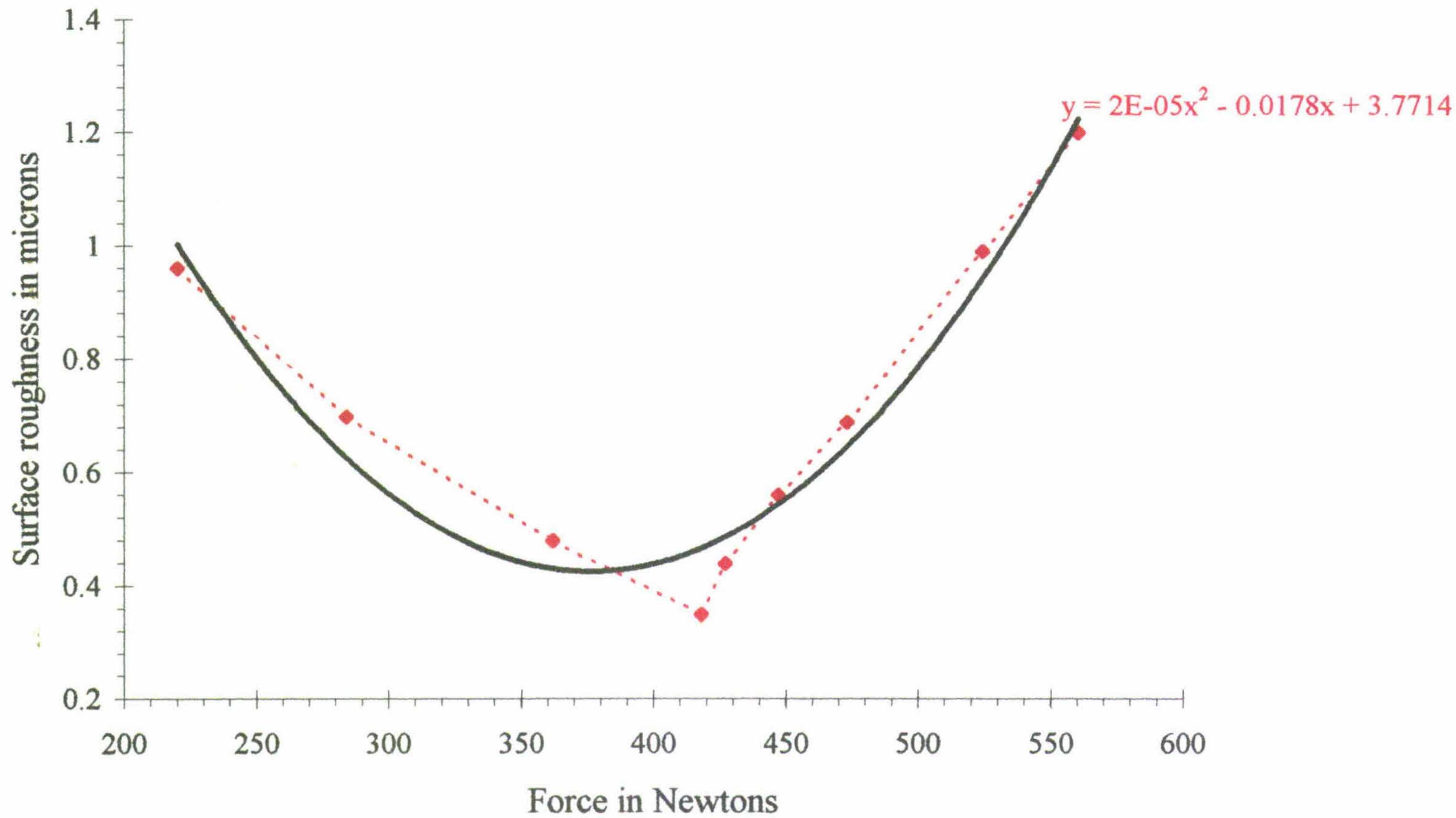





Figure 5.6 Effect of force on surface roughness for copper

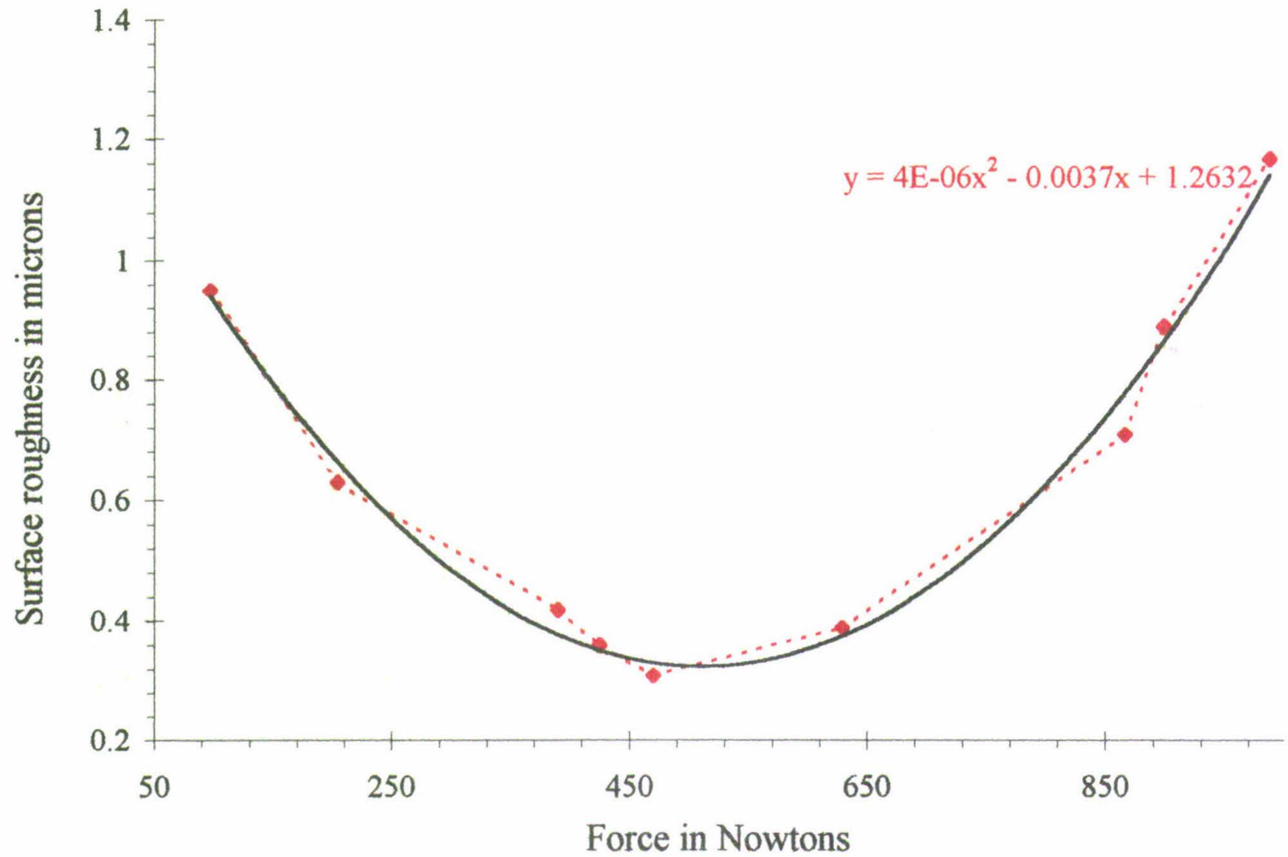



Figure 5.7 Effect of force on surface roghness for brass

| S.No | Force Newtons | Surface roughness Microns |
|---|---|---|
| 1 | 97 | 0.95 |
| 2 | 204 | 0.63 |
| 3 | 390 | 0.42 |
| 4 | 425 | 0.36 |
| 5 | 470 | 0.31 |
| 6 | 629 | 0.39 |
| 7 | 866 | 0.71 |
| 8 | 898 | 0.89 |
| 9 | 1042 | 1.25 |
| Material: Brass<br>Feed = 0.125mm/rev and Speed = 29.4 m/min | | |

Table 5.7 Effect of force on surface roughness for brass

| S.NO | Feed Microns | Surface roughness Microns |
|---|---|---|
| 1 | 40 | 0.79 |
| 2 | 50 | 0.58 |
| 3 | 70 | 0.36 |
| 4 | 125 | 0.26 |
| 5 | 185 | 0.49 |
| 6 | 210 | 0.77 |
| Material: Mild steel<br>Speed = 26.89m/min | | |

Table 5.8 Effect of feed on surface roughness for mild steel

| S.No | Feed Microns | Surface roughness Microns | |
|---|---|---|---|
| - | - | Aluminum | Copper |
| 1 | 40 | 0.57 | 0.71 |
| 2 | 50 | 0.46 | 0.56 |
| 3 | 70 | 0.34 | 0.43 |
| 4 | 125 | 0.2 | 0.32 |
| 5 | 185 | 0.37 | 0.49 |
| 6 | 210 | 0.51 | 0.62 |
| Speed = 29.4 m/min | | | |

Table 5.9 Effect of feed on surface roughness in roller burnishing

| S.No | feed Microns | Surface roughness Microns |
|---|---|---|
| 1 | 40 | 0.69 |
| 2 | 50 | 0.48 |
| 3 | 70 | 0.36 |
| 4 | 125 | 0.23 |
| 5 | 185 | 0.35 |
| 6 | 210 | 0.58 |
| Material: Brass<br>Speed = 26.89m/min | | |

able 5.10 Effect of feed on surface roughness for brass

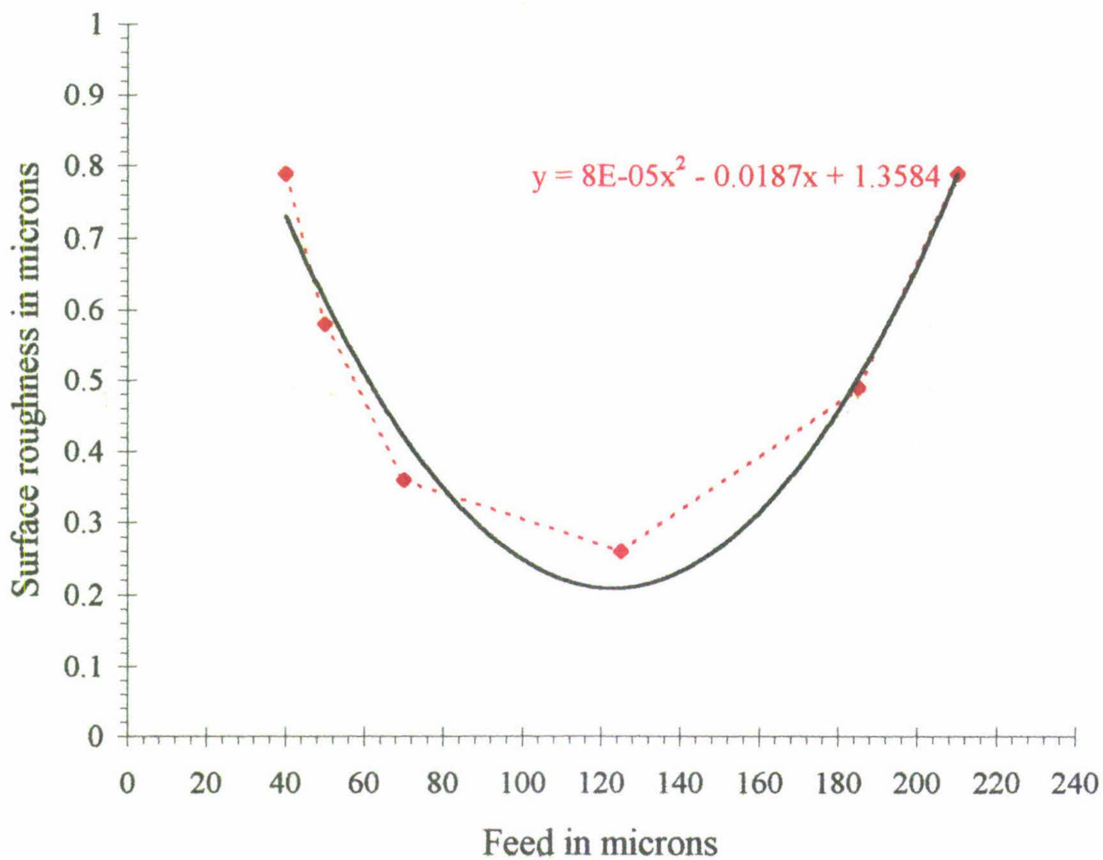



Figure 5.8 Effect of feed on surface roughness for mild steel

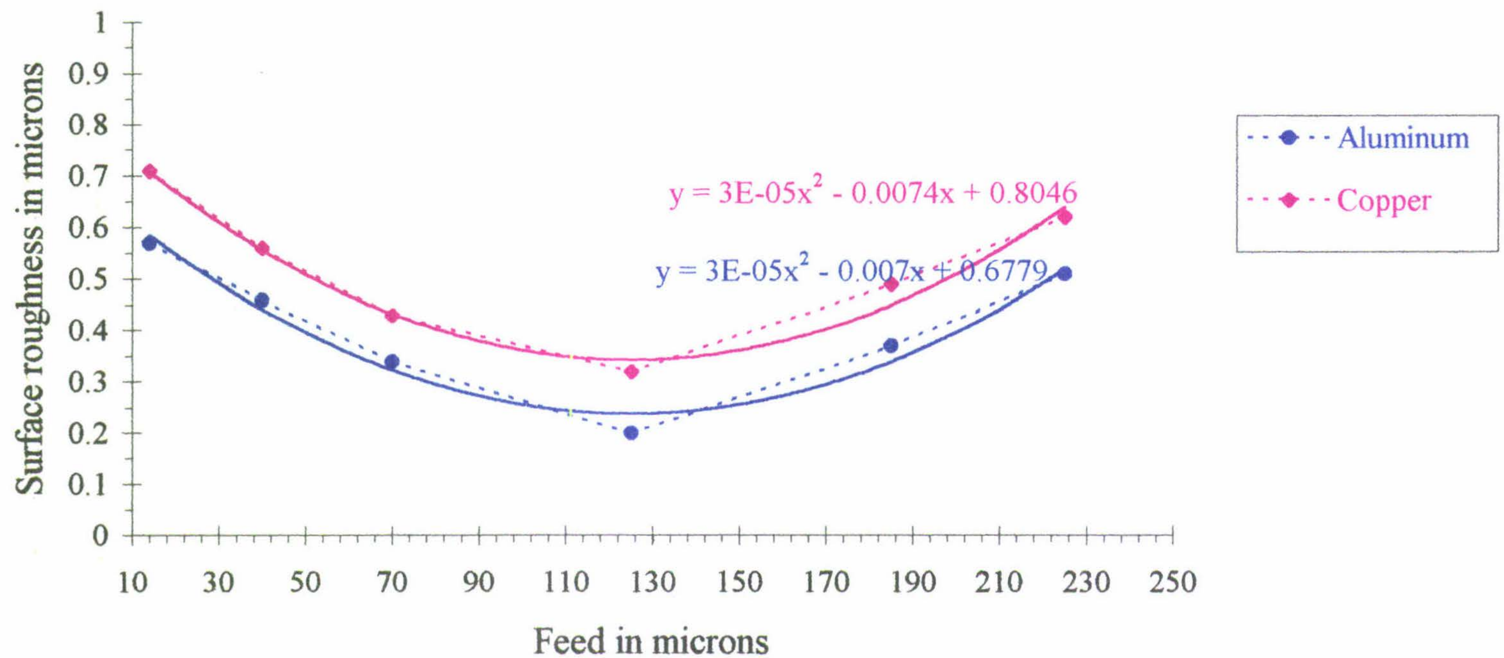



Figure 5.9 Effect of feed on surface roughness for aluminum and copper

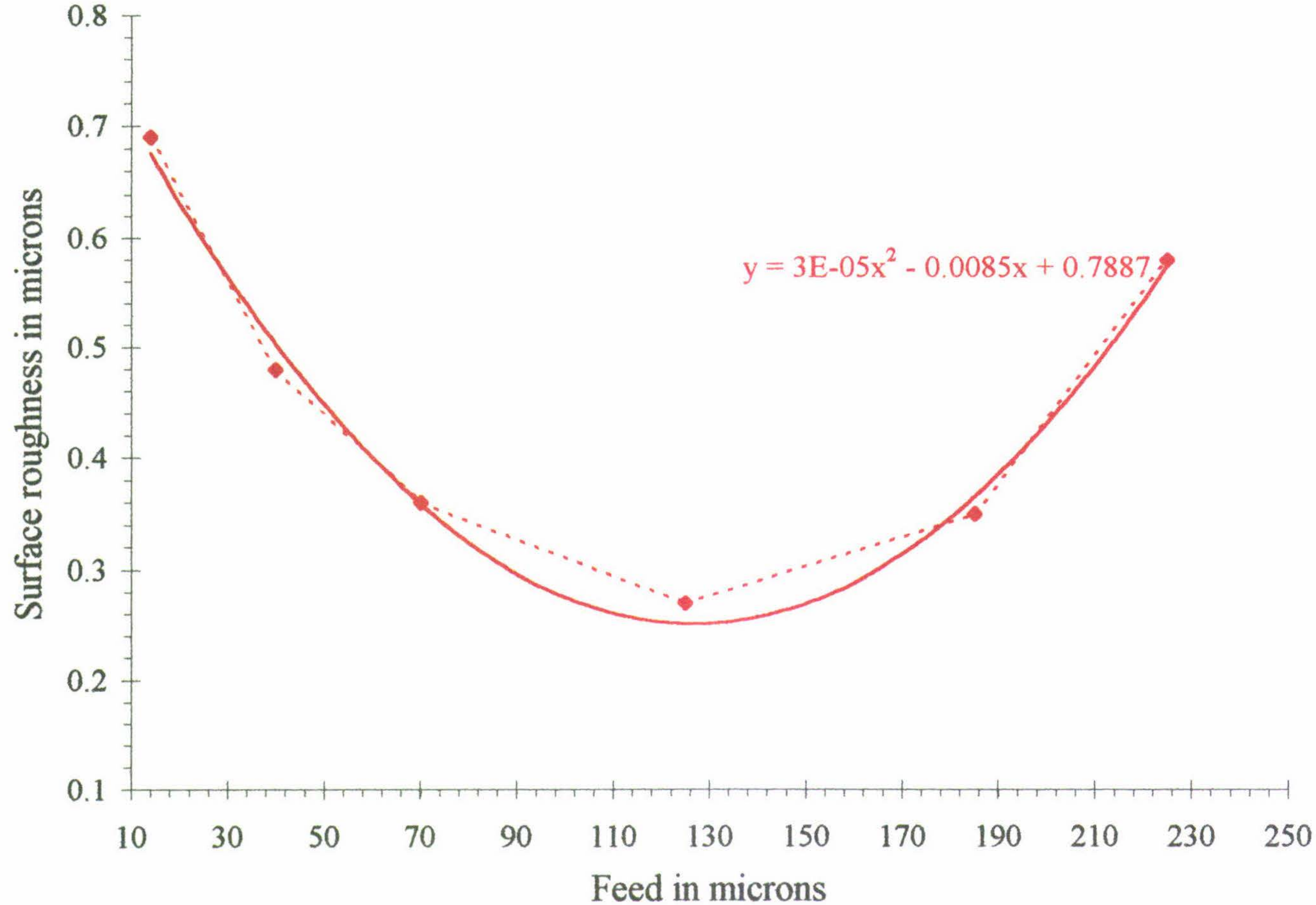



Figure 5.10 Effect of feed on surface roughness for brass

| S. No | Speed m/min | Surface roughness microns | | Speed m/min | Surface roughness Microns | Speed m/min | Surface roughness Microns |
|---|---|---|---|---|---|---|---|
| | | Aluminum | Copper | - | Brass | - | Mild Steel |
| 1 | 13.8 | 0.35 | 0.45 | 18.7 | 0.35 | 18.7 | 0.32 |
| 2 | 20.2 | 0.25 | 0.38 | 25.66 | 0.28 | 25.66 | 0.26 |
| 3 | 28.65 | 0.2 | 0.31 | 34.2 | 0.20 | 34.2 | 0.2 |
| 4 | 40.7 | 0.18 | 0.24 | 47.4 | 0.26 | 47.4 | 0.26 |
| 5 | 57.3 | 0.26 | 0.32 | 57.6 | 0.39 | 55.5 | 0.36 |
| 6 | 81.43 | 0.50 | 0.62 | 64 | 0.47 | 64 | 0.46 |
| Feed = 0.125mm/rev | | | Feed = 0.1mm/rev | | | | |

