3. Methodology

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Chapter 3
Methodology

To study the effect of burnishing on the mechanical and metallurgical properties of the components, various experimental and analytical approaches were followed. The detailed description of the equipment used and the methodologies applied are discussed in this chapter.

3.1 Experimental Approach:

To study the effect of various process parameters on the material and surface characteristics of roller burnishing, a series of experiments were conducted. The results obtained from these experiments form the backbone of the subsequent methodologies, optimization and finite element analysis, which are used to further investigate the burnishing process and its effect on the mechanical and material characteristics.

In this section, a brief discussion is carried out regarding the material and geometry of the work pieces, the tools and equipment used for various processes like turning, burnishing, cutting etc and the procedure for determining the surface characteristics – surface roughness, hardness, induced compressive stress, microstructure, wear resistance and corrosion resistance. Figure 3.1 shows the flow chart of the experimental approach.
3.1.1 Workpiece Materials:

Burnishing operation can be applied on most of the engineering materials. But the materials which are extensively used in the manufacturing engineering are considered for the current study. They are

1. Mild steel (AISI 1020)
2. Aluminium (AA1200)
3. Brass (C34000 or CuZn35Pb1)
4. Copper (C14310)

The properties, applications and other details of each of these materials are discussed below.

1. **Mild steel**: Mild steel is the most widely used form of steel because of its material properties, which make it suitable for many engineering applications. Its cost being less increases these applications even further. Mild steel is an alloy of iron and carbon, where the content of carbon varies from 0.16 to 0.29%. Thus it comes under the low carbon steel family. Other constituents of the alloy are – manganese (0.3%), silicon (0.2%), sulfur (0.05%), phosphorus (0.04%), chromium, nickel
etc. The density of mild steel is 7850 kg/m³, Poisson’s ratio is 0.27 and the Young’s modulus is 210 GPa. Major applications of mild steel are: bolts & nuts, chains, hinges, knives, pipes etc.

2. Aluminium: Aluminium is the second most abundant metallic element available in the earth’s crust. The light weight of aluminium makes it suitable for manufacturing the components for transportation industry. Most of the parts of airplanes are made of alloys of aluminium. Aluminium also finds wide usage in engines and robotic devices. High thermal and electrical conductivity makes them suitable to be used in the electrical and electronics industries. Density of aluminium is 2700 kg/m³, Poisson’s ratio is 0.35 and the Young’s modulus is 70 GPa. Aluminium is a reactive metal, but it develops an aluminium oxide film that protects it from corrosion in many environments. Because of the formation of this thin film, the corrosion rate of aluminium is very less.

3. Brass: Brass is an alloy of copper and zinc. There are many types of brasses, based on the compositions of various ingredients. The brass considered for the current study is medium leaded alpha brass, (Cu – 63%, Zn – 35%, Pb – 1.4%, other – 0.5 %, by weight). Brass finds many applications where low friction is required, such as valves, door knobs, gears, locks etc. It is also used widely in musical instruments, horns and bells for its acoustic properties. Its relatively low melting point and flow characteristics make it a good material for casting. Density of brass is 8400 kg/m³. Poisson’s ratio is 0.34; Young’s modulus of brass is 110 GPa. Medium leaded brass will be here after
referred as brass in this thesis. Brass has more corrosion resistance than copper but is subjected to erosion corrosion.

4. Copper: Copper is a ductile material with very high thermal and electrical conductivity. It has good machinability and formability. It is most widely used in electrical and electronic products. Due to its durability and ease of casting, copper is ideal for making gears, turbine blades and bearings. It is widely used in heat exchangers, pressure vessels where its heat conductivity is exploited. Density of copper is 8960 kg/m³, poisons ratio is 0.35 and Young's modulus is 118 GPa. Copper exhibits good corrosion resistance in marine and industrial atmospheres, but is subjected to impingement attack.

These materials have many advantages because of their good properties. But all of them suffer from corrosion and low wear resistance. Copper and brass have relatively better corrosion resistance than mild steel. But they are not completely free from corrosion. So, the components made from these materials are often subjected to secondary operation to improve these properties. This additional step can be eliminated by introducing burnishing operation as surface finishing process.

The work pieces were procured in the form of cylindrical bars of ø42 mm and then turned to ø40 mm, on a lathe using single point cutting tool. These workpieces were then by burnished using a roller burnishing tool. For some part of the work (optimization of tool related parameters) work pieces of ø25 mm were used.
3.1.2 Equipment:

The major equipment used for the experimental work is listed and explained below.

1. Gedee Weiler SS & SC Center lathe
2. Kistler lathe tool dynamometer
3. Roller Burnishing tool
4. Hacksaw machine
5. Handysurf Instrument
6. X-ray diffraction equipment

3.1.2.1. Gedee Weiler SS & SC Center Lathe:

Lathe is one of the most important equipment for burnishing. Major operations of the present work – turning, burnishing and wear testing are performed on it. Gedee Weiler Sliding Surface & Screw Cutting (SS & SC) center lathe was chosen for this purpose. This is a high accuracy lathe with 4 kW spindle motor, having step-less spindle speeds ranging from 45 – 2500 rpm. The distance between the centers is 800 mm. It has 300 mm swing over bed and 190 mm swing over cross slide. The chuck size is 148 mm diameter. It has longitudinal feed of 0.025 – 0.9 mm/U and cross feed of 0.009 – 0.32 mm/U.

3.1.2.2. Kistler lathe tool dynamometer:

Burnishing force is the most predominant factor that controls the response variables of burnishing operation. So the monitoring and control of this parameter has to be handled with care. Dynamometer can be used to observe the applied burnishing force. Kistler four-component 9272 lathe tool dynamometer is used for this purpose.
This dynamometer has the capability to measure cutting force (Fz), feed force (Fx), thrust force (Fy) and torque (Mz). Thrust force measured by the dynamometer is considered as the burnishing force. The magnitude of other forces and torque were very less when compared to the thrust force, so they were not considered.

The lathe tool dynamometer has two components, base and tool holder. The base can be fixed to the tool post of the lathe. The dynamometer tool holder has provision to hold the tool. Figure 3.2 shows the dynamometer, with tool holder and base. The detailed specifications of the dynamometer are presented in appendix 2.

![Figure 3.2: Kistler lathe dynamometer – Type 9272](image)

### 3.1.2.3. Roller burnishing Tool:

The roller burnishing tool used for the present work is shown in figure 3.3. It has three components.

1. Shank
2. Roller
3. Bolt and nut assembly
The shank is made of mild steel, which is heat treated to improve its hardness. One end of the shank has a square cross section, which is used to hold the tool in the tool holder. The other end of the shank looks like a fork, which has provision to fix the roller, using a bolt and nut assembly.

Two materials were considered for the roller, high carbon high chrominium (HCHCr) steel and tool steel. These materials were chosen because of high hardness, toughness and wear resistance. The composition of the HCHCr steel is given in the table 3.1. The presence of chrominium, silicon and manganese increases the hardness and strength of ferrite of HCHCr steel.