Table 5.11 Effect of speed on surface roughness in roller burnishing

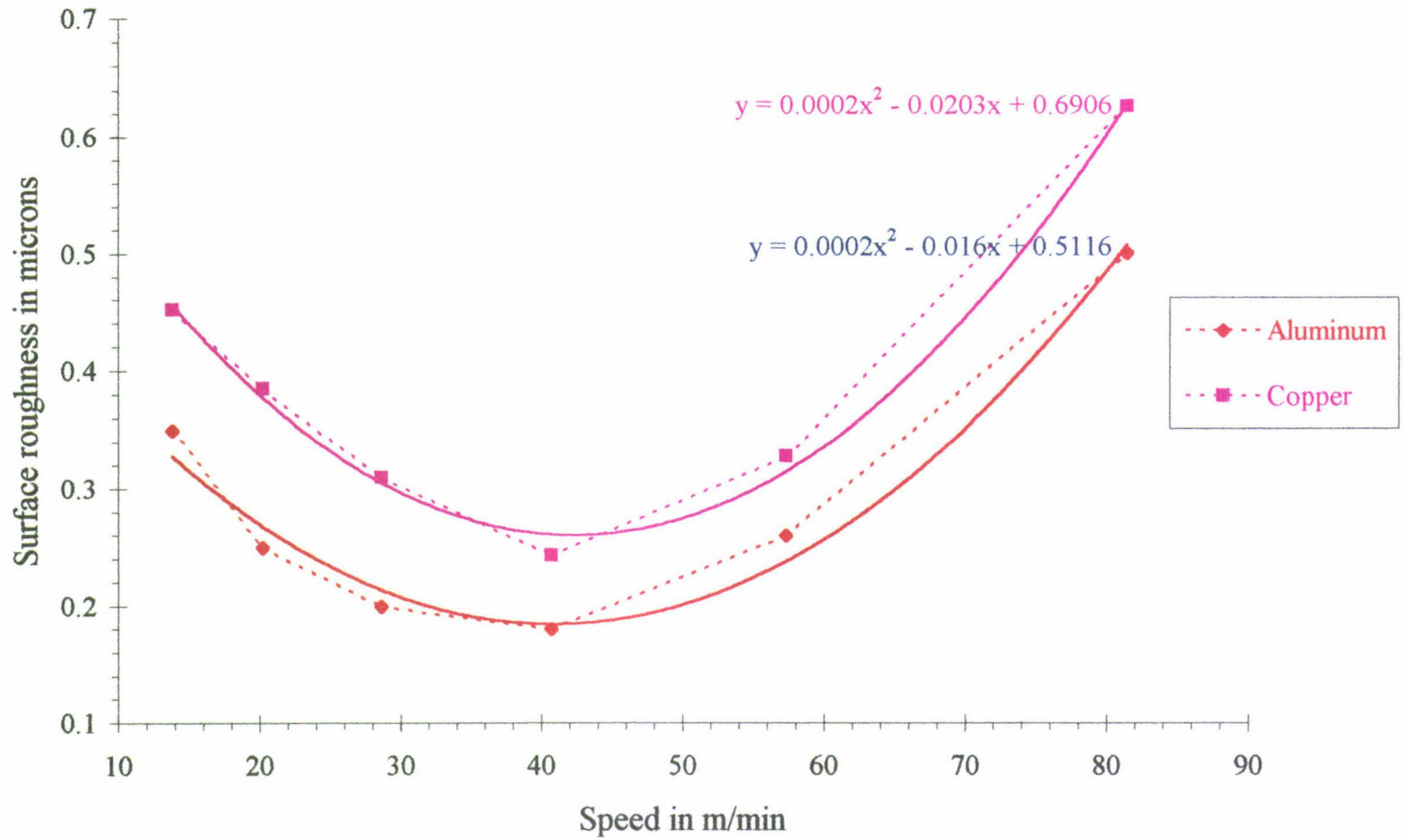



Figure 5.11 Effect of speed on surface roughness

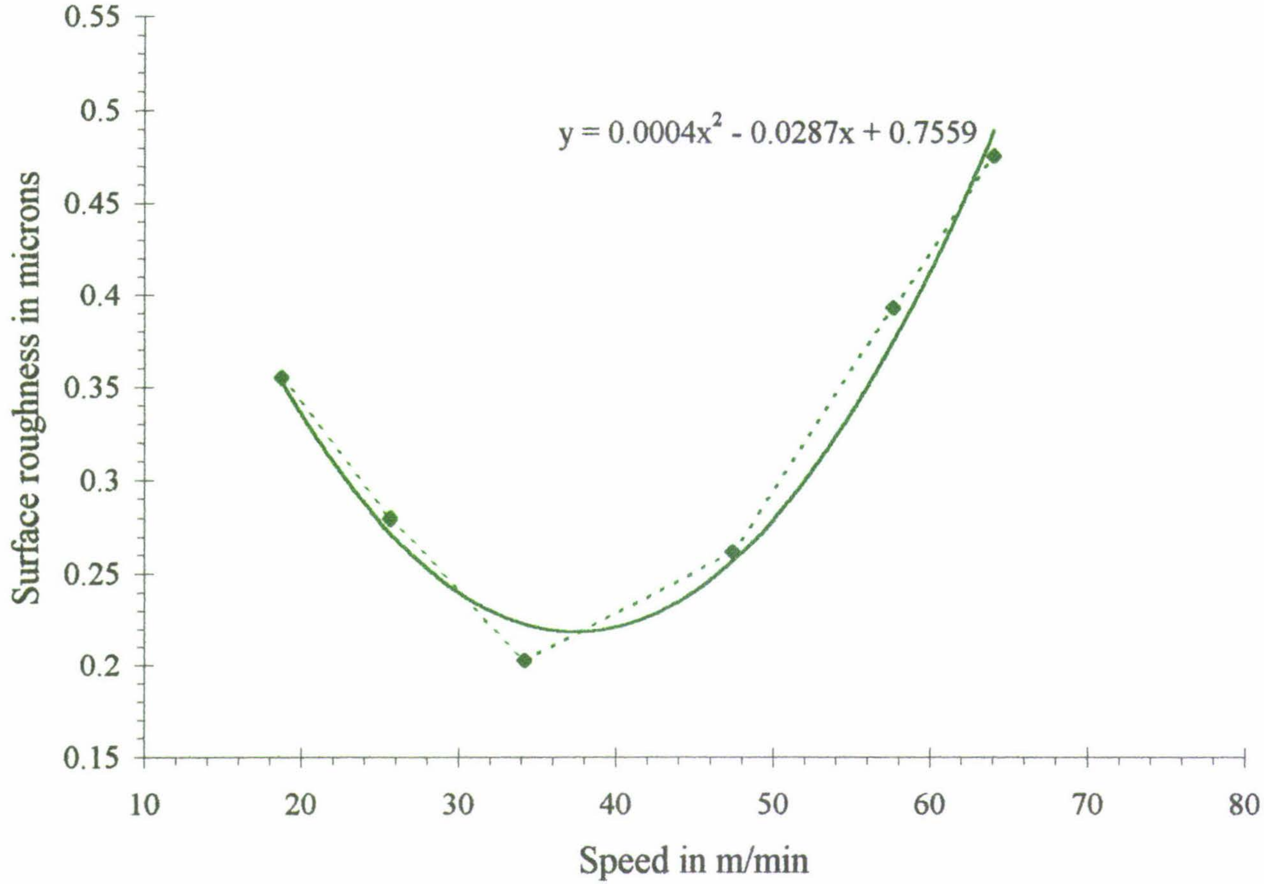





Figure 5.12 Effect of speed on surface roughness for brass

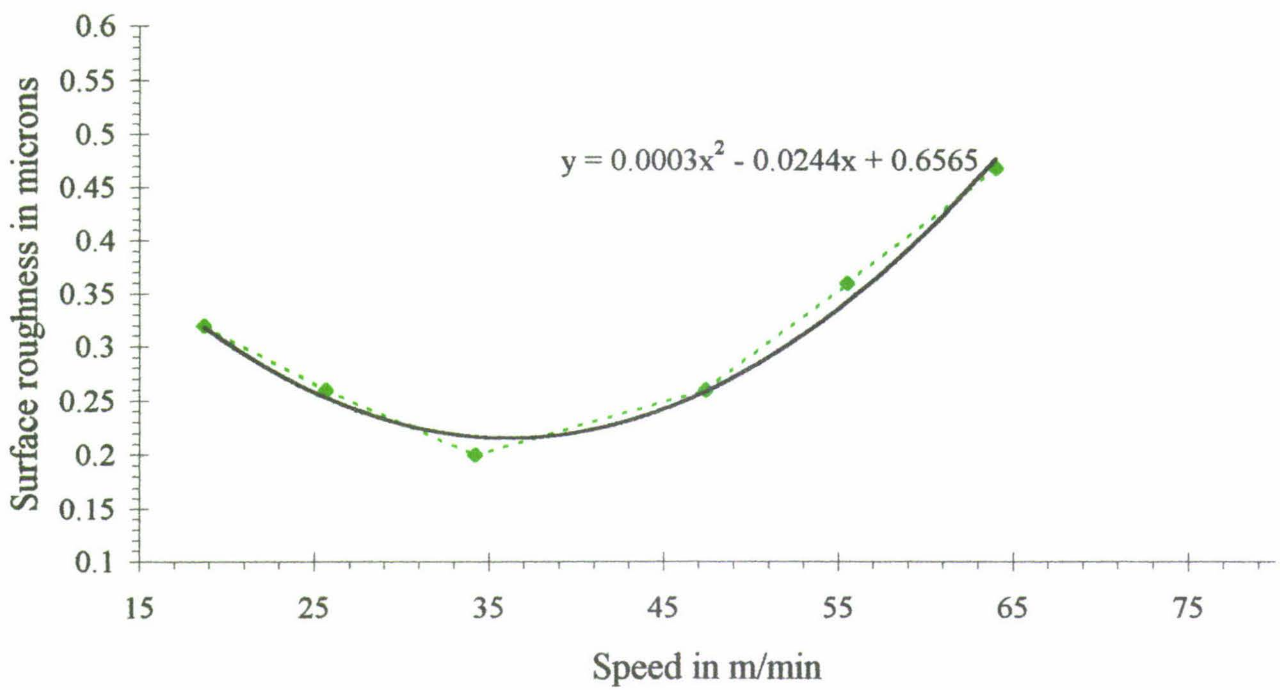



Figure 5.13 Effect of speed on surface roughness for mild steel

| S.No. | Depth of Penetration Microns | Surface Roughness in microns | | | |
|---|---|---|---|---|---|
| | | Copper | Aluminum | Mild Steel | Brass |
| 1 | 50 | 0.83 | 0.94 | 0.97 | 1.2 |
| 2 | 75 | 0.44 | 0.62 | 0.71 | 0.64 |
| 3 | 100 | 0.31 | 0.52 | 0.55 | 0.35 |
| 4 | 130 | 0.44 | 0.62 | 0.63 | 0.43 |
| 5 | 155 | 0.62 | 0.88 | 0.8 | 0.69 |
| 6 | 200 | 1.2 | 1.33 | 1.34 | 1.18 |
| | | Speed = 26.89m/min | | Speed = 20.29m/min | |
| Feed = 0.125mm/rev | | | | | |

Table 5.12 Effect of depth of penetration on surface roughness in roller burnishing

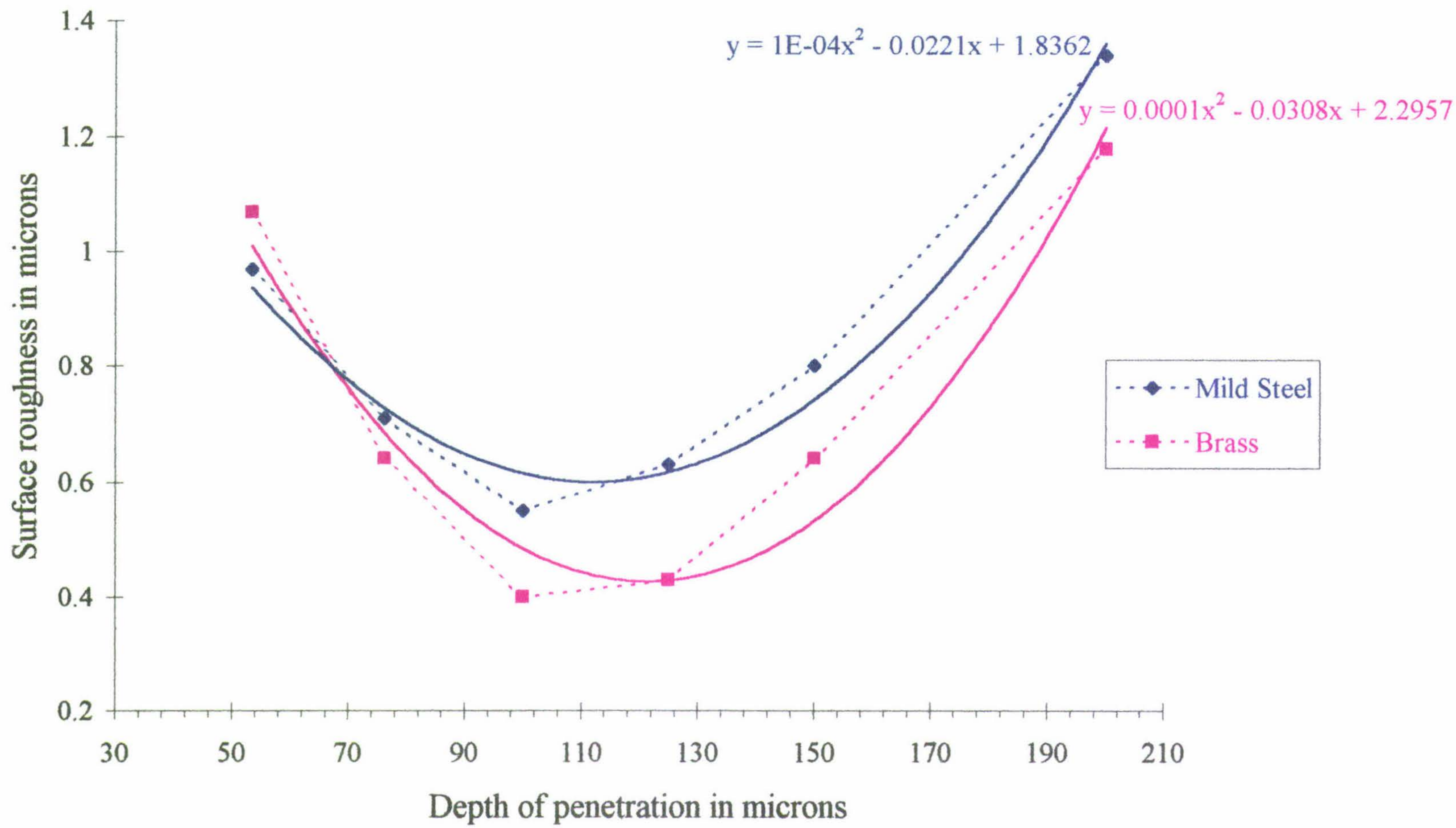



Figure 5.14 Effect of depth of penetration on surface roughness

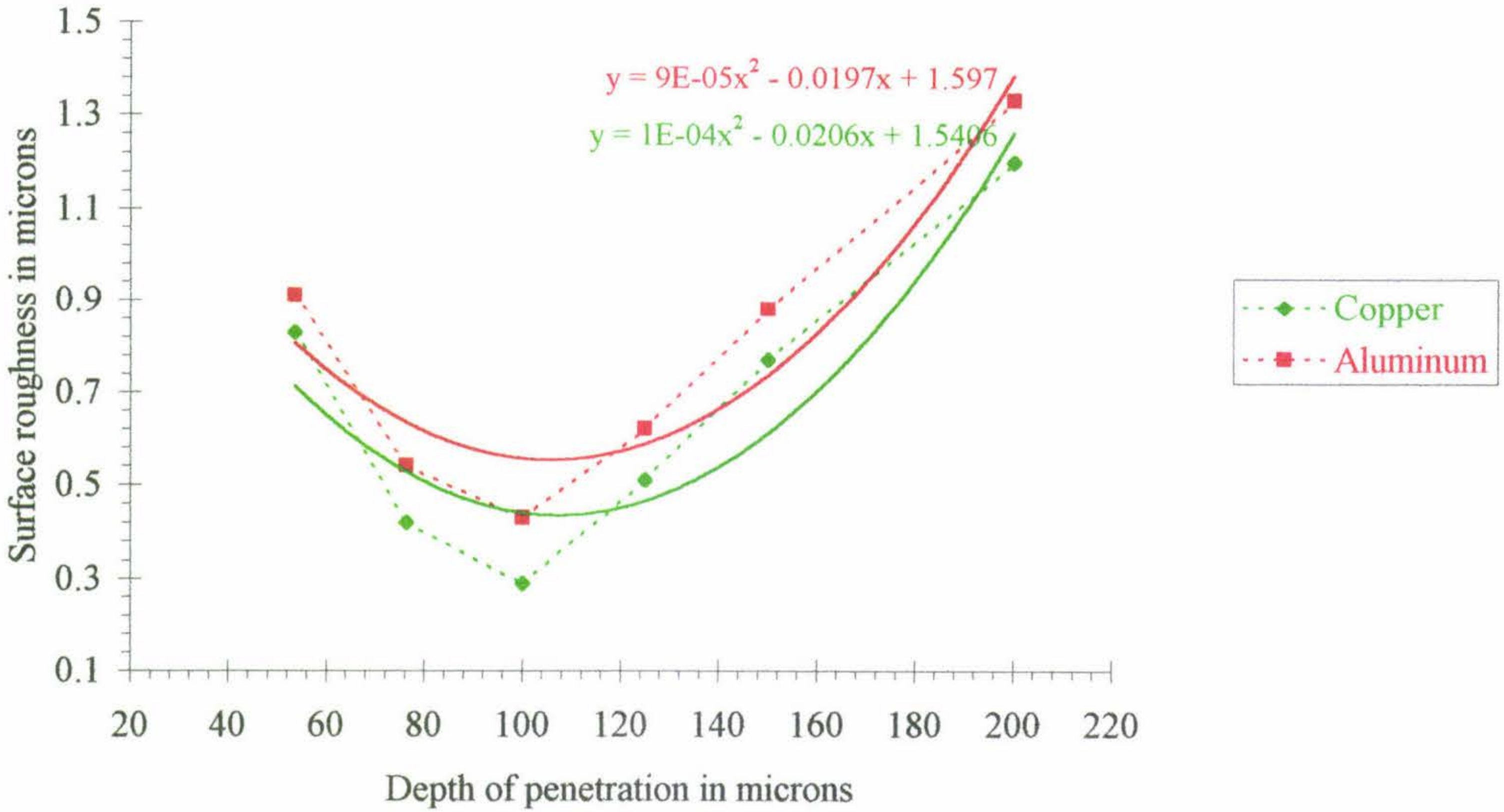



Figure 5.15 Effect of depth of penetration on surface roughness

# *Chapter 6*

# *Optimising the Burnishing process parameters conditions using designed experiments*

## 6.1 Introduction

It was felt that there may be interactions in the process parameters in relation to the final surface finish and therefore it was decided to use factorial experimental design and response surface methods to identify the optimum conditions.

Design of Experiments (DOE) is a set of tools that systematically applies statistical methods to the experimental process and provides practical and effective test plans that specify how to manipulate the control variables to answer well defined experimental objectives. DOE enables researchers, scientists, and engineers to change a number of variables according to a plan or design in order to evaluate their effects [Koorapati E. P et al (1997)]. As the experimental design is implemented, control variables are systematically and simultaneously changed. The effects of these changes are measured, modelled and mapped with statistical equations. The results enable extracting of the maximum amount of information per test run and an objective understanding of the system under study. Well-implemented DOE yields this information with the fewest number of experiments possible.

DOE coupled with available and applicable scientific knowledge gives the experimenter a greater understanding of, and power over, the experimental process [Loh N. H et al (1988)]. No other approach yields the same level of insight in the way a process works. Vastly superior to the one-factor-at-a-time approach, DOE continues to be a significant competitive advantage to companies using it effectively and an effective tool for experimenters investigating complete system with many interacting factors.

A strategic approach to DOE typically involves designing a second or third experiment based on the results of the originally designed experiment. The sequence of these experiments usually tracks the three categories of experimental design: Screening, Interaction and Response Surface. Each of these design categories addresses a different environment. A screening design is used in situations where there is little or no information about potentially important variables. Interaction and response surface designs provide precise information on a few critical variables [Loh N. H and Tam S. C (1989)].

The research begins with a screening experiment that identifies which variables are critical to the experimental plan and then implementing the appropriate interaction or response surface design to further investigate relationships among variables and responses.

For the purpose of this project to determine the optimum input parameter settings for minimizing the surface roughness, two different Designed Experiments methods, Factorial two level design and Central Composite Design (CCD), were used and analysed.

### 6.2 The experimental design process

The steps involved in experimental design process are as follows:

- Step 1. Gather information to state the problem to be solved.

  Gather information and state the problem to be solved. In a plastic deformation, cold working and non-metal removal, precision metal finishing processes, the process parameters needed to be analysed for optimum conditions to get fine finishing on the different materials like mild steel, aluminum, copper and brass.
- Step 2. Define the objective of the experiment.

  The objective of the experiment is to minimise the surface roughness on different materials, which is an essential quality problem for most of the machine parts where precision is required.

  To measure the quality in surface finish of the product, the following process parameters are chosen for investigation.

1. Feed rate in mm/rev
2. Speed of metal cutting in m/min
3. Depth of cut in mm
4. Burnishing Force in Newton
5. Roller approach angle in degrees
6. Roller radius in mm
7. Number of passes of the roller.

   All these process parameters are tested on a 40mm diameter and 200mm length rods of aluminum, copper, brass and mild steel.

- Step 3. Design the experiment.

  The first step in designing an experiment is to identify the factors that are believed to influence the performance characteristics. The input factors selected were feed, speed and depth of cut and two input levels were selected for each factor.

- Step 4. Select an orthogonal array and assign factors to columns.
  An eight run three factors three replicates, full factorial, two level design was chosen for the screening input factors to determine the optimum input levels which minimize the surface roughness.
- Step 5. Conduct the experiment and analyse the data.
- Step 6. Interpret the results and select optimum levels of the most influential control factors.

The same is represented by a flow chart in the Figure 6.1. After the step 6, the procedure repeated again if the results unsatisfactory otherwise the results from the runs are confirmed and applied.

### 6.3 Factorial two level three factors experimental design

A set of experiments that looks at 'k' factors with 'n' observations and with each factor set at two levels is called a two level factorial design. The observations in a two level experiment are not analysed separately, but as a unit to provide independent assessments of the effects of each factor under study. In addition to the factorial treatment combinations a set of centre points are added to provide a measure of the variability of the experiments and to indicate if any non-linearity is present. The number of observations in such an experiment is given by taking the number of levels to the power of the number of factors.

$$t_c = 2^k$$

Where $t_c$ is the treatment combination

K is the number of factors = 3

Hence number of observations $t_c = 8$

Centre points selected (CP) = 3

Total observations = 8 + 3 = 11

Total Runs = $(t_c + CP) \times r$

$= (8+3) \times 3 = 11 \times 3 = 33$

Where r- Number of replicates and CP- Number of centre points

The objectives of this full factorial two level experiments were to define the relations between the process parameters and the surface quality of the product, and to determine the optimum input levels of the chosen factors to obtain the desired product quality.

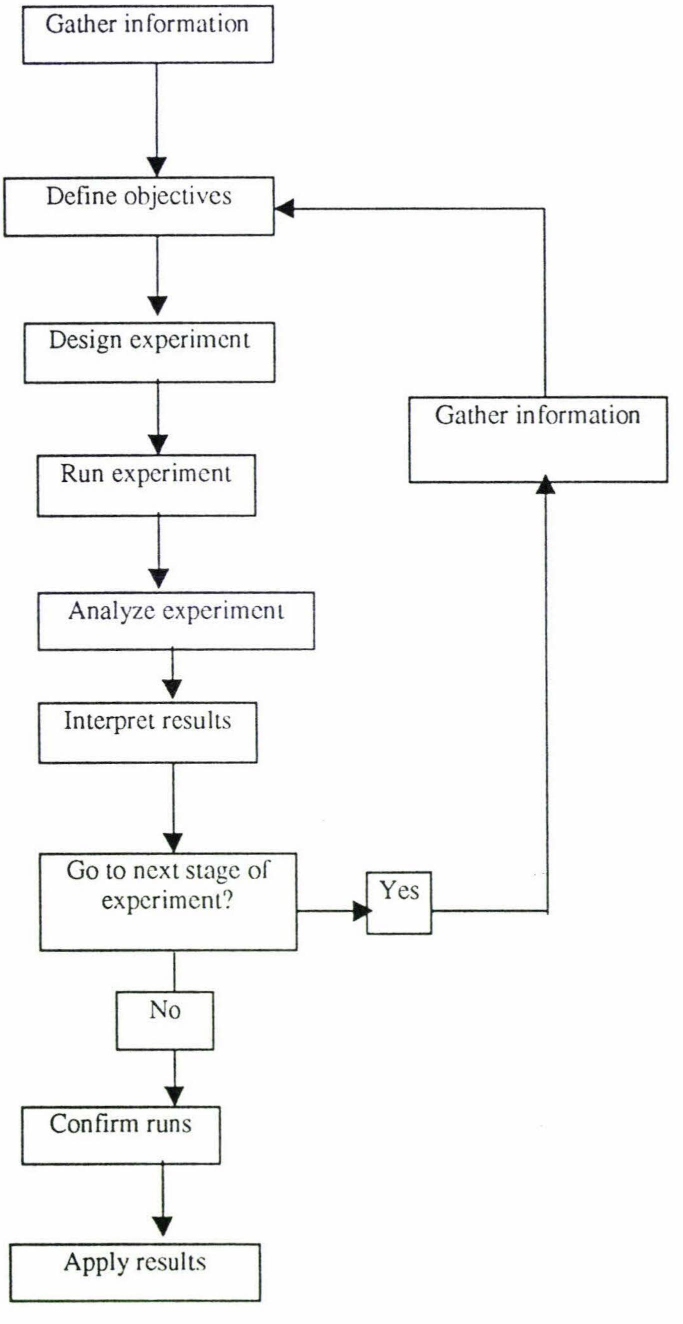



Figure 6.1 The experimentation process.

The orthogonal $2^3$ factorial design matrix shown in Table 6.1 has been used for the experiment. The software MINITAB is used for the design and analyses of the problem.

| Runs | Feed rate | Speed | Depth of Penetration |
|---|---|---|---|
| 1 | - | - | - |
| 2 | + | - | - |
| 3 | - | + | - |
| 4 | + | + | - |
| 5 | - | - | + |
| 6 | + | - | + |
| 7 | - | + | + |
| 8 | + | + | + |
| 9 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 |

(+) High level and (-) Low level

Table 6.1 Two level full factorial design matrix

| **Factors** | **High level (+)** | **Low level (-)** | **Center points (0)** |
|---|---|---|---|
| Feed rate in microns | 120 | 40 | 80 |
| Speed in m/min | 30 | 15 | 22.5 |
| Depth of cut in microns | 125 | 75 | 100 |

Table 6.2 High and Low values for factors

| Experiment No. | Feed (μm) | Speed M/min | Depth (μm) |
|---|---|---|---|
| 1 | 40 (-1) | 15 (-1) | 75 (-1) |
| 2 | 120 (1) | 15 (-1) | 75 (-1) |
| 3 | 40 (-1) | 30 (1) | 75 (-1) |
| 4 | 120 (1) | 30 (1) | 75 (-1) |
| 5 | 40 (-1) | 15 (-1) | 125 (1) |
| 6 | 120 (1) | 15 (-1) | 125 (1) |
| 7 | 40 (-1) | 30 (1) | 125 (1) |
| 8 | 120 (1) | 30 (1) | 125 (1) |
| 9 | 80 (0) | 22.5 (0) | 100 (0) |
| 10 | 80 (0) | 22.5 (0) | 100 (0) |
| 11 | 80 (0) | 22.5 (0) | 100 (0) |

Table 6.3 Experimental conditions and relating surface roughness for $2^3$ factorial design

### 6.3.1 Surface finish observations of two level factorial experiment

Preliminary experiments were conducted on four different materials The size of the work piece used is 40mm×200 mm and the material selected was mild steel for the analysis. The following observations were made as shown in the Table 6.4.

| Feed rate (μm) | Speed M/min | Depth of cut (μm) | Surface roughness(μm) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Runs | Replic-ate-1 | Runs | Replic-ate-2 | Runs | Replic-ate-3 |
| 40 (-1) | 15 (-1) | 75 (-1) | 1 | 0.36 | 12 | 0.34 | 23 | 0.36 |
| 120 (1) | 15 (-1) | 75 (-1) | 2 | 0.47 | 13 | 0.45 | 24 | 0.49 |
| 40 (-1) | 30 (1) | 75 (-1) | 3 | 0.35 | 14 | 0.34 | 25 | 0.36 |
| 120 (1) | 30 (1) | 75 (-1) | 4 | 0.39 | 15 | 0.4 | 26 | 0.38 |
| 40 (-1) | 15 (-1) | 125 (1) | 5 | 0.47 | 16 | 0.46 | 27 | 0.48 |
| 120 (1) | 15 (-1) | 125 (1) | 6 | 0.34 | 17 | 0.35 | 28 | 0.34 |
| 40 (-1) | 30 (1) | 125 (1) | 7 | 0.46 | 18 | 0.45 | 29 | 0.47 |
| 120 (1) | 30 (1) | 125 (1) | 8 | 0.32 | 19 | 0.33 | 30 | 0.31 |
| 80 (0) | 22.5 (0) | 100 (0) | 9 | 0.43 | 20 | 0.42 | 31 | 0.41 |
| 80 (0) | 22.5 (0) | 100 (0) | 10 | 0.41 | 21 | 0.40 | 32 | 0.42 |
| 80 (0) | 22.5 (0) | 100 (0) | 11 | 0.41 | 22 | 0.40 | 33 | 0.40 |

Table 6.4 Treatment table for two level full factorial design with three replicates

### 6.3.2 Analysis of results

Factorial design is more efficient than the conventional one-factor-at-a-time experiments commonly employed by researchers. In the $2^3$ factorial design used, three factors ( feed rate, speed and depth of penetration) were studied. Each qualitative and quantitative factor has two values and they are commonly known as "two levels", designated by -1 and +1.

Computation of the experimental data was carried out using MINITAB [Barnes D (1998)]. The main effect of each factor and the effects of interactions between factors were determined using the analysis of variance (ANOVA) technique.

It is observed from the Table 6.5 and Figure 6.1 that the $2^3$ factorial design and ANOVA doesn't provide an estimate of the experimental error unless some runs are repeated. A common method of including replication of $2^3$ factorial design is augment the design with several observations at the centre.

| Term | Effect | Coef. | StDev coef. | T | p |
|---|---|---|---|---|---|
| constant | | 0.39458 | 0.002357 | 167.41 | 0.000 |
| feed | -0.02750 | -0.01375 | 0.002357 | -5.83 | 0.000 |
| speed | -0.02917 | -0.01458 | 0.002357 | -6.19 | 0.000 |
| depth | 0.00750 | 0.00375 | 0.002357 | 1.59 | 0.131 |
| feed rate * speed | -0.02250 | -0.01125 | 0.0 02357 | -4.77 | 0.000 |
| feed rate * depth | -0.10583 | -0.05292 | 0.002357 | -22.45 | 0.000 |
| speed * depth | 0.01254 | 0.00625 | 0.002357 | 2.65 | 0.017 |
| feed * speed * depth | 0.01583 | 0.00792 | 0.002357 | 3.36 | 0.004 |

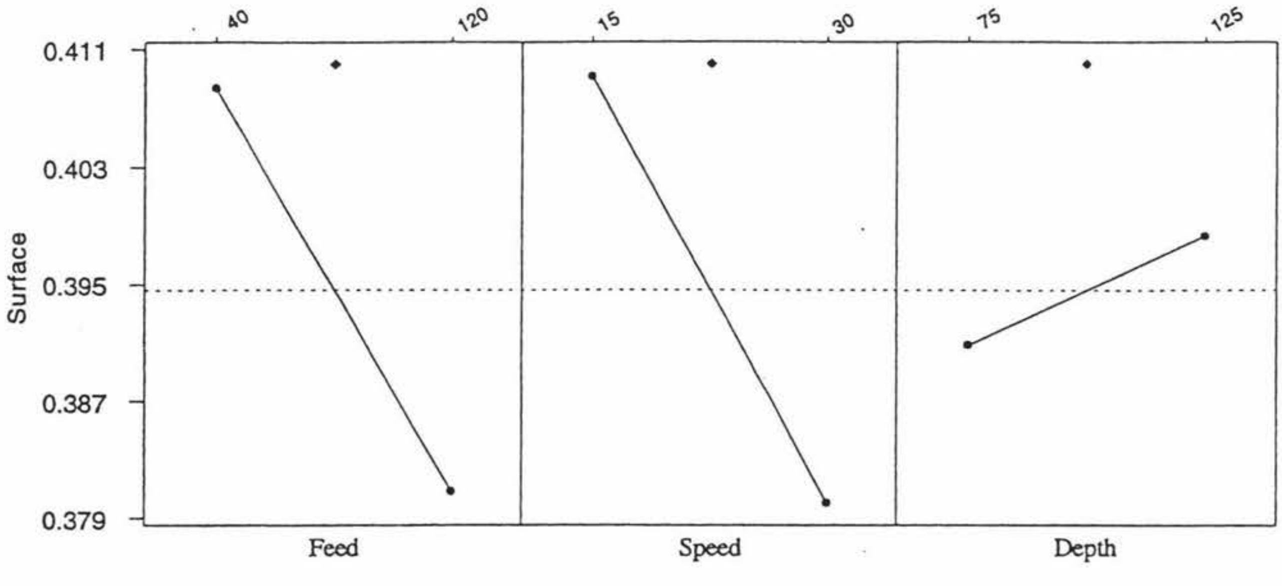
ANOVA (Analysis of variance for roughness)

| Source | DF | Seq. SS | Adj. SS | Adj. MS | F | p |
|---|---|---|---|---|---|---|
| Main Effects | 3 | 0.0099792 | 0.0099792 | 0.0033264 | 24.95 | .000 |
| 2WayInteractions | 3 | 0.0711792 | 0.0711792 | 0.0237264 | 177.95 | 0.000 |
| 3WayInteractions | 1 | 0.0015042 | 0.0015042 | 0.0015042 | 11.28 | 0.004 |
| Residual Error | 16 | 0.0021333 | 0.0002133 | 0.0001333 | | |
| Pure Error | 16 | 0.0021333 | 0.0021333 | 0.0001333 | | |
| Total | 23 | 0.0847958 | | | | |

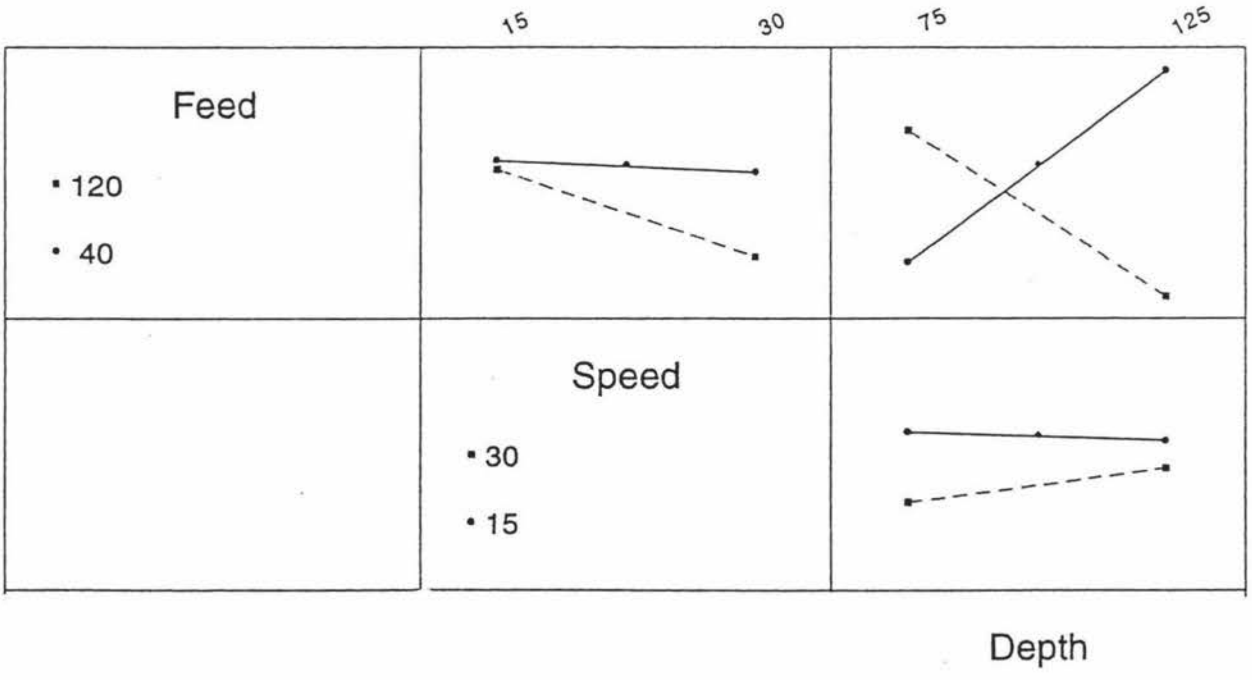
*Unusual observations for rough*

| Observation | rough | Fit | St Dev Fit | Residual | St Resid |
|---|---|---|---|---|---|
| 8 | 0.450000 | 0.470000 | 0.006667 | -0.020000 | -2.12R |
| 10 | 0.490000 | 0.470000 | 0.006667 | 0.020000 | 2.12R |

Table 6.5 Estimated coefficients for surface roughness




Main effects for surface roughness




Interaction effects for surface roughness

Figure 6.2 Main and Interaction effects

The addition of the center points to the $2^3$ factorial design doesn't influence the coefficients. Estimation of non-linear effects is impossible by this method. Hence another method for fitting the second order model is required. Central Composite Design (CCD) is used for design of experiments and Response Surface Methodology for analysis for fitting a second order or higher empirical relationship between the input factors and the resulting output.