![Figure 3.3: Roller brushing tool](image)

<table>
<thead>
<tr>
<th>Element</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (C)</td>
<td>1.1</td>
</tr>
<tr>
<td>Chrominium (Cr)</td>
<td>1.6</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>0.5</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>0.35</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>0.025</td>
</tr>
<tr>
<td>Sulphur (S)</td>
<td>0.025</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>~96.5</td>
</tr>
</tbody>
</table>

Table 3.1: Composition of burnishing roller material (HCHCr steel)
Necessary care was taken in the design of the roller. The surface of the roller is made to have certain nose radius, so as to eliminate any sharp edges. The land width of the roller is 3 mm. After machining, the rollers are subjected to heat treatment to improve the hardness. The hardness of the roller after heat treatment was found to be 60 HRC. The surface of the roller is cleaned by buffing to remove the scale deposited during heat treatment. The roller is then fitted in the shank using a bolt and nut assembly.

3.1.2.4. Hacksaw Machine:

The work pieces after burnishing have to be cut into slices, for further investigation. For this purpose a hacksaw machine was used, which is shown in figure 3.4. The hacksaw machine has four components.

1. Motor
2. Gear box
3. Hacksaw blade.
4. Work holder

The speed of the motor can be controlled by adjusting the resister. The gear box transforms the rotary motion into reciprocating motion of the hacksaw blade. The position and the force applied by the blade on the work piece should be controlled manually. The work piece is held securely in the work holder. The applied force and to & fro motion of the hacksaw blade cuts the work piece. Constant lubrication is very essential during cutting, to protect the blade from wear and for removal of the chips.
3.1.2.5. Handysurf Instrument:

Handysurf E-35A instrument is a portable machine, used for the measurement of surface roughness. This equipment has the capability to give 16 different readings like, $R_a$, $R_{\text{max}}$, r.m.s etc. instantaneously. It can be integrated with a computer to get the surface roughness values and the surface profile of the component being tested. Figure 3.5 shows the measurement of surface roughness using Handysurf instrument and the technical specifications are presented in appendix 3.
3.1.2.6. X-ray Diffraction Equipment:

StressTech Group’s Xstress 3000 G2 X-ray stress analyzer (figure 3.6) was used for the analysis of residual stresses and hardness of the components. This equipment measures the induced stresses on the crystalline material using the phenomenon called Bragg’s law, the details of which will be discussed in subsequent sections. This equipment makes use of the semiconductor detection technology, which reduces the measurement time considerably. Technical specifications of the equipment are presented in Appendix - 4.

This equipment consists of three major components,

**Main unit:** It has the power supply, high voltage generator and self contained cooling system. It controls the electronics and firmware.

**Goniometer:** It has two detectors symmetrically positioned on both sides of the incident beam. This makes it possible to have a single arc shaped detector holder in place of conventional 2θ-brackets. The 2θ angle can be adjusted instantly. Computer controlled DC motors
controls the movements, which eliminates all manual motions. Figure 3.7 shows the goniometer.

![Goniometer of XStress 3000 x-ray stress analyzer](image)

**X3000 Software:** This is dedicated software, which is the user interface that controls data acquisitions and used for analyses. It calibrates the system automatically, controls all the movements of the goniometer and calculates the response variables automatically. It also contains material library from which the appropriate one can be chosen, based on the work piece.

**3.1.3 Experimental Procedure:**

Burnishing operation is a finishing operation, which does not involve material removal from the component. The workpieces procured would generally have many inherent flaws like scaling, irregular diameter, out of roundness etc. These workpieces are generally not suitable to be burnished directly. They need to undergo certain preprocessing operations, to free themselves from the surface imperfections. Later these components can be burnished using a roller
burnishing tool. The procedure involved in this operation is listed below.

1. **Mounting and Facing:** The workpieces, obtained as cylindrical rods were mounted on the head stock of the center lathe, using a 3-jaw chuck. Necessary care should be taken not to have more over hanging length, as the forces applied during turning and burnishing will be considerable high. Facing operation was done on the free end of the workpiece surface, using a facing tool. Facing operation is shown in figure 3.8. A small indentation was created on the center of the face of the free end, using a countersink drill bit, to facilitate it to be mounted on the tail stock. After adjusting the tail stock, its longitudinal movement should be arrested. A dry run of the workpieces can be performed to make sure that the rotation is smooth and no wobbling occurs.

![Figure 3.8: Facing operation on a lathe](image)

2. **Turning:** Turning is the process of removal of metal from the rotating cylindrical components, on a lathe thereby reducing the size (diameter) and removing any scale formation from the surface. Single point cutting tool, made of high speed steel (HSS) is used for this turning. Figure 3.9 shows the turning operation, on the outer diameter, using a single point cutting tool. The work pieces for the
present study were turned in two stages. In the first stage scaling and other imperfections on the surface were removed by using higher depth of cut, feed and speeds. In the second stage (finish turning), the depth of cut and feed rate were reduced to obtain better surface finish.

3. **Burnishing:** The burnishing operation can be performed immediately after turning. The work piece need not be removed, or remounted on other machines, which saves good amount of production time. This is one of the main advantages of burnishing process, when compared to other surface finishing process, like grinding, honing or lapping, where the workpiece, after turning, has to be removed from the lathe and mounted on the respective machines.

The roller burnishing tool is mounted on the dynamometer, which is fitted to the lathe tool post. The position of the tool post is adjusted such that the roller touches the work piece surface exactly at the center, as shown in figure 3.10. If tail post is not used in the turning operation, it has to be introduced now, because the load
applied during burnishing is very high, which may lead to the distortion of the work piece.

![Figure 3.10: Alignment of roller and work piece during burnishing](image)

The work piece is then rotated by rotating the head stock. The tool post is then moved laterally until the roller touches the rotating work piece. The force with which the tool is pressed against the work piece (burnishing force) and the friction between the tool and work piece surfaces, forces the roller to rotate along with the work piece. This results in the burnishing of the workpiece. The tool post can be fed along the length of the work piece to burnish the work piece surface. The experimental set-up of the burnishing process is shown in figure 3.11.

![Figure 3.11: Burnishing operation on center lathe](image)
4. Cutting or Slicing: The work pieces after burnishing are cut into slices of 15 mm width, using a hacksaw machine. These slices of the work pieces will be used to study the corrosion and wear behavior. Some work pieces are turned and cut into slices of 15 mm width, which would be used to study the initial properties before burnishing.

3.1.4. Surface Roughness Measurement

Improving the surface finish is the primary aspect of burnishing. The surface roughness of the components before and after burnishing has to be measured in order to analyze the improvement in the surface finish by burnishing. There are many techniques for measuring the surface roughness of metallic components. They are broadly classified into:

1. Optical Instruments
2. Stylus Instruments

A brief description of each of these techniques is presented below.

3.1.4.1. Optical Instruments

When a beam of electro-magnetic radiation is focused onto a surface, it gets reflected off the surface in three different ways; specularly, diffusely or both. These are illustrated in figure 3.12. The roughness of the surface can be determined based on the type of the reflected radiation. One of the instruments that employ this technique is light-section microscope.
3.1.4.2. Stylus Instruments:

These instruments are based on the principle of moving a probe on the surface whose roughness has to be measured. Generally the stylus head, which comes in contact with the surface is made of a very hard material (generally diamond or tungsten), to withstand the wear. The vertical displacement of the stylus is controlled and magnified using a spring and gear system and the reading of the surface profile and roughness are determined. This was the technique used in the initial versions of the instruments. Later many developments took place in the instruments, but the basic principle remains the same. Figure 3.13 shows a schematic diagram of the principle of stylus instruments.