### 6.4 Response Surface Methodology

Response Surface Methodologies (RSM) are used to find the optimum value for settings in a complex operation. It is an experimental approach. In RSM, the key factors were varied in a systematic carefully chosen way. As each group of factors are varied, the resulting data are analysed to indicate the best way to vary the parameters for the next set of experiments to make the progress towards the optimum settings for the factors as rapid as possible. The steps of variation and measurement were repeated until the optimum or required value is achieved. This is normal, well planned experimentation [Appendix-2].

RSM is a collection of mathematical and statistical techniques useful for analysing problems in which several independent variables (parameters) influence a dependent variable (response), and the goal is to optimize this response. e.g. surface roughness parameter, Ra. Experiments were planned on the basis of Response Surface Methodology (RSM) technique with a Central Composite rotatable Design (CCD) for three parameters feed, burnishing speed and depth of penetration. To establish the range of burnishing parameters for the RSM, two sets of preliminary experiments were conducted. The RSM is normally considered to have two stages. The RSM with CCD was used to examine the first and second-order factorial designs. The second order CCD required a two-level factorial experiment to be implemented, plus additional experimental points consisting of the "centre points" and "star points" arranged along the axes of the variables and symmetrically positioned with respect to the centre point. The first-order design requires a two-level factorial experiment to be implemented (i.e. 8 corner points) plus additional 4 centre points (experiments at 'zero' or average levels repeated 4 times) giving a total of 12 points. This involves a total of 12 experiments. For the second order design, 8 additional experimental points consisting of 2 "centre points" and 6 "star points" were added. This gives a total of 20 experiments. Figure 6.3 illustrates the configuration of a three-parameter CCD. See appendix-3 for the coputer

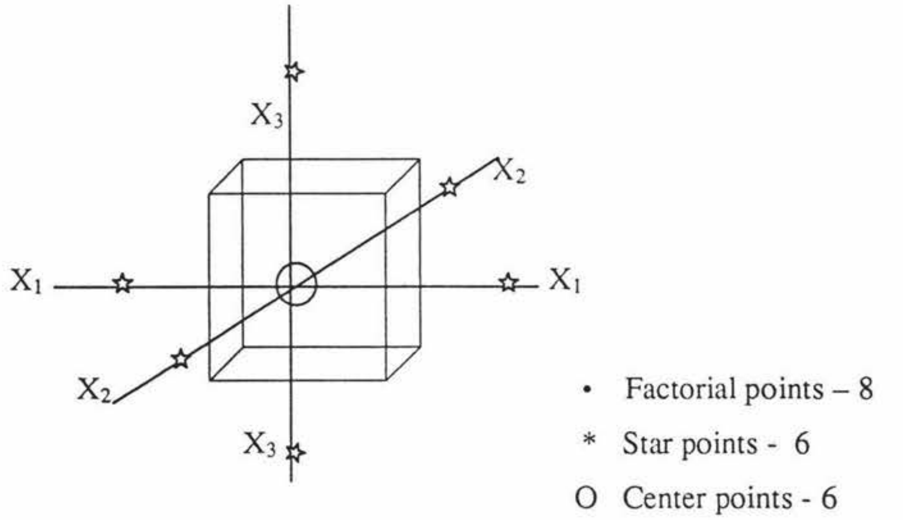



Figure 6.3 Schematic configuration of a three factor Central Composite Design

print outs of CCD designs. For optimisation of the surface finish, the range of the burnishing parameters used should contain the optimum points. From the preliminary experiments, the optimum depth of penetration and the optimum feed as observed from graphs 80μm and 110μm and the burnishing speed of 26.89m/min gave good finish for the preliminary work mentioned earlier [Chapter 5].

Therefore, the ranges of burnishing parameters used are as given below.

| Parameter | Range |
|---|---|
| Feed ($X_1$) | 40-80μm |
| Speed ($X_2$) | 15-30m/min |
| Depth of penetration ($X_3$) | 75-125μm |

The values of each of the three parameters were coded to simplify calculations. The range of each parameter was coded into three levels (-1, 0, +1) as follows. Tables 6.6 and 6.7 show the values of the parameters and their respective coded levels. The experiments were conducted according to the combination of various values of the process parameters. The first-order and second order designs by fitting polynomials were given in the Tables 6.8 and 6.9.

| Experiment No. | Feed (μm) | Speed m/min | Depth (μm) | Surface roughness Ra (μm) |
|---|---|---|---|---|
| 1 | 40 (-1) | 15 (-1) | 75 (-1) | 0.36 |
| 2 | 120 (1) | 15 (-1) | 75 (-1) | 0.47 |
| 3 | 40 (-1) | 30 (1) | 75 (-1) | 0.35 |
| 4 | 120 (1) | 30 (1) | 75 (-1) | 0.39 |
| 5 | 40 (-1) | 15 (-1) | 125 (1) | 0.47 |
| 6 | 120 (1) | 15 (-1) | 125 (1) | 0.42 |
| 7 | 40 (-1) | 30 (1) | 125 (1) | 0.46 |
| 8 | 120 (1) | 30 (1) | 125 (1) | 0.48 |
| 9 | 80 (0) | 22.5 (0) | 100 (0) | 0.43 |
| 10 | 80 (0) | 22.5 (0) | 100 (0) | 0.41 |
| 11 | 80 (0) | 22.5 (0) | 100 (0) | 0.41 |
| 12 | 80 (0) | 22.5 (0) | 100 (0) | 0.43 |

Table 6.6 Experimental conditions and relating surface roughness for first-order model

1$^{st}$ order model

$$Ra\ (\mu m) = b_0 + b_1X_1 + b_2X_2 + b_3X_3$$

2$^{nd}$ order model

$$Ra(\mu m) = bo + \sum_{i=1}^{k} biXi + \sum_{i=1}^{k} bijXi\hat{}2 + \sum_{i}^{k}\sum_{j}^{k} bijXiXj$$

Where k is the number of parameters (i.e. 3 in this case), i is 1,2,....k, j is 1,2,...k and Xi is the level of the i$^{th}$ parameter. MINITAB calculates the coefficients for the coded levels.
The fitting of a polynomial can be treated as a particular case of multiple linear regression where b terms are the regression coefficients that can be calculated. Table 6.6 is for the 1$^{st}$ order model. Twelve experiments were conducted with the combination of values shown in

the table. In $2^{nd}$ order model, additional eight experiments (two centre points and six star points) are added as shown in Table 6.7.

| Experiment No. | Feed (μm) | Speed m/min | Depth (μm) | Surface roughness Ra (μm) |
|---|---|---|---|---|
| 13 | 80 (0) | 22.5 (0) | 100 (0) | 0.33 |
| 14 | 80 (0) | 22.5 (0) | 100 (0) | 0.40 |
| 15 | 12.728 (-1.682) | 22.5 (0) | 100 (0) | 0.48 |
| 16 | 147.272 (1.682) | 22.5 (0) | 100 (0) | 0.62 |
| 17 | 80 (0) | 9.8866 (-1.682) | 100 (0) | 0.40 |
| 18 | 80 (0) | 35.1134 (1.682) | 100 (0) | 0.36 |
| 19 | 80 (0) | 22.5 (0) | 57.955 (-1.682) | 0.27 |
| 20 | 80 (0) | 22.5 (0) | 142.045 (1.682) | 0.45 |

Table 6.7 Additional points for second order model

| Source | DF | Seq. SS | Adj. SS | Adj. MS | F | p |
|---|---|---|---|---|---|---|
| Regression | 6 | 0.016950 | 0.016950 | 0.002825 | 4.84 | 0.052 |
| Linear | 3 | 0.010450 | 0.009880 | 0.003293 | 5.65 | 0.046 |
| Interaction | 3 | 0.006500 | 0.006500 | 0.002167 | 3.71 | 0.096 |
| Residual Error | 5 | 0.002917 | 0.002917 | 0.000583 | | |
| Lack of fit | 2 | 0.002517 | 0.002517 | 0.001258 | 9.44 | 0.051 |
| Pure Error | 3 | 0.000400 | 0.000133 | 0.000133 | | |
| Total | 11 | 0.019867 | | | | |

Table 6.8 Analysis of Variance (ANOVA) for First-Order Model

| Source | DF | Seq. SS | Adj. SS | Adj. MS | F | p |
|---|---|---|---|---|---|---|
| Regression | 9 | 0.0147034 | 0.0147034 | 0.016337 | 34.39 | 0.000 |
| Linear | 3 | 0.052932 | 0.052932 | 0.017644 | 37.14 | 0.000 |
| Square | 3 | 0.087603 | 0.087603 | 0.029201 | 61.47 | 0.000 |
| Interaction | 3 | 0.006500 | 0.006500 | 0.002167 | 4.56 | 0.0.017 |
| Residual Error | 16 | 0.007600 | 0.007600 | 0.000475 | | |
| Lack of fit | 5 | 0.006817 | 0.006817 | 0.001363 | 19.15 | 0.000 |
| Pure Error | 11 | 0.000783 | 0.000783 | 0.000071 | | |
| Total | 25 | 0.154635 | | | | |

Table 6.9 Analysis of Variance Table for Second-Order Model

### 6.4.1 First-order model

Using the Response Surface Methodology technique, the fitted first-order model is

$$Ra\ (\mu m) = 0.30833 + 0.00262X_1 - 0.0100X_2 + 0.00100X_3$$

It can be seen that the 'p' ratio for the regression term is lower than the initial ratio at the 5% significance level. This indicates that the burnishing parameters considered affect the burnishing process significantly. However, the lack of fit is also significant. Hence the first – order model fitted is not an adequate approximation of the response. The MINITAB computer print out of results and contour plots is included in the appendix-3.

### 6.4.2 Second-order model

To obtain a better approximation, a second-order model was fitted using the central composite design. The experimental results of these 8 additional experimental conditions are shown in Table 6.8.

The second-order model fitted is as follows

$$Ra\ (\mu m) = 0.41860 + 0.02885X_1 - 0.00730X_2 + 0.04307X_3 + 0.04565X_1^2 - 0.01446X_2^2 - 0.02153X_3^2 + 0.00001X_1X_2 - 0.02250\ X_1X_3 + 0.01750\ X_2X_3$$

The results of the analysis of variance performed to check the adequacy of the second-order model is shown in the table 6.9. Since the lack of fit is not significant, and the regression term is significant, the adequacy of the new model is established [Appendix-3].

### 6.4.3 Regression Analysis

By regression of the second-order model, the predicted best response, i.e. the optimum surface finish within the region explored, was found to be 0.39 µm, with a feed of 85µm and depth of penetration of 70µm.

The regression equation is

$$Ra\ (\mu m) = -\ 106 + 8.86\ X_3 + 0.000132\ X_1^3 - 0.0267X_3^2 - 0.0226\ X_1X_3$$

The regression output shows zero 'p' values (0.000). Value p is zero and F statistics is larger using ANOVA. R squared and adjusted R squared are over 94%. Hence the equation adequately describes a relationship between Feed and Depth of Penetration.

### 6.4.4 RS plots

The regression surface plots are drawn to find the optimum values of the significant factors Feed and Depth of Penetration. The computer print out is enclosed in appendix-3. The optimum values observed are Feed 85µm and Depth of Penetration 75µm for the response variable, Surface Roughness value of 0.32µm. This is observed in the graph of RS plot shown in the Figure 6.4. More graphs are in the appendix –3.

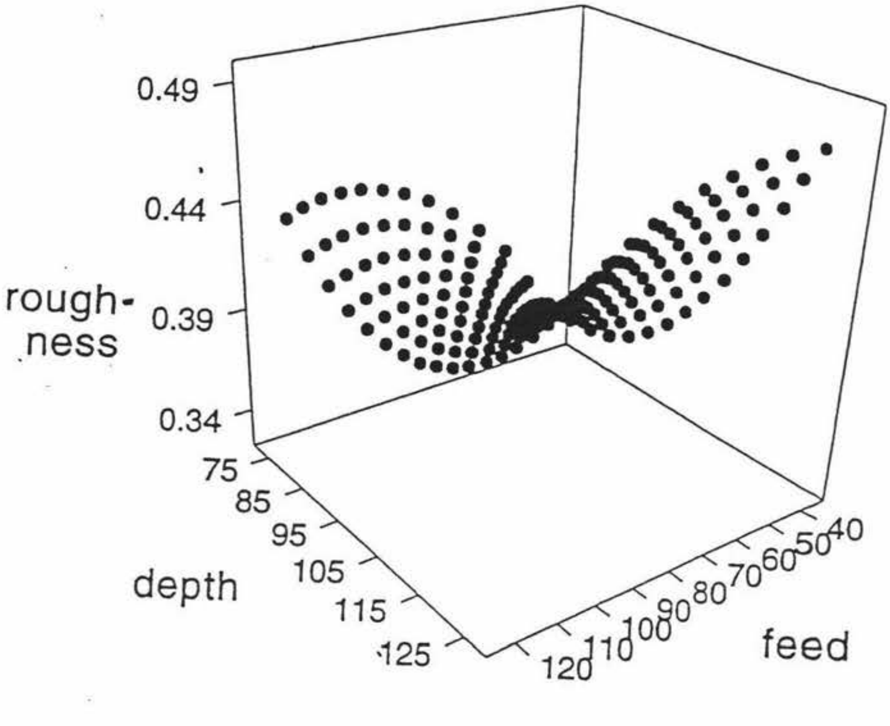



Figure 6.4 RS plot for feed and depth of penetration

# *Chapter 7*

# *Discussion and Conclusions*

## 7.1 Discussion on on-line acquired data and experimental design analysis

Two sets of confirmatory tests were conducted at the optimum conditions, i.e. a feed of 85μm burnishing speed of 29.86 m/min and a depth of penetration of 70μm with a roller radius of 10mm and approach angle of 8° limiting it to 3 passes. The number of passes of the roller burnishing tool was optimised at three. The optimum roller radius was 10mm and the optimum approach angle was 8°. The experimental confirmatory tests resulted in an average roughness value, $R_a$ of 0.42μm. One factor at-a-time experimental optimisation technique also gave a different surface roughness value as 0.40μm. This value might not be accurate as it does not taken into account the interactions between the factors. All the parameters were interdependent. The theoretical value obtained was different from the experimental one. The discrepancy in the values of the surface roughness may be due to the assumptions made in formulating the mathematical models for the optimisation of surface finish. This is not so in practice as the surface finish is also dependent on other parameters such as coolant used, number of passes and burnishing force etc. Another possible reason is that the actual mathematical model may be of a higher order.

From the experimental results the best surface finish of about 0.31μm from an initial finish of 4.62μm was obtained using a feed of 110μm, speed 26.89m/min and depth of penetration of 80μm.

## 7.2 Conclusions

- Roller burnishing can be performed on a most general purpose machine like a lathe and the lathe is a common machine in any workshop.
- The process is found to be cheaper as no separate or specialised machine is required for the finishing process. A very fine surface finish of 0.036μm could be obtained. Hence the process could be adopted as finishing process.
- A roller burnishing tool for burnishing external cylindrical surfaces was designed and fabricated for working within reasonable stiffness.

- Generally most of the parts require anti corrosion and wear resistance, the roller burnished surfaces possesses these two characteristics and components may be finished by roller burnishing at the end of the cycle of fabrication process.
- The surface roughness varies with feed, burnishing speed, force and number of passes and there is an optimum setting for these parameters which gives the lowest surface roughness [Chapter 5].
- On general engineering materials like aluminum, copper, mild steel and brass the roller burnishing is recommended to be done at the optimum values speed, feed and depth of penetration suggested for each material individually [Chapter 5].
- A very high initial finish is not required for burnishing to produce better results. This is not so in the case of other finishing processes such as honing, lapping and grinding [Lee S. G, Tam S. C and Loh N. H (1992)].
- The improvement in surface finish during burnishing is caused by the combined effect of displacement of metal from peaks into valleys and formation and modification of grooves.
- Microstructure examination showed that there was an elongation in the grain near the surface of the burnished work piece [Koti V.C and Ronanki L. M (1990)].
- The use of single factor experiments and experimental designs in the exploration of optimum process parameters has been described. Using a roller burnishing tool, within the operating region of feed 85μm , burnishing speed 26.89m/min and depth of penetration 70μm , the second-order mathematical model relating surface finish and three process parameters as follows:

$$R_a\,(\mu m) = 0.41860 + 0.02885X_1 - 0.00730X_2 + 0.04307X_3 + 0.04565X_1^2 - 0.01446X_2^2 - 0.02153X_3^2 + 0.00001X_1X_2 - 0.02250\,X_1X_3 + 0.01750\,X_2X_3$$

The best expected response, i.e. the optimum surface finish was found to be $R_a$ 0.32μm, when using a feed 85μm, speed 26.89m/min and depth of penetration of 70μm. Confirmatory tests performed using the optimum set of conditions indicated an average surface roughness value of $R_a$ 0.42μm.