For the present work, Handysurf E-35A instrument, which is based on this principle, is employed, for surface roughness measurement.
3.1.5 X-ray Diffraction:

X-ray diffraction is a phenomenon, where the atomic planes of a crystal cause the incident x-rays beam to interfere with one another as they leave the crystal. Diffraction occurs when waves are incident on the surface of a material with regular molecular structure, whose lattice spacing is same as the wavelength of the incident wave. For example, when light is incident on a grating having lines spaced by a few thousand angstroms (which is about the wavelength of light), it gets diffracted. Similarly, x-rays also have wavelengths of the order of few angstrom units, which is generally equal to the lattice spacing of crystalline solids. So X-rays can be diffracted by materials which are crystalline and have repeating atomic structure. X-ray diffraction is used in the current work, to determine the induced residual compressive stresses and the hardness of the components that are processed by burnishing.
The phenomenon of x-ray diffraction, which was proposed by Bragg and other details of the process are discussed in the following sections.

3.1.5.1. Bragg’s Law:

In 1913 William Lawrence Bragg and William Henry Bragg found that when x-rays are incident on crystalline solids, they produce surprising patterns. They found that these crystalline solids produce intense peaks of reflected radiations, which were named as Bragg’s peaks, when incident with certain wavelength and angle.

Bragg’s law states that constructive interference occurs when a beam of wavelength $\lambda$, is incident at an angle $\theta$, on a crystalline solid of lattice spacing of $d$, and when the following conditions are satisfied.

a. Angle of incidence ($\theta$) should be equal to the angle of scattering
b. The path-length difference ($d$) is equal to an integer number ($n$) of wavelength ($\lambda$).

This can be represented in the form of an equation as shown below.

$$n \lambda = 2d \sin \theta$$

Derivation of Bragg’s law:

Referring to figure 3.14, the lower beam must travel an extra distance ($AB + BC$) to continue traveling parallel and adjacent to the top beam.

Constructive interference occurs only when,

$$n \lambda = AB + BC$$

But from the figure 3.15 it can be noticed that $AB = BC$.

So, $n \lambda = 2AB$. 
But \( \sin \theta = \frac{AB}{d} \).

\[ AB = d \sin \theta \]

Therefore, \( n\lambda = 2d \sin \theta \)

![Diagram of Bragg's Law derivation](image)

**Figure 3.14: Deriving Bragg’s Law**

### 3.1.5.2. Applications of x-ray diffraction:

There are many applications of x-ray diffraction. But the ones that are relevant to the current context are listed below.

1. Non-destructive measurement of compressive and tensile residual stresses, on surface and subsurface layers.
2. Measurement of stresses associated with failure caused by stress corrosion or fatigue.
3. Measurement of hardness in thin layers, generally of the order of a few millimeters.

Among these applications, the current work makes use of the capabilities of x-ray diffraction, for measurement of compressive residual stresses and hardness of the surface and subsurface layers.
3.1.5.3. Measurement of Residual Stress by XRD:

The measurement of residual stress by x-ray diffraction depends on the interaction between the incident x-ray beam and the lattice structure of the crystal. For measuring the stresses induced in a material, the strain in the crystal lattice is measured and then associated with the stresses, using the elastic constants.

From figure 3.15, it can be noticed that the lattice spacing (d) was varied by the application of external force. This resulted in the strain, which can be calculated as Δd/d. Δd is the difference in the lattice spacing, before and after application of force, which can be determined using x-ray diffraction. This value of the strain can be used to calculate the stress using the modulus of elasticity, Poisson’s ratio and taking into consideration the elastic anisotropy of the material.

To measure the strain, the specimen is placed in the x-ray diffractometer and exposed to the x-ray beam. This beam interacts with the crystal lattice and causes diffraction patterns. From this
diffraction patterns, the diffraction peaks are located and further calculations are made to determine the stain and the induce stresses.

3.1.5.4. Measurement of hardness by x-ray diffraction:

X-ray diffraction can be used to measure the hardness on the surface and subsurface layers. The measurement of hardness using this technique is an indirect process. Its value is measured using the breadth of the diffraction peaks profiles, obtained from the x-ray diffraction, and fitted into Cauchy distribution function.

The hardness on the surface of the component is mechanically measured using conventional hardness measuring technique, Brinell hardness tester, with tungsten carbide ball of 5 mm diameter and a normal force of 250 Kgf (hence the units: HBW 5/250). This procedure is repeated for various surface harnesses of the material. Later, x-ray diffraction is performed for these surfaces of different hardness and the full width at half height of the diffraction peak is measured using Pearson VII function peak profile plotting. An empirical curve is plotted relating the diffraction peak width to the hardness. This graph can be then used to determine the hardness of the component at various depths based on the value of the diffraction peak width. But the equipment used for the current study has a extensive library of such empirical curves for most of the commonly available materials. As the materials chosen for the current study were standard materials, the library of empirical curves were used, to determine the hardness of the component from the full width at half height of the diffraction peak. The actual graphs in the library of XStress 3000 G2
could not be exported, so a sample graph for Brinell hardness as a function of diffraction peak half width is shown in figure 3.16.

Figure 3.16: Brinell hardness as a function of Diffraction-peak width angle at half height of the peak

### 3.1.6 Microstructure Analysis:

Microstructure can be defined as the structure of the surface, revealed by microscopic observation under a magnification of above 25X. The procedure of observing and analyzing the prepared surface of a component is called microstructure analysis. The microstructure can be revealed by selective etching of the surface with appropriate solution and then observing it using an optical microscope. The chemical reactivity of each of the grains depends on crystallographic orientation. Thus the incident light is reflected differently by grains of different orientation. This is responsible for the apparent differences in grain color. The observed microstructure can be photographed, using microscopes equipped with high resolution cameras. This procedure is called micrography.
The influence of microstructure on any metal’s physical properties like strength, hardness, corrosion resistance wear resistance etc, is very high. For example, yield strength is a measure of the resistance to plastic flow, which is controlled by the mechanism of dislocation motion. Dislocations are line defects, whose motion is more sensitive at the grain boundaries than at the lattice. The lattice constitutes the microstructure. Thus microstructure controls the strength of the material.

**Metallography:** Microstructure does not reveal the crystal structure or the atomic bonding. It explains the arrangement and alignment of the crystals in the matrix. The study of microstructure, named as metallography, bridges the crystal structure and the physical appearance of the specimen, as shown in figure 3.17.

3.1.6.1. **Microstructure of ferrous alloys:**

The micro structure of iron based alloys is influenced by composition, homogeneity, processing and other factors. This makes
the analysis of these alloys very complicated. For example, the microstructure of a cast product looks different from a wrought product, even if they are made from the same material. So, composition of the material of the product is not sufficient to analyze the microstructure.

Etching of the surfaces of the specimen is very much needed, if the examination is not for inclusions or nitrides. Nital, usually 2 – 4% is most commonly used as etchant. It is very good for revealing the grain boundaries for low-carbon steels. Other etchants which can be used are picral, aqueous sodium metabisulfite etc, which have specific applications and advantages. There are also certain etchants, called tints, which are used to color certain constituents of steel. They can be used to study the grain size and grain boundaries.

There are many microstructural constituents in ferrous alloys. Some of them are listed below:

**Alpha iron and Ferrite:** Alpha iron refers to the body centered cubic (BCC) form of pure iron, which is stable above 912 °C. Ferrite is a solid solution of one or more elements in BCC iron. Often Alpha iron and ferrite are used as synonyms, which is incorrect.

**Gamma iron and Austenite:** Gamma iron refers to only face centered cubic (FCC) form of pure iron that is stable below 912 °C. Austenite is a solid solution of one or more elements of FCC iron. These two should not be used interchangeably.

**Delta Iron and Delta Ferrite:** Delta iron is the BCC form of pure iron that is stable above 1394 °C. Delta ferrite is the stable high
temperature (above 1394 °C) solid solution of one or more elements in bcc iron.

**Graphite and Cementite:** Graphite is the stable form of carbon in iron (mainly observed in cast iron) while cementite is meta-stable and can transform to graphite under long-term, high-temperature exposures.

**Pearlite** is a meta-stable, composite of fine and alternating layers of ferrite and cementite that forms at temperatures below the lower critical temperature

**Other Constituent:** There are many other minor constituents in ferrous alloys, such as nitrides, carbo-nitrides and non-metallic inclusions such as sigma and chi.

### 3.1.6.1. Microstructure of non-ferrous metals:

The non-ferrous materials considered for this study were Aluminium, Brass and Copper. This section explains the microstructure of these materials.

**Aluminium:** Aluminium is the second most abundantly available metal in earth’s crust. The crystal structure of aluminium is face centered cube (FCC). Generally used etchant for aluminium is diluted hydrofluoric acid (HF)

**Brass:** Most common of the copper alloys is Brass. Alpha brass is stable for concentrations upto 35% of Zn by weight. This phase has FCC crystal structure and is relatively ductile and easily cold worked. For microscopic analysis of brass, careful preparation of the surface is
necessary. This preparation should include surface treatment with appropriate chemical reagents, generally cerium oxide with water.

**Copper:** The crystal structure of copper is face centered cube (FCC). The number of atoms per unit cell is 4. The surface of copper would generally be etched by Ammonium persulphate diluted in water.

### 3.1.7 Corrosion Resistance:

Corrosion is the deterioration or disintegration of the metal components, when they react with the foreign elements, which can be any fluid or even solids. This is caused because of the chemical reaction that takes place between metal and the corrosive environment. This may leads to mechanical failure of the machinery or structure, because the strength of the components diminishes by corrosion. To avoid the adverse effects of corrosion, engineers always strive towards the development of a process that can reduce or eliminate corrosion. Burnishing is one such process, which reduces the corrosion of metal components.

#### 3.1.7.1. Types of Corrosion:

Corrosion can be classified based on the appearance of the corroded metals. In most of the cases mere naked eye examination may be sufficient and in some cases, magnification may be needed. Examination of the corroded surface before cleaning is particularly desirable, for this purpose.

There are eight major forms of corrosions. They are:
1. **Uniform corrosion**: This is the most common form of corrosion. This generally occurs by chemical or electro chemical reaction over the entire exposed surface. The life of the component exposed to such corrosion can be predicted, because the rate of corrosion will mostly be constant throughout its life.

2. **Galvanic or Two-Metal Corrosion**: When two metals are immersed in corrosive solution, there will be some potential difference. If these components come in contact physically or connected electrically, electrons flow between them, because of the potential difference. This leads to the corrosion of the components.

3. **Crevice Corrosion**: Localized corrosion occurs in crevice areas of the metal surfaces. This corrosion is caused because of small values of solution captured in the holes around the gaskets, bolts, joints etc.

4. **Pitting**: It is an extremely localized attack that occurs in holes (pits), which are usually very small. These holes are some times very small and closely located that they look like a rough surface. This type of corrosion is very difficult to predict and prevent.

5. **Intragranular corrosion**: In some metals the grain interfaces are very reactive. Localized attack at the grain boundaries (with very little or no corrosion of grains) occur. This is called intragranular corrosion.

6. **Selective Leaching**: It is the removal of one element of an alloy by corrosion. This type of corrosion is some times referred to as parting, in metallurgy.
7. **Erosion corrosion:** Erosion is caused by the relative movement between the corrosive fluid and the metal. The rate of corrosion increases because of this relative movement.

8. **Stress corrosion:** Stress corrosion cracking is caused when the component with residual tensile stresses is exposed to corrosive environment. In this type of corrosion, the entire surface is not attacked, but fine cracks are initiated and progresses through the component, which results in the failure of the component.

   In this thesis, uniform corrosion is considered and the effect of burnishing on improving the corrosion resistance is studied.

### 3.1.7.2. Corrosion Rate:

The corrosion resistance of a metal can be compared with another only if there is a way to express its corrosion rate quantitatively. Corrosion rate can be expressed in many ways, such as percentage of weight loss, milligrams per square centimeter per day, grams per square inch per hour. These units measure the corrosion only from the perspective of weight loss and not in terms of penetration. But the penetration perspective is very much needed to predict the life of the component, by estimating the tinning of the component. The expression ‘mils per year penetration’ is the most desirable way of expressing the corrosion and this will be used throughout this thesis. This expression is calculated using the weight loss of the specimen during the corrosion test. The formula for calculating the corrosion resistance using this approach is given below in equation 3.1.
\[ mpy = \frac{22,300 \, W}{A \, D \, T} \rightarrow \text{eq. 3.1} \]

Where,

\( mpy = \) mils per year penetration, (1 mil is one thousandth of an inch)

\( W = \) weight loss (g)

\( D = \) density of specimen (g/cm\(^3\))

\( A = \) Area of specimen exposed to corrosion (sq. in.)

\( T = \) exposure time (days)

This calculation is done based on some assumptions, which are listed below:

1. The penetration is uniform across the specimen surface.
2. There is no localized attack on the work piece surface.
3. The area of the specimen is unchanged throughout the exposure period.
4. Weight of the specimen is not affected by the procedure used for removal of the corrosion product, like rust.
5. The rate of penetration is constant throughout the exposure period.

3.1.7.3. Measurement of corrosion resistance:

Corrosion resistance is a relative term. If two components that are exposed to the same corrosive environment, the one with lower corrosion rate is said to have more corrosion resistance than the other. So measurement of corrosion resistance is indirectly a measure of corrosion rate.
In this thesis, the components whose corrosion resistance is required to be measured are exposed to two corrosive environments (normal atmosphere and brine solution) and the corrosion rate (in mpy) is determined. This value is compared against the values of its counter parts and the discussion is done on corrosion resistance.

The two corrosive environments chosen to study the corrosion resistance of burnished components were:

1. Normal atmosphere
2. Brine solution

A detailed description of these two corrosive environments and the general behavior of the mild steel, aluminium, brass and copper in these environments are discussed below.

1. Atmospheric Corrosion:

Atmospheric corrosion refers to the attack on metals exposed to air. Corrosion by atmosphere accounts of more failure than any other corrosive environment. The atmospheric parameters that contribute to corrosion are temperature, moisture, rainfall, solar radiation, wind velocity, etc. Air pollution such as sulfur dioxide, oxides of nitrogen, carbon dioxide etc also contributes to corrosion.