The difference between the expected and observed surface roughness values may be due to the fact that only three burnishing parameters were taken into account in the optimisation of the surface finish. In actual fact there are other burnishing parameters that also affect the surface finish such as burnishing force, number of passes and coolant used, and therefore should be considered.

## 7.3 Recommendations for further studies

While there is a wide range of instrumentation available for examining the roughness or topography of surfaces, profiling devices based on contacting stylus techniques are still superior for providing quantitative statistical descriptions.

The most modern instruments are based on digital techniques and, as in other fields, an ever increasing use is being made of digital computers both on and off line for the analysis of surface topography. Optical diffraction technique is the best one at present.

As an optical method a confocal microscope was used [Appendix-4]. During operation of the microscope, laser light passing through the illumination pinhole is focused on a certain point of the specimen. The light is then rapidly scanned over the specimen in X, Y directions, thereby providing a point by point excitation and detection of the fluorescence of the specimen at the chosen focal plane. Subsequent focal planes of the specimen can be scanned by a step-wise shift of the height of the microscope stage. Because the pathway of the light is symmetrical, only the fluorescence of the material in the focal point can pass the detector pinhole. Hence the name confocal. The detector records the light intensity of each point; simultaneously, the X, Y and Z positions of that point are also recorded. After scanning certain area of the specimen the image can be viewed on the computer screen.

Ultrasonic roller burnishing may give higher surface finish improvement than normal roller burnishing.

In the future empirical analysis could be extended to three levels taking more parameters into consideration like tool material, work material, lubricant and force etc. This could be the subject of future experiments.

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# *APPENDICES*

Appendix-1

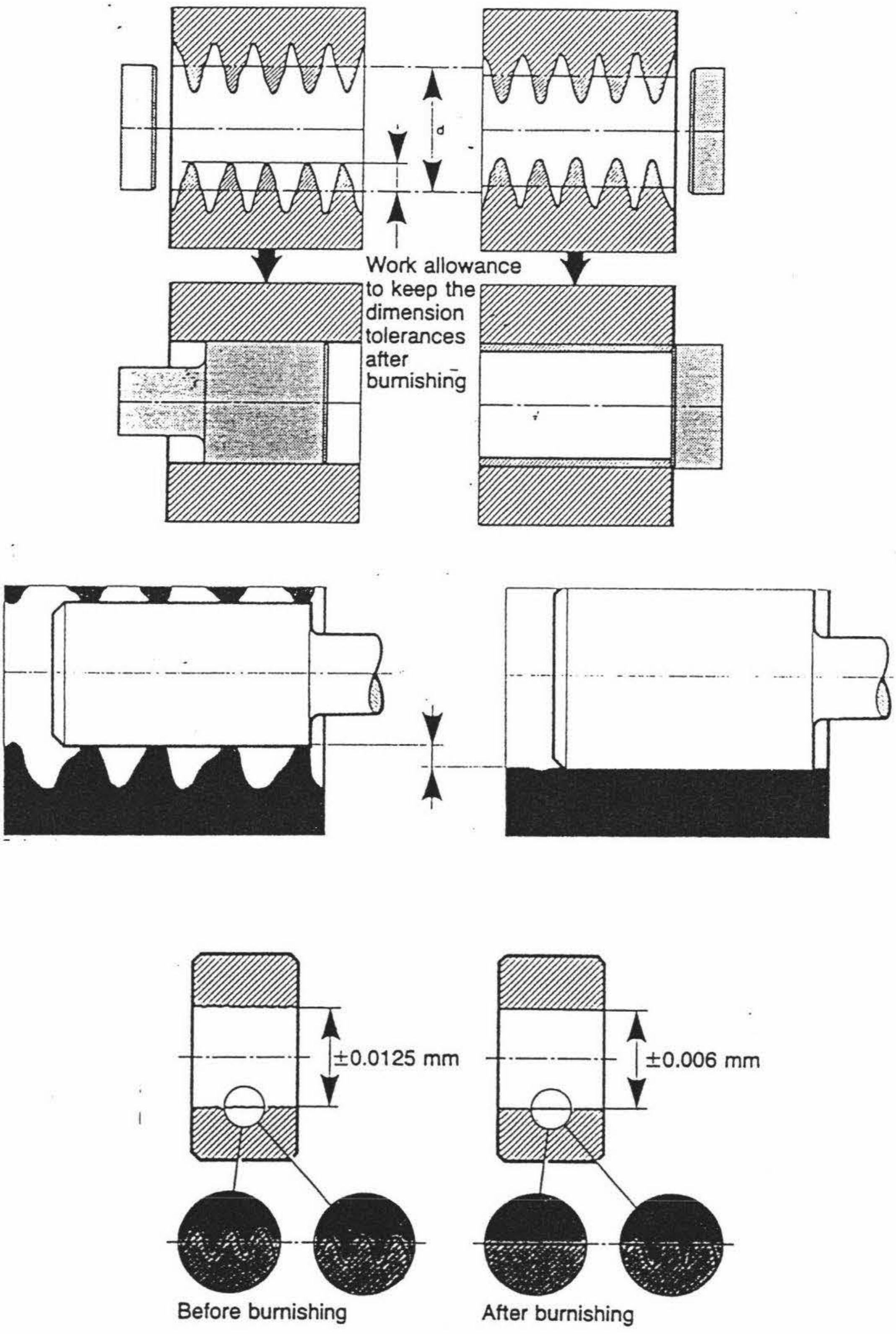


Figure App-1.1 Applications of roller burnishing tool

# Appendix-2

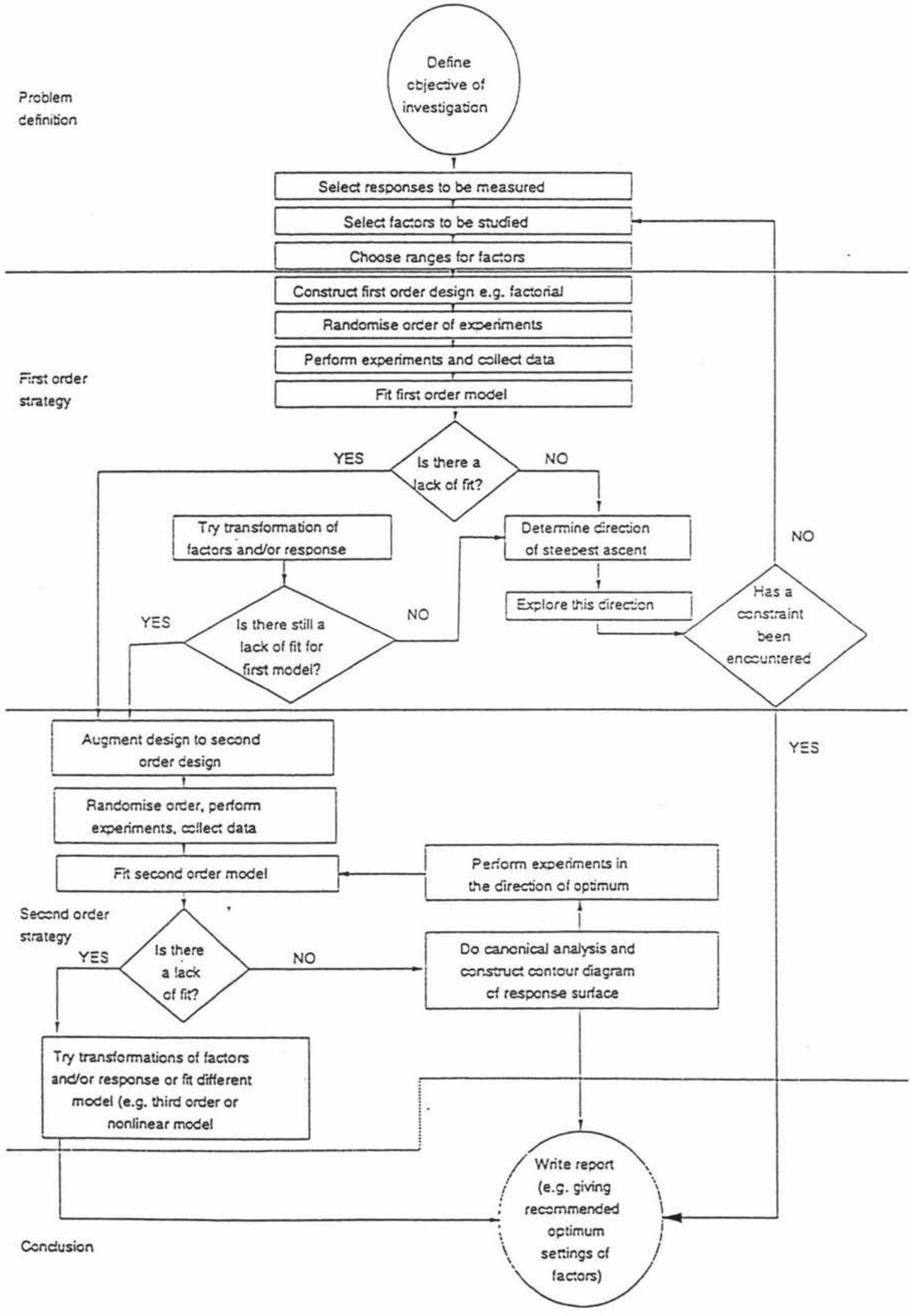


Figure App-2.1 Outline of flow of experimentation for Response Surface Methodology

## Appendix-3

## Computer output

```
Worksheet size: 100000 cells


MTB > New
MTB > Name C1 'StdOrder' C2 'RunOrder' C3 'Blocks' C4 'Feed' C5 'Speed' C6 'Depth'
MTB > FFDesign 3 8;
SUBC>   CPBlocks 3;
SUBC>   Replicates 3;
SUBC>   SOrder 'StdOrder' 'RunOrder';
SUBC>   Alias 3;
SUBC>   XMatrix 'Feed' 'Speed' 'Depth';
SUBC>   Levels 40 120 15 30 75 125.
```

## Factorial Design

```
Full Factorial Design

Factors:   3    Base Design:        3, 8
Runs:     27    Replicates:            3
Blocks: none    Center pts (total):    3

All terms are free from aliasing


MTB > FFactorial 'Surface roughness' = C4 C5 C6 C4*C5 C4*C6 C5*C6 C4*C5*C6;
SUBC>   RType 1;
SUBC>   Means C4 C5 C6 C4*C5 C4*C6 C5*C6 C4*C5*C6.
```

## Fractional Factorial Fit

```
Estimated Effects and Coefficients for Surface

Term                  Effect      Coef  StDev Coef       T      P
Constant                       0.39630    0.002405  164.78  0.000
Feed                -0.02750  -0.01375    0.002551   -5.39  0.000
Speed               -0.02917  -0.01458    0.002551   -5.72  0.000
Depth                0.00750   0.00375    0.002551    1.47  0.158
Feed*Speed          -0.02250  -0.01125    0.002551   -4.41  0.000
Feed*Depth          -0.10583  -0.05292    0.002551  -20.74  0.000
Speed*Depth          0.01250   0.00625    0.002551    2.45  0.024
Feed*Speed*Depth     0.01583   0.00792    0.002551    3.10  0.006

Analysis of Variance for Surface

Source                 DF     Seq SS     Adj SS     Adj MS       F      P
Main Effects            3  0.0099792  0.0099792  0.0033264   21.30  0.000
2-Way Interactions      3  0.0711792  0.0711792  0.0237264  151.93  0.000
3-Way Interactions      1  0.0015042  0.0015042  0.0015042    9.63  0.006
Residual Error         19  0.0029671  0.0029671  0.0001562
  Curvature             1  0.0006338  0.0006338  0.0006338    4.89  0.040
  Pure Error           18  0.0023333  0.0023333  0.0001296
Total                  26  0.0856296

Unusual Observations for Surface

Obs    Surface        Fit  StDev Fit   Residual   St Resid
 10   0.450000   0.471713   0.007165  -0.021713     -2.12R

R denotes an observation with a large standardized residual

Means for Surface

                              Mean     StDev
    Feed
     40                     0.4100  0.003506
    120                     0.3825  0.003506
   Speed
   15.0                     0.4109  0.003506
   30.0                     0.3817  0.003506
   Depth
     75                     0.3925  0.003506
    125                     0.4000  0.003506
    Feed*   Speed
```

```
      40      15.0                   0.4134  0.005030
     120      15.0                   0.4084  0.005030
      40      30.0                   0.4067  0.005030
     120      30.0                   0.3567  0.005030
    Feed*    Depth
      40        75                   0.3534  0.005030
     120        75                   0.4317  0.005030
      40       125                   0.4667  0.005030
     120       125                   0.3334  0.005030
   Speed*    Depth
    15.0        75                   0.4134  0.005030
    30.0        75                   0.3717  0.005030
    15.0       125                   0.4084  0.005030
    30.0       125                   0.3917  0.005030
    Feed*    Speed*    Depth
      40      15.0        75         0.3550  0.007165
     120      15.0        75         0.4717  0.007165
      40      30.0        75         0.3517  0.007165
     120      30.0        75         0.3917  0.007165
      40      15.0       125         0.4717  0.007165
     120      15.0       125         0.3450  0.007165
      40      30.0       125         0.4617  0.007165
     120      30.0       125         0.3217  0.007165

Center Point       0.4100
MTB > %FFMain C4 C5 C6;
SUBC>   Resp 'Surface roughness'.
Executing from file: C:\MTBWIN11\MACROS\FFMain.MAC

Macro is running ... please wait
MTB > %FFInt C4 C5 C6;
SUBC>   Resp 'Surface roughness'.
Executing from file: C:\MTBWIN11\MACROS\FFInt.MAC

Macro is running ... please wait


Calculating forward interactions ...

MTB >
```