Atmosphere can be broadly classified into three types.

1. Industrial/Urban
2. Marine
3. Rural

**Industrial/Urban:** The most effective causes of corrosion in industrial environments are sulfur oxides and nitrogen oxides. These
pollutants are produced by the burning of fuels in industries and automobiles. Other elements that contribute towards corrosion in these environments are chlorides, phosphates, ammonia and other slats.

**Marine:** Corrosion in marine atmosphere is mostly dominated by the presence of sodium chloride. The quantity of NaCl in the atmosphere can vary drastically based on the velocity of the wind that carries salt vapors onto the land. This (NaCl) contaminated air causes severe corrosion. The main culprit in marine atmospheres is the chloride (Cl⁻) derived from NaCl.

**Rural:** Rural environments are usually free from aggressive agents like sulfur oxides, NaCl, ammonia etc. Rural environment is generally not aggressive towards metals. This atmosphere is the least corrosive as it does not contain any reactive components and pollutants.

The corrosion behavior of the metals considered for the current study, mild steel, aluminium, brass and copper when exposed to atmosphere is discussed here.

As it is one of the most widely used metal, the corrosion study of **mild steel** has gained great interest. In polluted environments sulfur oxides and chlorides are common pollutants. SO₂ reacts with the surface of the metal component to acidify the moisture layer at the metal interface to produce FeSO₄, which under goes hydrolysis reactions to produce iron oxides (FeO, Fe₂O₃; which are widely know as rust) or even H₂SO₄ which further attacks the metal surface. Other
pollutants like NO$_x$ and O$_3$ and other atmospheric parameters like moisture, effect the corrosion of mild steel.

**Aluminium** undergoes black staining when exposed to humid atmospheres. This staining is formed due to the rain or condensation of moisture. The degree of attaining depends on the rate of diffusion of oxygen into the thin film of condensed water. This stained area is mostly bayerite (Al$_2$O$_3$.3H$_2$O), which has generally thickness of a few thousand angstroms. Other factors that influence the corrosion of aluminium are SO$_2$, chlorides and pH of rain water. The corrosion product formed when aluminium reacts with SO$_2$ present in atmosphere include aluminium sulphate (Al$_2$(SO$_4$)$_3$.18H$_2$O) Compared to other metals aluminium corrodes at a very slow rate because of the formation of amorphous oxide film, which has very less solubility in air and aqueous solutions. But its corrosion rate increases in marine and industrial atmospheres, because of the presence of pollutants.

**Brass** is generally less reactant to organic and inorganic reagents. When exposed to atmosphere, it forms a green protective film of corrosion products. But when brass reacts with some corrodents, preferential dissolution of Zn occurs, which leads to dezincification of the alloy. Formation of nitric acid, on the surface exposed to atmosphere with high moisture and rain fall, lead to the corrosion of brass.

Corrosion of **copper** exposed to atmosphere occurs in a sequence of reactions. Initially oxygen and water react with fresh copper surface forming a layer containing predominantly cuprite
(Cu$_2$O) and copper oxide (CuO). Later this layer then reacts with pollutants like SO$_2$, NO$_2$, chlorine, ozone etc, which result in the formation of various compounds, on top of the initially formed cuprite layer. These compounds vary based on the type of atmosphere. Cu$_4$SO$_4$ (OH)$_6$, H$_2$O, posnjakite, and Cu$_4$SO$_4$ (OH)$_6$, brochantitie are formed in rural areas and Cu$_2$SO$_4$ (OH)$_4$, antlerite, and Cu$_2$CO$_3$(OH)$_2$, malachite in industrial areas [110].

The corrosion behavior of burnished and unburnished specimen was studied in marine, industrial and rural areas. The duration of this test was chosen as 1 year, to analyze the corrosion behavior in all the seasons of the year.

2. Corrosion in brine solution:

Brine solution can be made up from salts like sodium chloride, magnesium chloride etc. Brine also refers to the naturally occurring salt water in sea, ocean or salt lakes. The water in the sea has a salinity of about 3.5% by weight, where as artificially prepared brine solution can have concentration varying from 1% to 28% (saturation point of brine) at room temperature. At elevated temperatures the saturation point of brine can be increased further.

Addition of salt/impurities accelerates the electrochemical corrosion by increasing the conductivity of the solvent. Corrosion in brine is caused mainly by dissolved gasses, especially oxygen. Corrosion can also be caused by CO$_2$, H$_2$S and chlorine. Sodium chloride (NaCl) reacts with water resulting the in the formation
sodium hydroxide, hydrogen and chlorine gases. This reaction is shown below.

$$2 \text{NaCl} + 2 \text{H}_2\text{O} \rightarrow 2 \text{NaOH} + \text{H}_2 + \text{Cl}_2$$

The byproducts (Sodium hydroxide, hydrogen and chlorine gas) of this chemical reaction, react with the components immersed, resulting the corrosion. Commercially available salt (NaCl) contain small percentage of impurities like magnesium, calcium, which have effect on the corrosion of the products exposed to brine solution. But the presence of dissolved oxygen in brine is the major threat to the metals, in the form of corrosion.

The corrosion behavior of the different metals in brine solution is discussed here. The electrochemical reaction in the brine solution with mild steel occurs in two locations. Anode reaction occurs at the metal surface and the cathode reaction occurs with water. These two reactions are show below.

$$\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^- \rightarrow \text{Anode reaction}$$

$$\text{O}_2 + 2\text{H}_2\text{O} + 2\text{e}^- \rightarrow 4\text{(OH)}^- \rightarrow \text{Cathode reaction}$$

Combining these two reactions, we get the complete reaction.

$$\text{O}_2 + 2\text{H}_2\text{O} + 2\text{Fe} \rightarrow 2 \text{Fe(OH)}_2 \rightarrow \text{Complete reaction}$$

This iron hydroxide (Fe(OH)$_2$) further reacts with oxygen to give the final reddish corrosion product rust (Fe$_2$O$_3$.H$_2$O). These reactions are shown in figure 3.18.
The corrosion rate is controlled by the dissolved oxygen in the brine, which diffuses to the metal. So the corrosion rate varies based on the availability of dissolved oxygen and its diffusion in the solution. Other elements that have influence, relatively less when compared with oxygen, on corrosion of mild steel in brine is hydrogen sulfide H$_2$S and carbon dioxide CO$_2$.

The corrosion behavior of *aluminium* in brine is similar to mild steel. The anodic reaction is shown in the below equation.

$$\text{Al} \rightarrow \text{Al}^{3+} + 3e^- \quad \rightarrow \text{Anode reaction}$$

The liberated aluminium ions react with water to form aluminium hydroxide.

$$\text{Al}^{3+} + 3\text{H}_2\text{O} \rightarrow \text{Al(OH)}_3 + 3\text{H}^+$$

Dissolved oxygen reacts with Al(OH)$_3$ to form a stable and inner layer of aluminium oxide Al$_2$O$_3$, which protects the base metal form further corrosion. But under severe conditions, like presence of aggressive chloride ions, pits are initiated at weak locations of the
oxide layer. The chloride ions combine with H\(^+\) ions to form hydrochloric acid (HCl), which cause pitting. So the presence of chloride ions aggravates the corrosion of aluminium in brine.

**Brass** inherently resists attack by external agents. When exposed to corrosive environment, it forms a protective corrosive film. The rate of formation of this corrosive layer diminishes as oxygen is excluded from the metal surface. But selective corrosion (dezincification, which is a type of dealloying) occurs in brass with higher percentage (> 15%) of zinc, because of zinc’s high galvanic series ranking. This creates a porous and weak copper and copper oxide layer on the surface of brass, which leads to serious deterioration of mechanical properties. If not arrested, dezincification may penetrate into deeper layers of brass, resulting in the replacement of brass with copper. Dezincification is evident especially under stagnant conditions of the corroding environment.

**Copper** resistance to corrosion relies on a small amount of corrosion that forms a protective or semi-passive layer that resists further corrosion. This protective layer contains corrosive products, oxides of copper. The chemical reactions that take place are shown below.

\[
\text{Cu} \rightarrow \text{Cu}^{2+} + \text{e}^{-}
\]

The copper ions form solid complexes by reacting with various negatively charged ions like hydroxides (OH\(^-\)), Chlorides (Cl\(^-\)), and sulfates (SO\(_4^{2-}\)).
In the presence of dissolved oxygen, the electrons liberated from copper are absorbed by oxygen to form oxygen ions, which further react with Copper ions to form different oxides of copper.

\[
O_2 + 4e^- \rightarrow 2O^{2-}
\]

\[
4Cu + O_2 \rightarrow 2Cu_2O
\]

\[
2Cu + O_2 \rightarrow 2CuO
\]

The oxides of the copper formed in the above reaction are the major constituents of the protective layer formed on the surface.

**3.1.8 Wear Resistance:**

When two or more moving components come in contact with each other, they undergo certain dimensional changes because of material loss. This deterioration of the material of the moving parts because of the relative motion is called wear. The component with lower hardness experiences more weight loss and dimensional changes than its counterpart with higher hardness. The ability of a component to endure wear is called wear resistance.

**3.1.8.1. Types of wear:**

The type of relative motion between the contacting surfaces and the type of surfaces coming in contact are used to define various types of wears.

1. **Abrasive wear:** Abrasion is very often used as a synonym of wear. Abrasion is caused by the sharp surface irregularities of the contacting surface, as shown in figure 3.19. In the current thesis, the abrasive wear of the burnished and unburnished components are compared and the improvement in the wear resistance is studied.
2. **Adhesive wear**: This type of wear is due to the localized bonding between the contacting solid surfaces, which leads to the transfer of material from one surface to the other. This is shown in figure 3.20

3. **Catastrophic wear**: When the surface damage or deterioration occurs very rapidly, by which the service life of the part is shortened drastically is called catastrophic wear.

4. **Corrosion wear**: Wear in which chemical or electrochemical reaction with the environment plays a significant role is called corrosion wear.
5. Erosion: When the particles in the fluids strike the solid surface, which results in the wear of the solid surface is called erosion.

6. Fatigue Wear: This type of wear is caused by the fracture arising from fatigue of the material.

3.1.8.2. Measurement of wear:

When a component is subjected to wear, it loses material on the surface. This results in the reduction of its weight. The difference in the weight of the component before and after subjecting to wear gives a measure of the wear of the component.

A disc made of high carbon high chromium steel is heat treated and mounted on the head stock of the lathe. The flat surface of the rotating disc, which is very much harder than the workpieces being tested works as the wearing surface. The workpieces are cut into round slices of 15 mm width. Two holes were drilled on the flat surface of these slices. A fork-like workpiece holder (figure 3.21) is fabricated to hold these slices, using bolt and nut assembly. No movement or rotation of the work piece is allowed because of the pair of bolt fastened. This fork which holds the work piece is held by a lathe tool dynamometer, which is mounted on the tool post of the lathe. The dynamometer is used to measure the force (wear force, $f_w$) with which the work piece is pressed against the rotating disc. The tool post is adjusted longitudinally to make to work piece come in contact with the rotating disc. Figure 3.22 shows the schematic representation of the wear test set-up.
The disc, mounted on the head stock of the lathe is rotated at a speed of 450 rpm for a fixed duration, which was arbitrarily chosen as 2 minutes. The weight of the work piece before and after the wear test is measure using a digital weighting machine. The difference in this weight, before and after this test, gives a measure of wear. This wear test was repeated on specimens before and after burnishing. Since other parameters like, wear force, wear duration, specimen density and geometry, of this wear test are same, the weight loss can be directly related to the wear of the component. By comparing this weight loses of the burnished and unburnished specimen, the improvement in the wear resistance can be analyzed.
3.1.9 Electrical Conductivity:

The electrons, which are subatomic particles, carry a negative charge. These electrons under certain conditions move from one atom to another. This movement of electrons between the atoms will be random, unless driven by some external force. The directional movement of electrons when controlled by an external electromotive force would constitute electricity. The ability of a material to conduct electric current is called electrical conductivity (or specific conductance). It is commonly represented by the Greek letter $\sigma$ (sigma).

Ohms law states that when an electrical potential $V$ (volts) is applied across a material, a current of magnitude $I$ (amperes) flows. Figure 3.23 shows the circuit diagram for Ohm’s law. In most of the metals, at low values of $V$, the current is proportionate to $V$ and is given by the equation

$$I = \frac{V}{R}$$

Where $R$ is the electrical resistance (ohms, $\Omega$). $R$ depends on the intrinsic resistivity ($\rho$) of the material and the geometry (length $l$ and area $A$ thru which the current passes) of the component.

$$R = \frac{\rho l}{A}$$
The electrical conductivity ($\sigma$) of the material is the inverse of resistivity ($\rho$).

$$\sigma = \frac{1}{\rho}$$

Electrical conductivity varies from one material to another, by over 27 orders of magnitude, the greatest variation of any property. Electrical conductivity of different materials is shown in figure 3.24.

The general range of electrical conductivity of different materials is given below.

Metals: $\sigma > 10^5 \, (\Omega\text{m})^{-1}$

Semiconductors: $10^{-6} < \sigma < 10^5 \, (\Omega\text{m})^{-1}$

Insulators: $\sigma < 10^{-6} \, (\Omega\text{m})^{-1}$

From the above range it is clearly visible that the electrical conductivity of metals is very high when compared to the semi
conductors and insulators. Figure 3.25 shows the energy bands of conductors, semiconductors and insulators.

Conduction occurs by promoting the electrons into the conduction state that starts right above the Fermi level. The electrical conductivity of metals is very high because there is an overlap between the valance band and the conduction band of electrons, as shown in figure 3.25. The energy provided by an electric field is sufficient to excite many electrons into the conduction state.

3.1.9.1. Unit for electrical conductivity:

Electrical conductivity is a measure of how well a material accommodates the movement of electric charge. Its SI derived unit is **Siemens per meter**. But conductivity values are often reported as **percent IACS**. IACS is an acronym for International Annealed Copper Standard. The standard was established in 1913 by the International Electrotechnical Commission. The conductivity of annealed copper (5.8001 x 10^7 S/m or 1.7241x10^-8 ohm-meter) is defined to be 100% IACS at 20°C. All other conductivity values are related back to this conductivity value of annealed copper. Iron with a conductivity value
of 1.04 x 10^7 S/m, has a conductivity of approximately 18% of that of annealed copper and this is reported as 18% IACS.