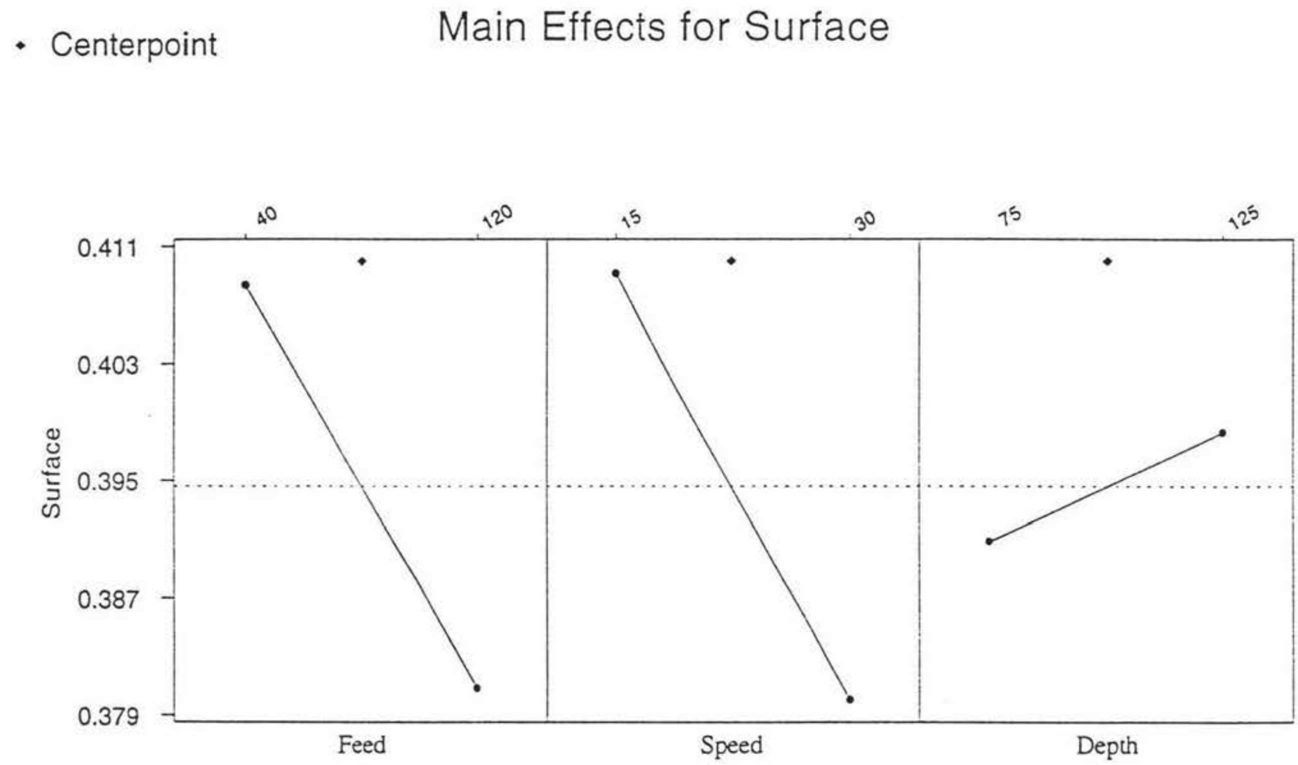


Figure App-3.1 Main effects plot for surface roughness

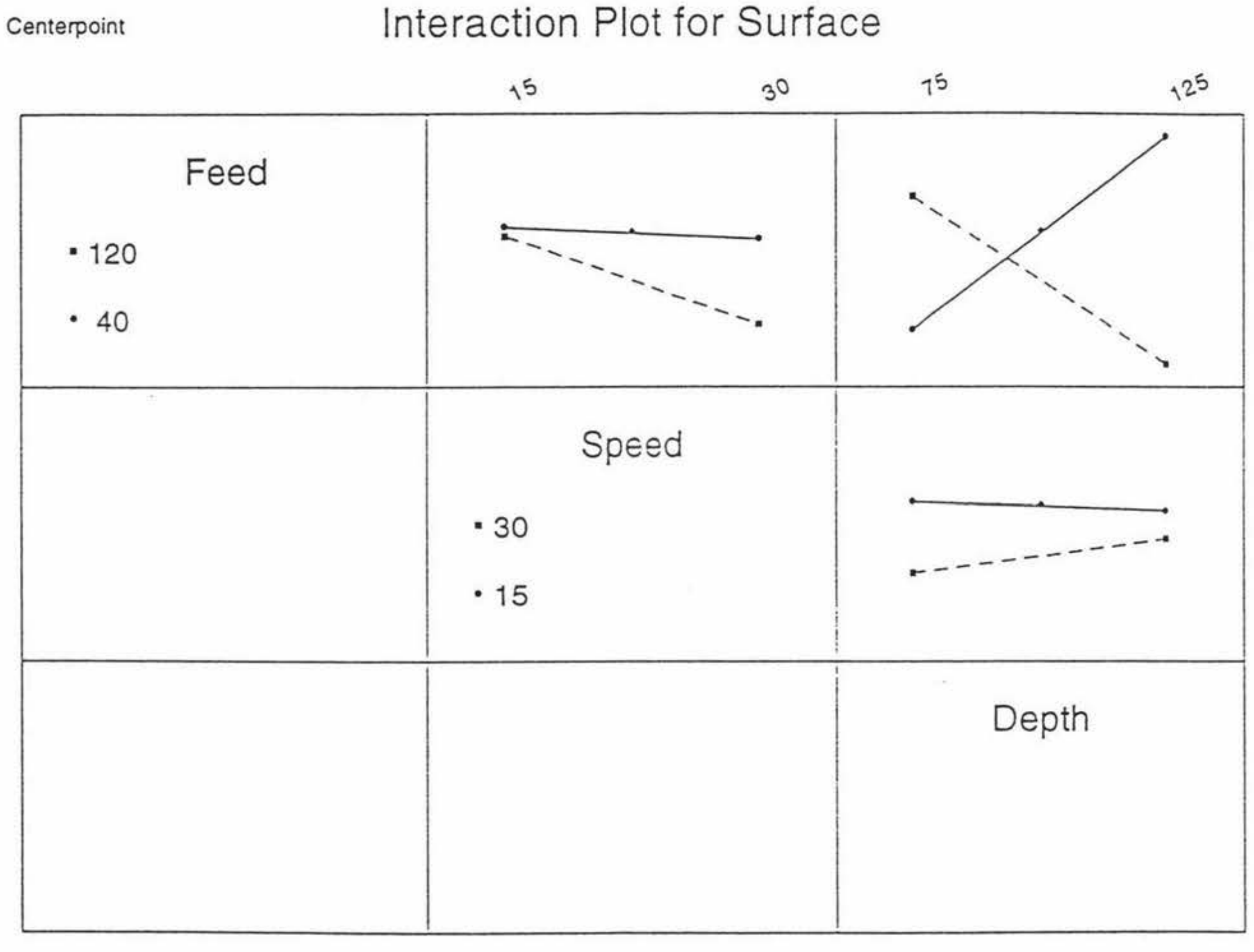


Figure App-3.2 Interaction effects plot for surface roughness

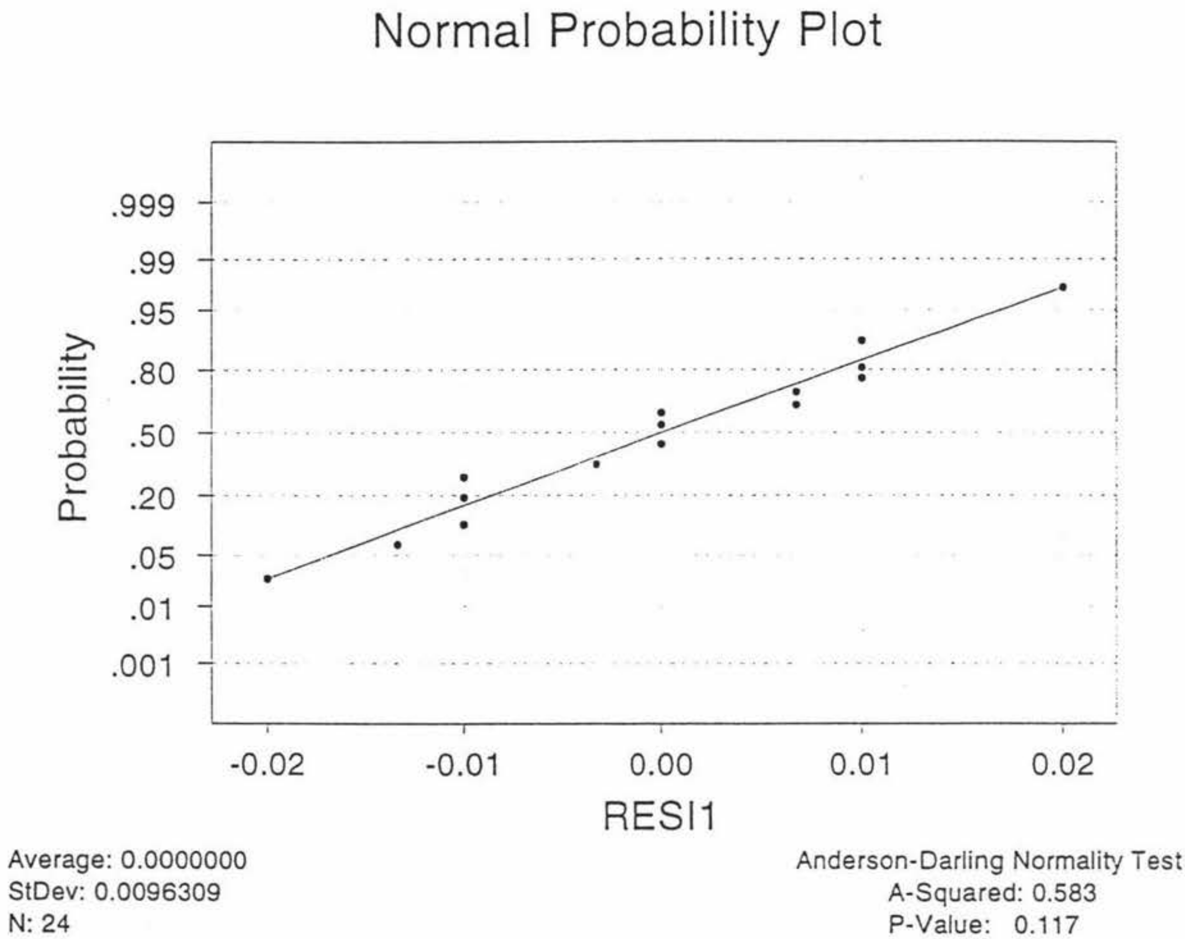


Figure App-3.3 Normal probability plot

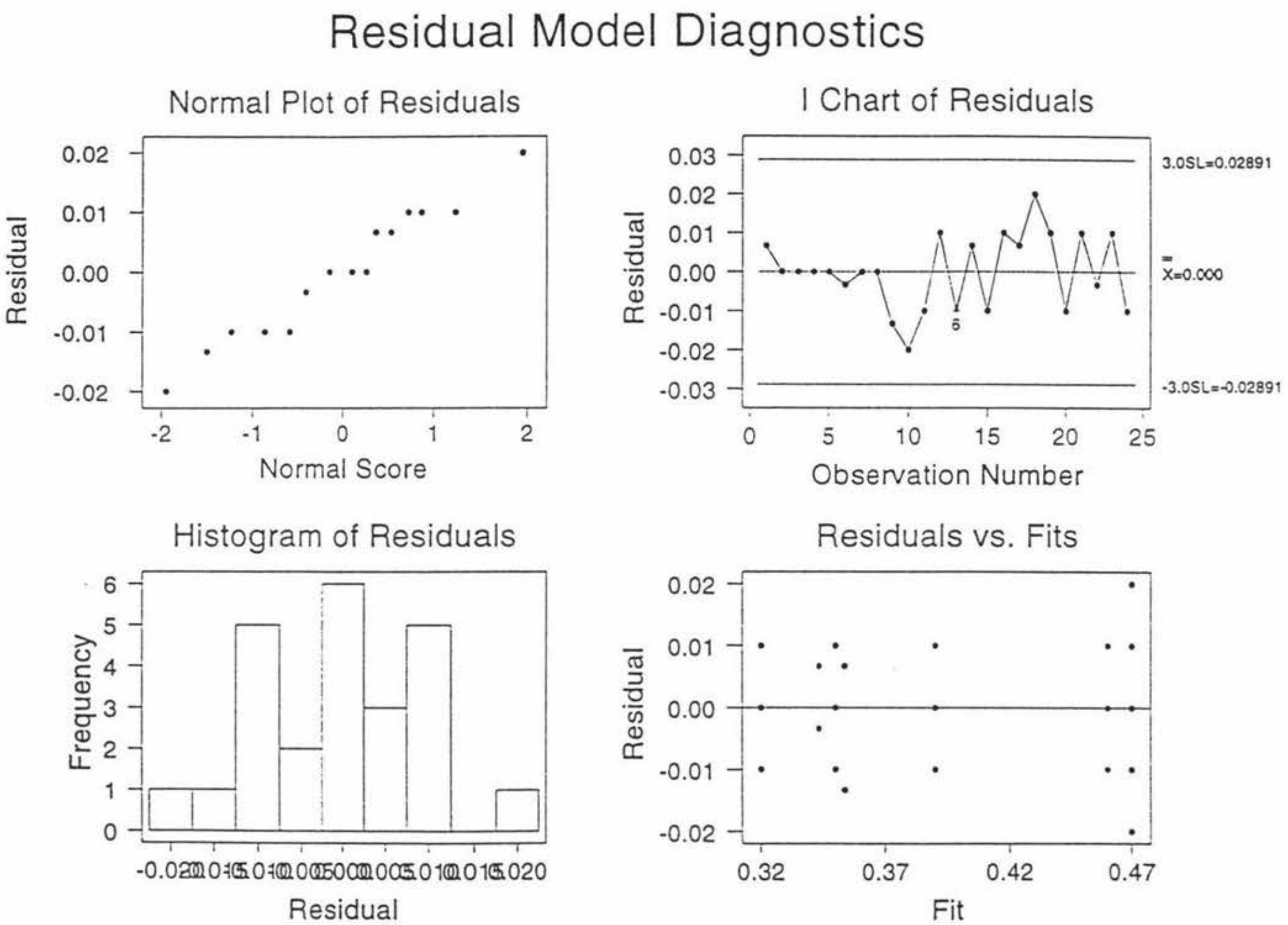


Figure App-3.4 Residual model

## Response Surface Regression

Estimated Regression Coefficients for Roughnes

| Term | Coef | StDev | T | P |
| --- | --- | --- | --- | --- |
| Constant | 0.30833 | 0.141262 | 2.183 | 0.081 |
| Feed | 0.00262 | 0.001089 | 2.412 | 0.061 |
| Speed | -0.01000 | 0.005217 | -1.917 | 0.113 |
| Depth | 0.00100 | 0.001278 | 0.782 | 0.469 |
| Feed*Speed | 0.00000 | 0.000028 | 0.000 | 1.000 |
| Feed*Depth | -0.00002 | 0.000009 | -2.635 | 0.046 |
| Speed*Depth | 0.00009 | 0.000046 | 2.049 | 0.096 |

S = 0.02415    R-Sq = 85.3%    R-Sq(adj) = 67.7%

Analysis of Variance for Roughnes

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
| --- | --- | --- | --- | --- | --- | --- |
| Regression | 6 | 0.016950 | 0.016950 | 0.002825 | 4.84 | 0.052 |
| Linear | 3 | 0.010450 | 0.009880 | 0.003293 | 5.65 | 0.046 |
| Interaction | 3 | 0.006500 | 0.006500 | 0.002167 | 3.71 | 0.096 |
| Residual Error | 5 | 0.002917 | 0.002917 | 0.000583 | | |
| Lack-of-Fit | 2 | 0.002517 | 0.002517 | 0.001258 | 9.44 | 0.051 |
| Pure Error | 3 | 0.000400 | 0.000400 | 0.000133 | | |
| Total | 11 | 0.019867 | | | | |

MTB >

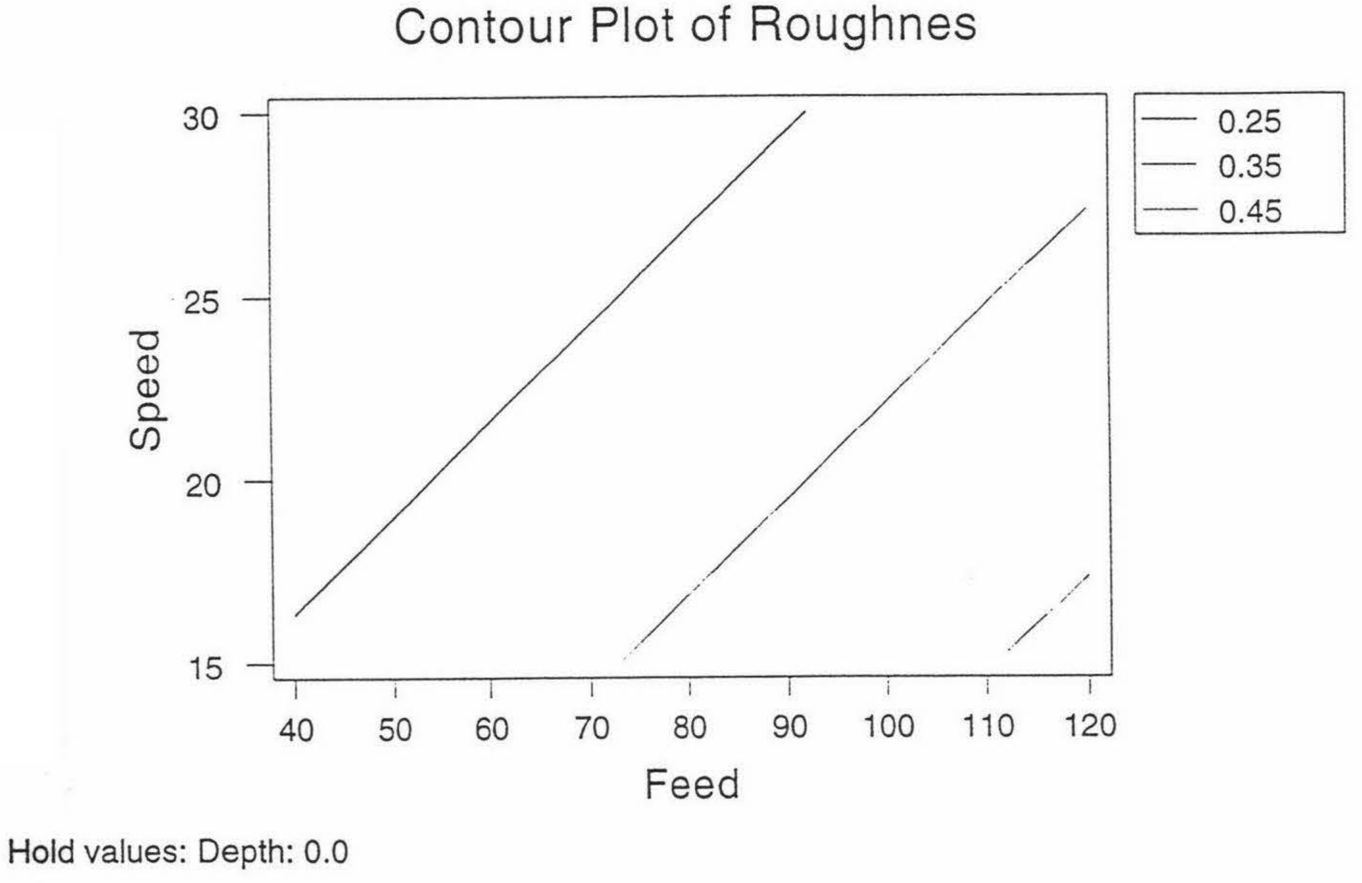


Figure App-3.5 Contour plot of surface roughness for feed and speed

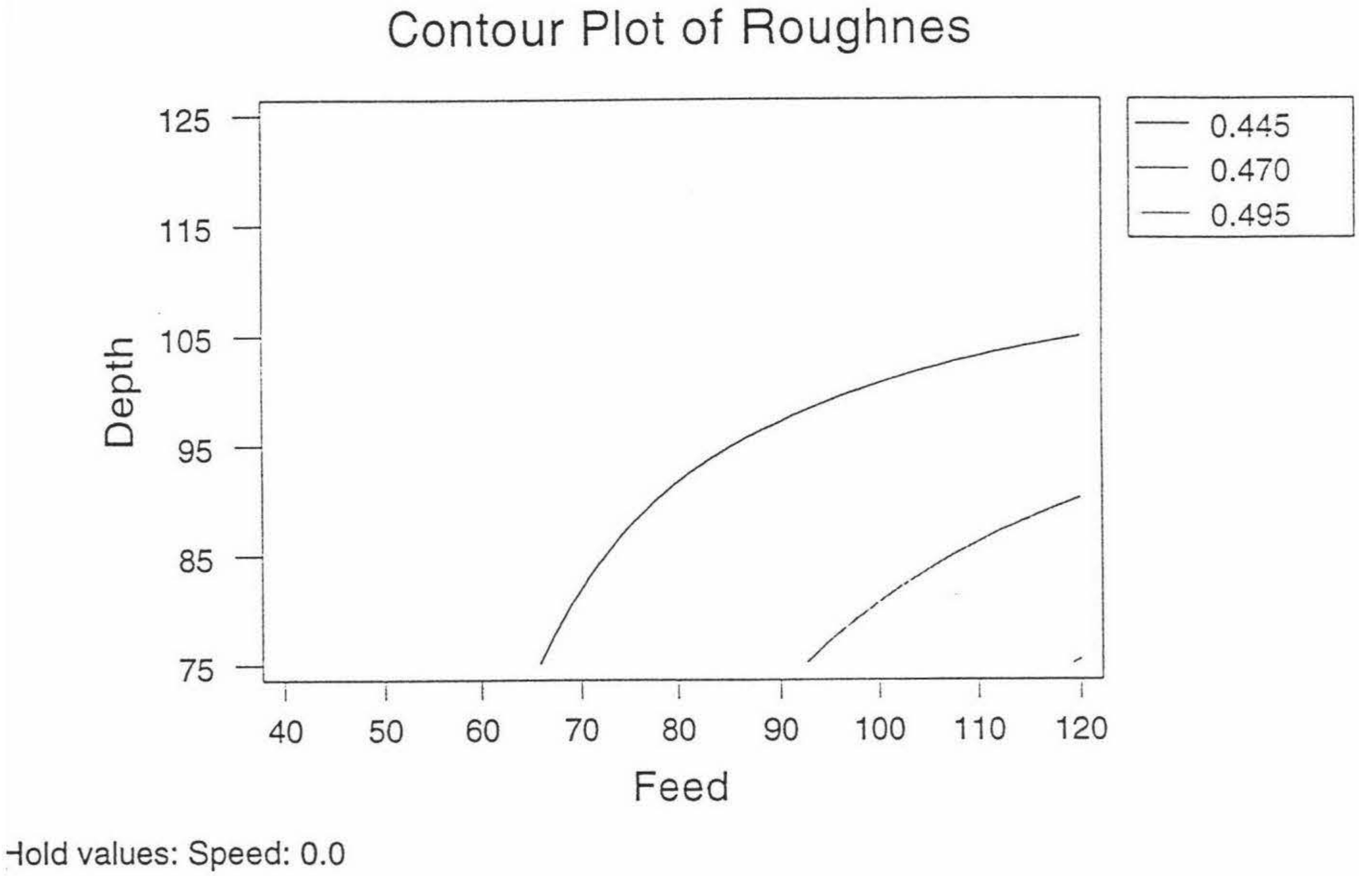


Figure App-3.6 Contour plot of surface roughness for feed and depth of penetration

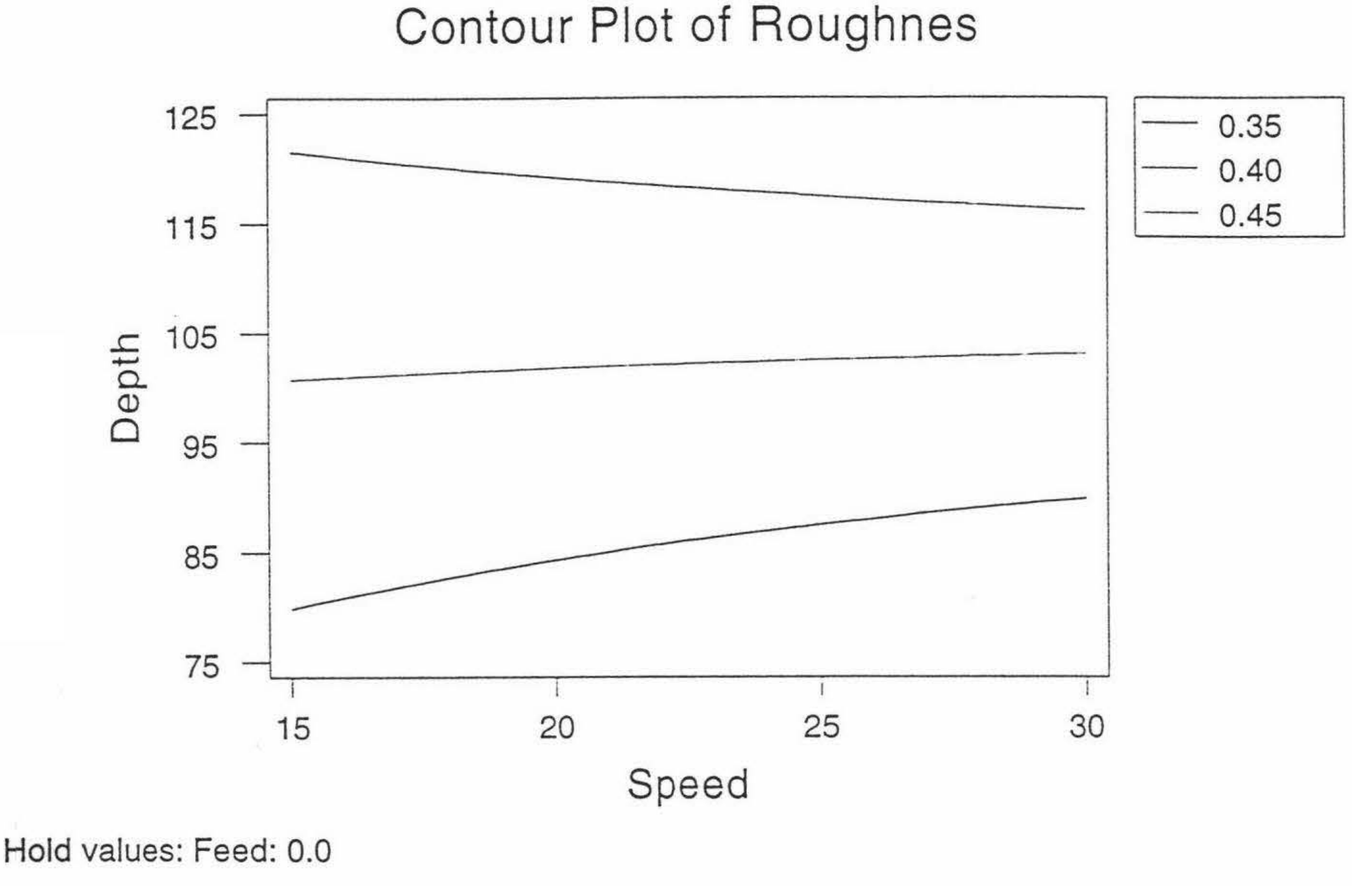


Figure App-3.7 Contour plot of surface roughness for speed

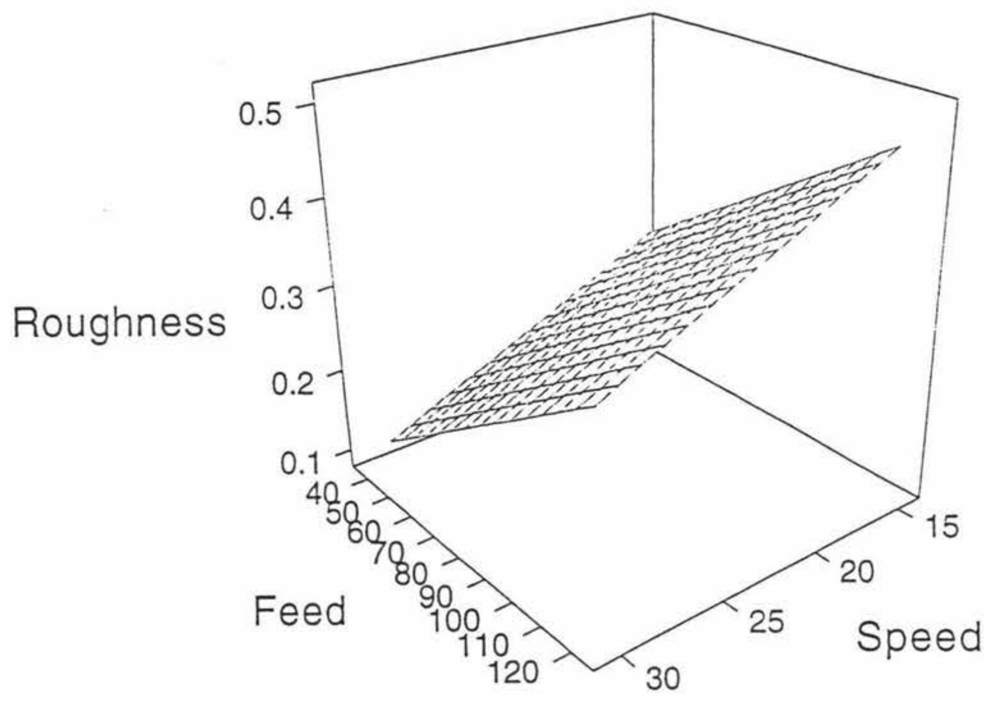


Figure App-3.8 RS plot for surface roughness with full factorial design

Worksheet size: 100000 cells

## Central Composite Design

Central Composite Design

| | | | | | |
|---|---|---|---|---|---|
| Factors: | 3 | Blocks: | none | Center points: | 6 |
| Runs: | 20 | Alpha: | 1.682 | | |

## Response Surface Regression

The analysis was done using coded units.

Estimated Regression Coefficients for C7

| Term | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | 0.41860 | 0.008885 | 47.112 | 0.000 |
| Feed | 0.02885 | 0.004959 | 5.818 | 0.000 |
| Speed | -0.00730 | 0.004959 | -1.471 | 0.161 |
| Depth | 0.04307 | 0.004959 | 8.684 | 0.000 |
| Feed*Feed | 0.04565 | 0.004703 | 9.706 | 0.000 |
| Speed*Speed | -0.01446 | 0.004703 | -3.075 | 0.007 |
| Depth*Depth | -0.02153 | 0.004703 | -4.578 | 0.000 |
| Feed*Speed | 0.00000 | 0.007706 | 0.000 | 1.000 |
| Feed*Depth | -0.02250 | 0.007706 | -2.920 | 0.010 |
| Speed*Depth | 0.01750 | 0.007706 | 2.271 | 0.037 |

S = 0.02179 R-Sq = 95.1% R-Sq(adj) = 92.3%

Analysis of Variance for C7

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 9 | 0.147034 | 0.147034 | 0.016337 | 34.39 | 0.000 |
| Linear | 3 | 0.052932 | 0.052932 | 0.017644 | 37.14 | 0.000 |
| Square | 3 | 0.087603 | 0.087603 | 0.029201 | 61.47 | 0.000 |
| Interaction | 3 | 0.006500 | 0.006500 | 0.002167 | 4.56 | 0.017 |
| Residual Error | 16 | 0.007600 | 0.007600 | 0.000475 | | |
| Lack-of-Fit | 5 | 0.006817 | 0.006817 | 0.001363 | 19.15 | 0.000 |
| Pure Error | 11 | 0.000783 | 0.000783 | 0.000071 | | |
| Total | 25 | 0.154635 | | | | |

Unusual Observations for C7

| Obs | C7 | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|
| 3 | 0.350 | 0.309 | 0.017 | 0.041 | 2.91R |
| 6 | 0.420 | 0.467 | 0.017 | -0.047 | -3.38R |

R denotes an observation with a large standardized residual

Unusual Observations for C7

| Obs | C7 | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|
| 3 | 0.350 | 0.309 | 0.017 | 0.041 | 2.91R |
| 6 | 0.420 | 0.467 | 0.017 | -0.047 | -3.38R |

## Response Surface Regression

Estimated Regression Coefficients for C7

| Term | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | -0.05153 | 0.158287 | -0.326 | 0.749 |
| Feed | -0.00159 | 0.001079 | -1.477 | 0.159 |
| Speed | 0.00126 | 0.005975 | 0.211 | 0.836 |
| Depth | 0.00831 | 0.001881 | 4.419 | 0.000 |
| Feed*Feed | 0.00003 | 0.000003 | 9.706 | 0.000 |
| Speed*Speed | -0.00026 | 0.000084 | -3.075 | 0.007 |

| | | | | |
|---|---|---|---|---|
| Depth*Depth | -0.00003 | 0.000008 | -4.578 | 0.000 |
| Feed*Speed | 0.00000 | 0.000026 | 0.000 | 1.000 |
| Feed*Depth | -0.00002 | 0.000008 | -2.920 | 0.010 |
| Speed*Depth | 0.00009 | 0.000041 | 2.271 | 0.037 |

S = 0.02179    R-Sq = 95.1%    R-Sq(adj) = 92.3%

Analysis of Variance for C7

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Regression | 9 | 0.147034 | 0.147034 | 0.016337 | 34.39 | 0.000 |
| Linear | 3 | 0.052932 | 0.016009 | 0.005336 | 11.23 | 0.000 |
| Square | 3 | 0.087603 | 0.087603 | 0.029201 | 61.47 | 0.000 |
| Interaction | 3 | 0.006500 | 0.006500 | 0.002167 | 4.56 | 0.017 |
| Residual Error | 16 | 0.007600 | 0.007600 | 0.000475 | | |
| Lack-of-Fit | 5 | 0.006817 | 0.006817 | 0.001363 | 19.15 | 0.000 |
| Pure Error | 11 | 0.000783 | 0.000783 | 0.000071 | | |
| Total | 25 | 0.154635 | | | | |

| Obs | C7 | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|
| 1 | 0.360 | 0.359 | 0.017 | 0.001 | 0.10 |
| 2 | 0.470 | 0.461 | 0.017 | 0.009 | 0.62 |
| 3 | 0.350 | 0.309 | 0.017 | 0.041 | 2.91R |
| 4 | 0.390 | 0.412 | 0.017 | -0.022 | -1.55 |
| 5 | 0.470 | 0.455 | 0.017 | 0.015 | 1.08 |
| 6 | 0.420 | 0.467 | 0.017 | -0.047 | -3.38R |
| 7 | 0.460 | 0.475 | 0.017 | -0.015 | -1.08 |
| 8 | 0.480 | 0.488 | 0.017 | -0.008 | -0.56 |
| 9 | 0.480 | 0.499 | 0.013 | -0.019 | -1.10 |
| 10 | 0.620 | 0.596 | 0.013 | 0.024 | 1.36 |
| 11 | 0.400 | 0.390 | 0.013 | 0.010 | 0.58 |
| 12 | 0.360 | 0.365 | 0.013 | -0.005 | -0.31 |
| 13 | 0.270 | 0.285 | 0.013 | -0.015 | -0.88 |
| 14 | 0.450 | 0.430 | 0.013 | 0.020 | 1.14 |
| 15 | 0.430 | 0.419 | 0.009 | 0.011 | 0.57 |
| 16 | 0.410 | 0.419 | 0.009 | -0.009 | -0.43 |
| 17 | 0.410 | 0.419 | 0.009 | -0.009 | -0.43 |
| 18 | 0.430 | 0.419 | 0.009 | 0.011 | 0.57 |
| 19 | 0.410 | 0.419 | 0.009 | -0.009 | -0.43 |
| 20 | 0.420 | 0.419 | 0.009 | 0.001 | 0.07 |
| 21 | 0.490 | 0.499 | 0.013 | -0.009 | -0.53 |
| 22 | 0.610 | 0.596 | 0.013 | 0.014 | 0.79 |
| 23 | 0.390 | 0.390 | 0.013 | 0.000 | 0.00 |
| 24 | 0.370 | 0.365 | 0.013 | 0.005 | 0.26 |
| 25 | 0.280 | 0.285 | 0.013 | -0.005 | -0.30 |
| 26 | 0.440 | 0.430 | 0.013 | 0.010 | 0.57 |

R denotes an observation with a large standardized residual

## Regression Analysis

The regression equation is
Results = - 0.637 - 0.00063 Feed + 0.0035 Speed + 0.0267 Depth -0.000020 Feed^2
+0.000000 Feed^3 + 0.00009 Speed^2 -0.000005 Speed^3
-0.000224 Depth^2 +0.000001 Depth^3

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | -0.6366 | 0.3921 | -1.62 | 0.124 |
| Feed | -0.000633 | 0.001654 | -0.38 | 0.707 |
| Speed | 0.00347 | 0.02132 | 0.16 | 0.873 |
| Depth | 0.02674 | 0.01166 | 2.29 | 0.036 |
| Feed^2 | -0.00001998 | 0.00002378 | -0.84 | 0.413 |
| Feed^3 | 0.00000020 | 0.00000010 | 2.06 | 0.056 |
| Speed^2 | 0.000086 | 0.001009 | 0.09 | 0.933 |
| Speed^3 | -0.00000508 | 0.00001488 | -0.34 | 0.737 |
| Depth^2 | -0.0002239 | 0.0001209 | -1.85 | 0.082 |
| Depth^3 | 0.00000063 | 0.00000040 | 1.57 | 0.136 |

S = 0.02485    R-Sq = 93.6%    R-Sq(adj) = 90.0%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 9 | 0.144753 | 0.016084 | 26.04 | 0.000 |
| Error | 16 | 0.009882 | 0.000618 | | |
| Total | 25 | 0.154635 | | | |

| Source | DF | Seq SS |
|---|---|---|
| Feed | 1 | 0.016079 |
| Speed | 1 | 0.001028 |
| Depth | 1 | 0.035825 |
| Feed^2 | 1 | 0.076334 |
| Feed^3 | 1 | 0.002621 |
| Speed^2 | 1 | 0.001312 |
| Speed^3 | 1 | 0.000072 |
| Depth^2 | 1 | 0.009957 |
| Depth^3 | 1 | 0.001525 |

Unusual Observations

| Obs | Feed | Results | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 2 | 120 | 0.47000 | 0.41575 | 0.01627 | 0.05425 | 2.89R |
| 6 | 120 | 0.42000 | 0.48075 | 0.01627 | -0.06075 | -3.23R |

R denotes an observation with a large standardized residual

## Best Subsets Regression

Response is Results

| Vars | R-Sq | R-Sq (adj) | C-p | S | Feed | Speed | Depth | Feed^2 | Feed^3 | Speed^2 | Speed^3 | Depth^2 | Depth^3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 36.7 | 34.1 | 136.5 | 0.063866 | | | | | X | | | | |
| 1 | 25.4 | 22.3 | 164.7 | 0.069311 | | | | X | | | | | |
| 2 | 61.3 | 57.9 | 76.9 | 0.051002 | X | | | | X | | | | |
| 2 | 61.1 | 57.7 | 77.4 | 0.051132 | | | | X | X | | | | |
| 3 | 84.5 | 82.4 | 20.9 | 0.033031 | X | | X | | X | | | | |
| 3 | 84.3 | 82.1 | 21.4 | 0.033241 | | | X | X | X | | | | |
| 4 | 88.8 | 86.7 | 12.0 | 0.028684 | | | X | X | X | | | X | |
| 4 | 88.8 | 86.7 | 12.0 | 0.028714 | X | | X | | X | | | X | |
| 5 | 90.6 | 88.2 | 9.6 | 0.026991 | | | X | X | X | | X | X | |
| 5 | 90.5 | 88.1 | 9.8 | 0.027100 | X | | X | | X | | X | X | |
| 6 | 92.6 | 90.2 | 6.6 | 0.024604 | | X | X | X | X | | X | X | |
| 6 | 92.6 | 90.2 | 6.6 | 0.024619 | | | X | X | X | X | X | X | |
| 7 | 93.5 | 91.0 | 6.2 | 0.023542 | | X | X | X | X | | X | X | X |
| 7 | 93.5 | 91.0 | 6.2 | 0.023559 | | | X | X | X | X | X | X | X |
| 8 | 93.6 | 90.6 | 8.0 | 0.024115 | X | X | X | X | X | | X | X | X |
| 8 | 93.6 | 90.6 | 8.0 | 0.024130 | X | | X | X | X | X | X | X | X |
| 9 | 93.6 | 90.0 | 10.0 | 0.024852 | X | X | X | X | X | X | X | X | X |

## Regression Analysis

The regression equation is
Results = - 0.653 + 0.0036 Speed + 0.0268 Depth -0.000029 Feed^2
+0.000000 Feed^3 +0.000082 Speed^2 -0.000005 Speed^3
-0.000224 Depth^2 +0.000001 Depth^3

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | -0.6530 | 0.3798 | -1.72 | 0.104 |
| Speed | 0.00364 | 0.02077 | 0.18 | 0.863 |
| Depth | 0.02681 | 0.01137 | 2.36 | 0.031 |
| Feed^2 | -0.00002887 | 0.00000479 | -6.03 | 0.000 |
| Feed^3 | 0.00000024 | 0.00000003 | 7.41 | 0.000 |
| Speed^2 | 0.0000820 | 0.0009834 | 0.08 | 0.935 |
| Speed^3 | -0.00000508 | 0.00001450 | -0.35 | 0.730 |

| | | | | |
|---|---|---|---|---|
| Depth^2 | -0.0002242 | 0.0001178 | -1.90 | 0.074 |
| Depth^3 | 0.00000063 | 0.00000039 | 1.61 | 0.125 |