### 3.1.9.2. Factors affecting electrical conductivity of metals:

The major factors that affect conductivity are

1. Temperature
2. Impurities
3. Imperfections (deformations or defects)

**Matthiessen rule** states that the total electrical resistivity of crystalline metallic specimen is the sum of resistivity due to thermal agitation, impurities and imperfections.

\[
\rho_{\text{total}} = \rho_{\text{thermal}} + \rho_{\text{impurity}} + \rho_{\text{imperfections}}
\]

Resistivity increases linearly with temperature, which increases thermal vibrations. Resistivity also increases with the increase in the impurities, which may be alloying elements or undesired impurities. The presence of any imperfections like cracks, pores etc or misalignments in the grain structure increases the resistivity, as shown in figure 3.26. But the effect of imperfections on the resistivity is weaker then the influence of temperature and impurities.

![Figure 3.26: Increase in resistivity by imperfections (pores and misalignment of grains)](image)
3.1.9.3. Measurement of electrical conductivity:

There are many techniques available for measuring the electrical conductivity of metals. But the most widely used technique is eddy current inspection. Eddy current inspection is a non-destructive testing method that uses the principle of electromagnetism.

**Basic Principle:**

When alternating current (AC) is applied to a conductor, such as copper wire, a magnetic field develops in and around the conductor. This magnetic field extends as the AC rises to maximum and collapses as the current is reduced to zero. If another electrical conductor is brought into the close proximity of this changing magnetic field, current will be induced in this second conductor, as shown in figure 3.27. This electrical current flow in circular path and is called eddy current. These currents affect the electrical impedance of the test probe. The change in the impedance is proportional to the electrical conductivity of the test part.

![Figure 3.27: Basic principle of eddy current testing](image)
**Procedure for measuring electrical conductivity:**

The procedure to determine the electrical conductivity using eddy current testing is explained below.

1. A probe which consists of a long coil made of electrical conducting material is made.
2. Alternating current (AC) is allowed to flow through the coil at a chosen frequency.
3. A dynamically expanding and collapsing magnetic field forms in and around the coil, as the alternating current flows through the coil.
4. An electrical conducting material (test specimen) is placed in the coil’s dynamic magnetic field. This results in the electromagnetic induction, which induces eddy currents in the test specimen, as shown in figure 3.28.

![Figure 3.28: Eddy currents induced in the conducting material](image)

5. The eddy currents flowing in the material will create their own secondary magnetic field (figure 3.29), which will oppose the...
coils primary magnetic field. This entire process of creation of eddy currents and its electromagnetic field repeats up to several million times, depending on frequency of the applied AC.

![Diagram of secondary magnetic field created by eddy currents](image)

Figure 3.29: Secondary magnetic field created by the eddy currents

6. The opposing magnetic field created by the eddy currents affects the impedance of the primary coil. This alters the current flow in the primary coil, and the electrical conductivity of the test specimen can be determined from the voltmeter reading in the primary coil circuit.

**Equipment used for measuring electrical conductivity:**

Technofour Conductivity Meter – Type 979, which works on the principle of eddy current, is used for measuring the electrical conductivity in this work, which is shown in figure 3.30. This equipment has the capacity to measure the electrical conductivity of non-ferrous materials in the range of 10% to 102% IACS, with an accuracy of ±1% IACS. The readings can be taken on the spot by
means of a hand held probe. It has a direct digital display with 0.1% IACS as least count.

![Technofour Conductivity Meter – Type 979](image)

The probe induces the eddy currents at fixed frequency in the test part. These currents affect the electrical impedance of the test probe. The change in the impedance is proportional to the electrical conductivity of the test part. Thus, electrical conductivity measurement is possible by measuring the corresponding change in probe impedance.

**3.1.10 Bearing Ratio and Bearing Ratio Curve:**

During any machining process, the tool profile is generally transferred onto the work component surface. The surface roughness profile of this machined surface depends on many working parameters like tool condition, operator skill etc. This determines the height, shape and direction of the surface irregularities. From the surface profile curves, the distribution of material in the irregularities can be determined. These results can be used to characterize the quality, surface roughness and bearing capacity of the components.
Surface roughness is not a one-dimensional problem. But parameter Ra, which averages the peak and valley displacement from a mean line, is a measure of only height of the surface irregularities. It does not provide any information about the height of the peaks or depth of the valleys or the ability of the component to bear a load. Two surfaces can have the same Ra, but may behave in two different ways. So it is necessary to evaluate another parameter which explains the quality of the surface to a better extent. One such parameter is bearing ratio curve (BRC), which can be used to better understand the bearing capacity of the surface. Bearing ratio curve (BAC), which is also known as Abbott-Firestone curve (AFC), describes the surface texture of an object. It was first proposed by EJ Abbott and FA Firestone, in 1933. The surface of the bearings can be understood better from this curve.

3.1.10.1. Bearing Ratio:

Bearing ratio \( T_p \) is the length of the bearing surface expressed as a percentage of the assessment length at a depth from the highest peak. It is very useful because it simulates the wear at various cutting depths of the surface. At a given depth, the profile is sliced horizontally and the material percentage is calculated, as shown in figure 3.31.

The cross sectional lengths \( L_i \) at each level (depth = c) from the highest peak and summed and its percentage of the total length (L) is calculated. This gives the bearing ratio at the depth c. This is shown in figure 3.32.
3.1.10.2. Bearing Ratio Curve:

Bearing ratio curve or Abbott-Firestone curve is similar to the Accumulative Distribution Curve, used in statistics. The bearing ratios are calculated at various depths. This data is sorted in descending order and plotted from 0% to 100%, as shown in figure 3.33.
3.1.10.3. Advantages of bearing ratio curve:

The following are the advantages that can be derived from bearing ratio curves.

1. The bearing capacity of the component can be assessed by the material ratio and by the shape of the bearing ratio curve.
2. These curves graphically represent the distribution of the material within the profile heights.
3. The quality of machining process can be assessed from the shape of the curves.
4. These curves can be used to anticipate the surface wear and functional properties of the parts.

3.1.10.4. Evaluation of the bearing ratio curve:

There is a significant amount of information encapsulated in the shape of the bearing ratio curve for a surface. This information is summarized in few parameters, called $R_k$ parameters. These parameters were introduced in the year 1985 (DIN-4776) and are currently standardized in ISO 13565-2. To discuss more on these parameters, the bearing ratio curve is distinguished into three parts.
1. Projection part (Peaks, $R_{pk}$), contain a summary of the highest projections of the surface profile, which will disappear during the functioning of the part surface.

2. Central exploitation part (Core/Kernel, $R_k$), is the most important part, which determines the life of the parts.

3. Low depression part (Valleys, $R_{vk}$), which is not available for the functioning of the parts and serves for holding the lubricant during the functioning of the part.

The following procedure should be followed to arrive at the $R_k$ parameters.

**Step 1: Establish the Kernel ($R_k$)**

The first step is to slide a 40% ‘window’ across the bearing curve, looking for minimum secant slope. As the window slides across the curve, it intersects two points on the curve. The goal is to find the position where the slope between the two points is minimized. Figure 3.34 explains this procedure.