S = 0.02422    R-Sq = 93.6%    R-Sq(adj) = 90.5%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 8 | 0.144662 | 0.018083 | 30.83 | 0.000 |
| Error | 17 | 0.009972 | 0.000587 | | |
| Total | 25 | 0.154635 | | | |

| Source | DF | Seq SS |
|---|---|---|
| Speed | 1 | 0.001028 |
| Depth | 1 | 0.035825 |
| Feed^2 | 1 | 0.039338 |
| Feed^3 | 1 | 0.055163 |
| Speed^2 | 1 | 0.001434 |
| Speed^3 | 1 | 0.000072 |
| Depth^2 | 1 | 0.010277 |
| Depth^3 | 1 | 0.001525 |

Unusual Observations

| Obs | Speed | Results | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 2 | 15.0 | 0.47000 | 0.41323 | 0.01450 | 0.05677 | 2.93R |
| 6 | 15.0 | 0.42000 | 0.47823 | 0.01450 | -0.05823 | -3.00R |

R denotes an observation with a large standardized residual

## Regression Analysis

The regression equation is
Results = 0.0306 + 0.00717 Depth -0.000033 Feed^2 +0.000000 Feed^3
 -0.000027 Depth^2

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | 0.03058 | 0.09591 | 0.32 | 0.753 |
| Depth | 0.007174 | 0.001883 | 3.81 | 0.001 |
| Feed^2 | -0.00003269 | 0.00000544 | -6.01 | 0.000 |
| Feed^3 | 0.00000026 | 0.00000004 | 7.31 | 0.000 |
| Depth^2 | -0.00002726 | 0.00000932 | -2.92 | 0.008 |

S = 0.02868    R-Sq = 88.8%    R-Sq(adj) = 86.7%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 4 | 0.137357 | 0.034339 | 41.74 | 0.000 |
| Error | 21 | 0.017278 | 0.000823 | | |
| Total | 25 | 0.154635 | | | |

| Source | DF | Seq SS |
|---|---|---|
| Depth | 1 | 0.035825 |
| Feed^2 | 1 | 0.039338 |
| Feed^3 | 1 | 0.055163 |
| Depth^2 | 1 | 0.007031 |

Unusual Observations

| Obs | Depth | Results | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 2 | 75 | 0.47000 | 0.40205 | 0.01133 | 0.06795 | 2.58R |
| 6 | 125 | 0.42000 | 0.48818 | 0.01133 | -0.06818 | -2.59R |

R denotes an observation with a large standardized residual

## Regression Analysis

The regression equation is
Results = - 0.203 + 0.0103 Depth +0.000006 Feed^2 -0.000043 Depth^2

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | -0.2027 | 0.1664 | -1.22 | 0.236 |
| Depth | 0.010263 | 0.003377 | 3.04 | 0.006 |
| Feed^2 | 0.00000646 | 0.00000181 | 3.57 | 0.002 |
| Depth^2 | -0.00004270 | 0.00001671 | -2.56 | 0.018 |

S = 0.05278      R-Sq = 60.4%      R-Sq(adj) = 55.0%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 3 | 0.093350 | 0.031117 | 11.17 | 0.000 |
| Error | 22 | 0.061285 | 0.002786 | | |
| Total | 25 | 0.154635 | | | |

| Source | DF | Seq SS |
|---|---|---|
| Depth | 1 | 0.035825 |
| Feed^2 | 1 | 0.039338 |
| Depth^2 | 1 | 0.018187 |

## Regression Analysis

The regression equation is
C14 = - 203 + 10.3 Depth + 0.00646 Feed^2 - 0.0427 Depth^2

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | -202.7 | 166.4 | -1.22 | 0.236 |
| Depth | 10.263 | 3.377 | 3.04 | 0.006 |
| Feed^2 | 0.006460 | 0.001807 | 3.57 | 0.002 |
| Depth^2 | -0.04270 | 0.01671 | -2.56 | 0.018 |

S = 52.78      R-Sq = 60.4%      R-Sq(adj) = 55.0%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 3 | 93350 | 31117 | 11.17 | 0.000 |
| Error | 22 | 61285 | 2786 | | |
| Total | 25 | 154635 | | | |

| Source | DF | Seq SS |
|---|---|---|
| Depth | 1 | 35825 |
| Feed^2 | 1 | 39338 |
| Depth^2 | 1 | 18187 |

## Regression Analysis

The regression equation is
C14 = 30.6 + 7.17 Depth - 0.0327 Feed^2 +0.000265 Feed^3 - 0.0273 Depth^2

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | 30.58 | 95.91 | 0.32 | 0.753 |
| Depth | 7.174 | 1.883 | 3.81 | 0.001 |
| Feed^2 | -0.032688 | 0.005442 | -6.01 | 0.000 |
| Feed^3 | 0.00026471 | 0.00003620 | 7.31 | 0.000 |
| Depth^2 | -0.027258 | 0.009325 | -2.92 | 0.008 |

S = 28.68      R-Sq = 88.8%      R-Sq(adj) = 86.7%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 4 | 137357 | 34339 | 41.74 | 0.000 |
| Error | 21 | 17278 | 823 | | |
| Total | 25 | 154635 | | | |

| Source | DF | Seq SS |
|---|---|---|
| Depth | 1 | 35825 |
| Feed^2 | 1 | 39338 |
| Feed^3 | 1 | 55163 |
| Depth^2 | 1 | 7031 |

Unusual Observations

| Obs | Depth | C14 | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 2 | 75 | 470.00 | 402.05 | 11.33 | 67.95 | 2.58R |
| 6 | 125 | 420.00 | 488.18 | 11.33 | -68.18 | -2.59R |

R denotes an observation with a large standardized residual

## Regression Analysis

The regression equation is
C14 = - 86.8 + 8.62 Depth - 0.0044 Feed^2 +0.000152 Feed^3 - 0.0265 Depth^2 - 0.0200 C15

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | -86.79 | 97.89 | -0.89 | 0.386 |
| Depth | 8.622 | 1.782 | 4.84 | 0.000 |
| Feed^2 | -0.00443 | 0.01233 | -0.36 | 0.723 |
| Feed^3 | 0.00015188 | 0.00005564 | 2.73 | 0.013 |
| Depth^2 | -0.026509 | 0.008351 | -3.17 | 0.005 |
| C15 | -0.019965 | 0.008005 | -2.49 | 0.022 |

S = 25.67    R-Sq = 91.5%    R-Sq(adj) = 89.3%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 5 | 141455 | 28291 | 42.93 | 0.000 |
| Error | 20 | 13179 | 659 | | |
| Total | 25 | 154635 | | | |

| Source | DF | Seq SS |
|---|---|---|
| Depth | 1 | 35825 |
| Feed^2 | 1 | 39338 |
| Feed^3 | 1 | 55163 |
| Depth^2 | 1 | 7031 |
| C15 | 1 | 4099 |

Unusual Observations

| Obs | Depth | C14 | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 6 | 125 | 420.00 | 475.97 | 11.26 | -55.97 | -2.43R |

R denotes an observation with a large standardized residual

## Regression Analysis

The regression equation is
C14 = - 106 + 8.86 Depth +0.000132 Feed^3 - 0.0267 Depth^2 - 0.0226 C15

| Predictor | Coef | StDev | T | P |
|---|---|---|---|---|
| Constant | -106.32 | 79.66 | -1.33 | 0.196 |
| Depth | 8.863 | 1.616 | 5.48 | 0.000 |
| Feed^3 | 0.00013245 | 0.00001255 | 10.55 | 0.000 |
| Depth^2 | -0.026659 | 0.008165 | -3.26 | 0.004 |
| C15 | -0.022604 | 0.003095 | -7.30 | 0.000 |

S = 25.13    R-Sq = 91.4%    R-Sq(adj) = 89.8%

Analysis of Variance

| Source | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 4 | 141370 | 35343 | 55.95 | 0.000 |
| Error | 21 | 13264 | 632 | | |

| | | |
|---|---|---|
| Total | 25 | 154635 |

| Source | DF | Seq SS |
|---|---|---|
| Depth | 1 | 35825 |
| Feed^3 | 1 | 56743 |
| Depth^2 | 1 | 15106 |
| C15 | 1 | 33696 |

Unusual Observations

| Obs | Depth | C14 | Fit | StDev Fit | Residual | St Resid |
|---|---|---|---|---|---|---|
| 6 | 125 | 420.00 | 474.81 | 10.56 | -54.81 | -2.40R |

R denotes an observation with a large standardized residual

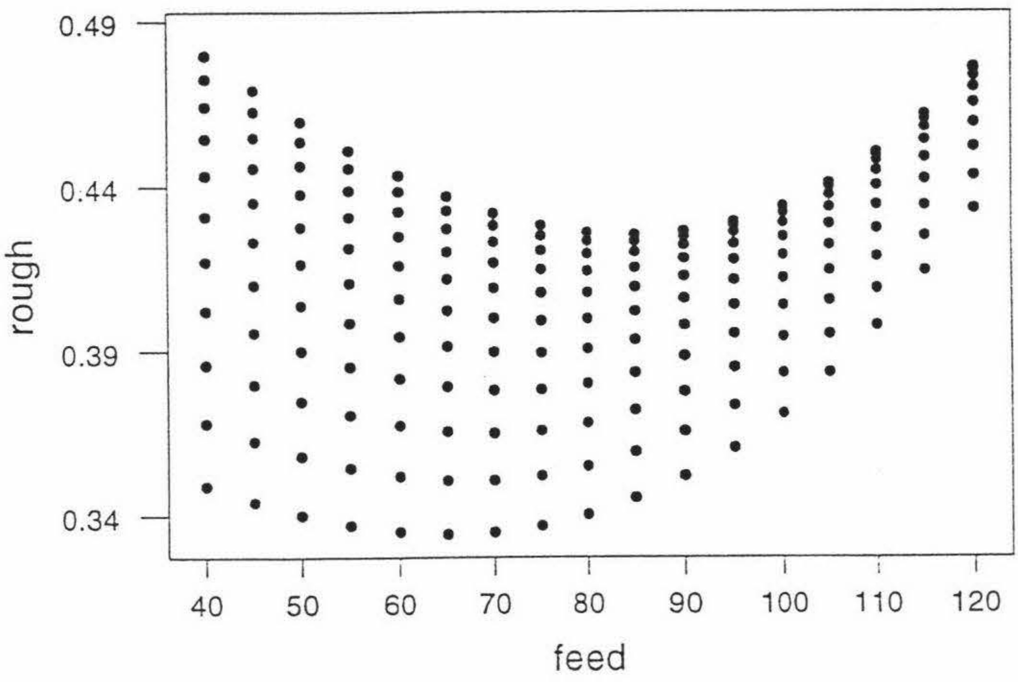


Figure App-3.9 RS plot for surface roughness with feed

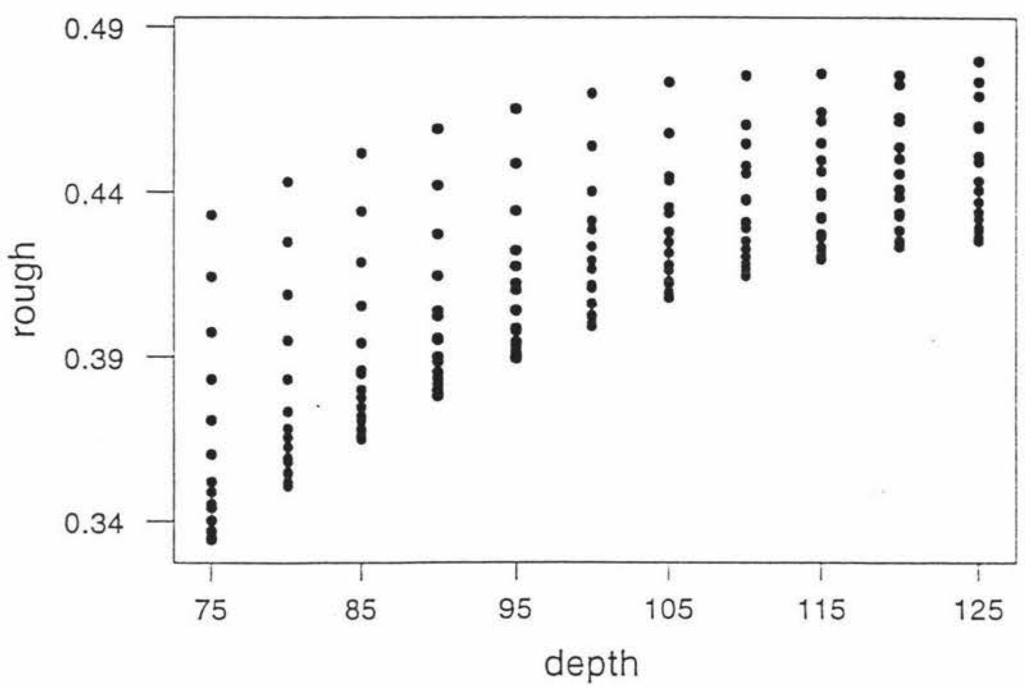


Figure App-3.10 RS plot for surface roughness with depth

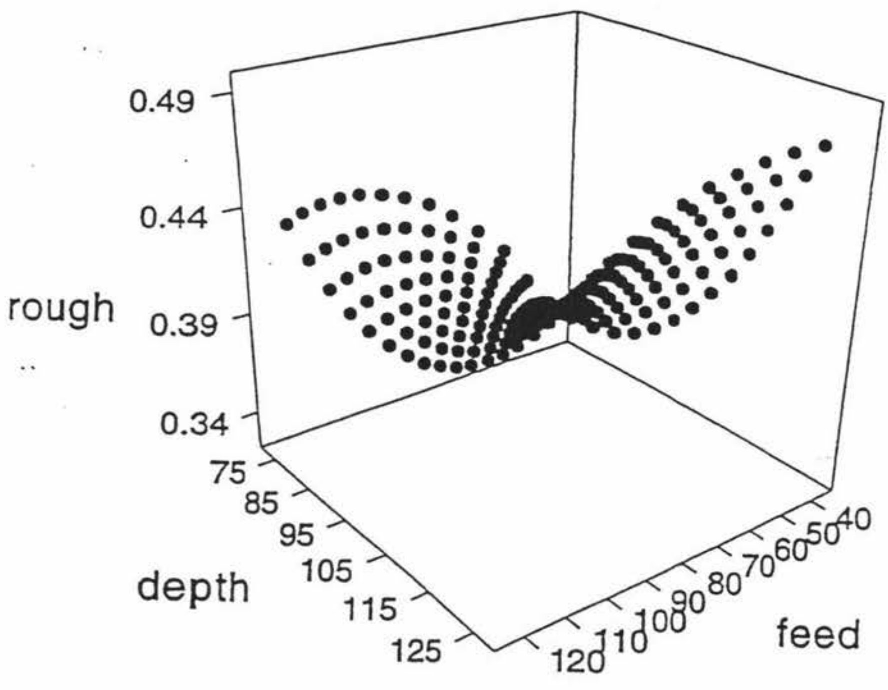


Figure App-3.11 RS plot for surface roughness with feed and depth

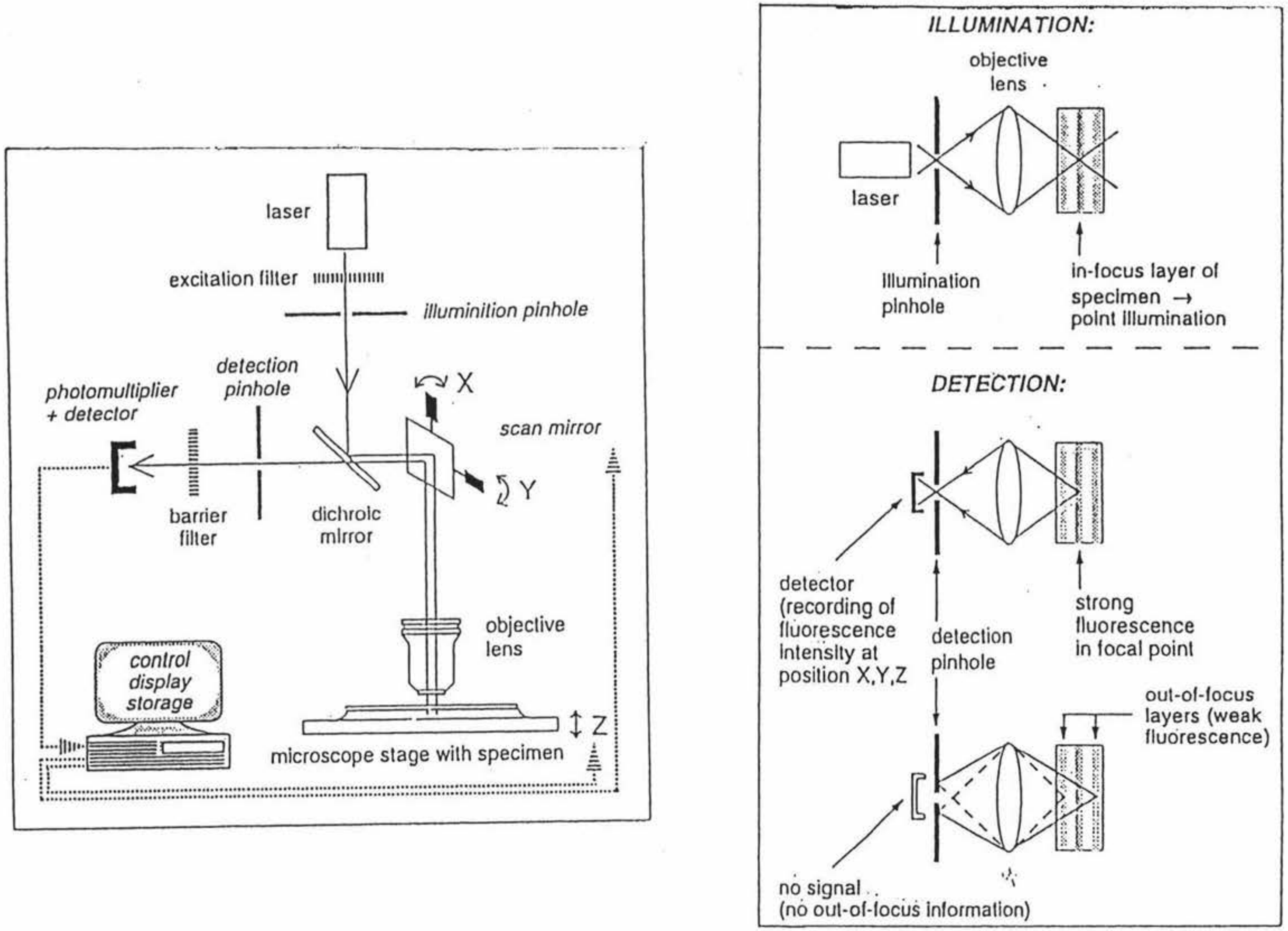


Figure App-4.1 Confocal Microscope