Once the window with minimum 40% secant slope is found, name the points where the window intersects the curve as A and B. Now, draw a straight line through these two points (A and B) and find the intercepts with 0% and 100%, and mark them as C and D. The vertical distance between the points C and D is the parameter $R_k$. This region between the points C and D represent the Kernel.
Figure 3.34: Rk Construction – Establish the Kernel

Figure 3.35: Rk Construction – Determine the parameters
Step 2: Determine the ‘Peak’ and ‘Valley’ parameters ($R_{pk}$ and $R_{vk}$).

Draw a horizontal line across, from point C to the bearing area curve, and name it E. Find the area below the bearing area curve and above the line CE, which is shown, shaded in the figure 3.35. Now mark a point G, such that the area of the triangle CEG will be equal to the area between the bearing curve and the line CE. Now the value of the parameter $R_{pk}$ will be the height of the triangle CEG, i.e. length of the line CG.

Now draw a line through C, and name its intersection with the curve as F. Compute the area of the space between the line CF and the bearing area curve, shown shaded in the lower part of the figure 3.35. Now mark a point H, such that the area of the triangle DFH will be equal to the area between the line CF and the curve. Now the value of the parameter $R_{vk}$ will be equal to the height of the triangle DFH, which will be equal to the length of the line DH.

Draw two vertical lines through E and F and mark their intersection with the datum line as I and J. Now the distances from the origin (O) to the point I will be $MR_1$ and J will be $MR_2$.

3.1.10.5. Significance of $R_k$ parameters:

$R_k$ correlates with the depth of the working part of the surface. After the initial running-in period, i.e. after the peaks represented by $R_{pk}$ are worn out, this part of the surface (represented by $R_k$) carries the load and contacts the mating surface. Some times this part of the
surface is called the ‘core roughness’ or the ‘Kernel’, hence the subscript k.

$R_{pk}$ is an estimate of the small peaks above the main plateau of the surface. These peaks will typically be worn out during the run-in period. Generally it would be desired to have a fairly small $R_{pk}$ value.

$R_{vk}$ is an estimate of the depth of the valleys, which retain the lubricant film in the functional parts. Generally it would be desirable to have a moderate value for the $R_{vk}$ parameter.

$MR_1$ will be the fraction of the surface which consists of small peaks above the main plateau.

$MR_2$ is the fraction of the surface which will carry load during the practical life time of the component. 100% – $MR_2$ is the fraction of the surface that consists of deep valleys that will retain the lubricant during working conditions.

Thus by calculating all the above mentioned parameters, the bearing performance of the component can be established.

3.2 Optimization:

When designing a process, the values of the parameters have to be chosen such that the process results in maximum output, with minimal effort and cost. There are basically two ways by which this can be achieved, which are discussed below.

**Trial and error approach:** In this procedure a series of experiments have to be performed, with all the possible combinations of the process parameters, until the desired output is attained. This process is generally referred to as the ‘Full factorial design’. This
process is a time and resource consuming one. The results obtained after experimenting with each combination should be measured and analyzed carefully, which requires skilled personnel. When the number of parameters to optimize is more these results grow abnormally and becomes almost impossible to analyze. So this procedure is less desired and is only suited for processes with less number of process parameters. This process was

**Design of experiments:** In this method, the optimum values of the process parameters can be determined by conducting less number of experiments, compared to the full factorial design methodology. This process is generally referred to as ‘Fraction factorial design’, because only a fraction of all the possible combinations have to be tested experimentally. Since this technique limits the number of experimental trails, the time and resources consumed will be reduced drastically, when compared to the full factorial design. So this approach was followed in the present work to realize the optimum values of the burnishing process. The detailed discussion and procedure for optimization using this technique is explained in the following sections

**3.2.1 Design of experiments:**

Design of experiments (DOE) is procedure which can be followed to plan the experiments, such that the expected output can be obtained in minimum number if trails, there by reducing the time and resources required. This approach generally tries to determine a subset of all the combinations of the process parameters which affect the
process outcome, in such a way that the sub-set can represent the entire experimental work.

3.2.1.1. Steps involved in DOE:

The procedure for DOE has to be carried out in 6 steps.

1. Define Process Objective: In this step the desired outcome of the process has to be finalized. This includes the determination of the values of the response variables, like surface roughness, corrosion resistance etc, that are expected out of the procedure.

2. Determine the process parameters: The parameters that affect the final outcome of the process are determined. The operational range of each parameter is noted down.

3. Create orthogonal arrays: Based on the number of parameters considered and the levels of each parameter, a suitable orthogonal array has to be chosen from the available standard ones.

4. Conduct Experiments: Experiments are conducted for the combination of the parameters indicated by the orthogonal array. The values of the response variables (process outcome) are noted after each run. Each combination can be repeated multiple times to estimate the noise factor.

5. Data Analysis: The data obtained from the experiments can be used along with the procedure proposed by Fisher, to determine the optimum combination of the process parameters.
6. Verification (Optional): To verify the results obtained from this procedure, one or more sample runs of experiments can be performed at optimum values determined by this procedure.

3.2.1.2. Taguchi’s technique for design of experiments:

R. A. Fisher of England proposed this approach to organize the parameters which have an effect on the process. Instead of running the process at all the possible combinations of the parameters, this approach specifies certain subset of the combinations which constitute the backbone of the process. Based on the results of this sub-set of experiments, the best possible combination of the process parameters can be determined. A series of special mathematical arrays proposed by Taguchi, called orthogonal arrays are the key tools for this approach.

Optimization:

To illustrate how this approach can be applied a simple example of optimizing a process is explained here. Three parameters are considered for optimization of this process, to yield the best result out of the process.

The nomenclature used for this example is:

A, B, C → Three parameters
R → Response Variable

The three process parameters A, B and C have two possible values, i.e. they operate at two levels. Since there are three parameters operating at 2 levels, L4 orthogonal array (table 3.2) was chosen for this example. In the L4 orthogonal array, each column represents a
process parameter and the values 1 and -1 represent the two levels of
the parameters.

Table 3.2: Taguchi’s L4 orthogonal array

<table>
<thead>
<tr>
<th>Parameter A</th>
<th>Parameter B</th>
<th>Parameter C</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1 (A1)</td>
<td>-1 (B1)</td>
<td>-1 (C1)</td>
</tr>
<tr>
<td>-1 (A1)</td>
<td>1 (B2)</td>
<td>1 (C2)</td>
</tr>
<tr>
<td>1 (A2)</td>
<td>-1 (B1)</td>
<td>1 (C2)</td>
</tr>
<tr>
<td>1 (A2)</td>
<td>1 (B2)</td>
<td>-1 (C1)</td>
</tr>
</tbody>
</table>

The above orthogonal array specifies the subset of all the combinations of the process parameters, which form the backbone of the experimental work. Each row of the orthogonal array represents one experimental trail. So, 4 trails of the experiments have to be done. This is called fractional factorial method, because only a fraction of all the possible combinations are tested, experimentally. If the same process had to be optimized by trial and error method a total of 8 trails had to be performed. But this number has come down to 4, by the usage of Taguchi’s technique of design of experiments. This reduction in number of trails, by DOE, will be huge if the number of factors and their levels are more.

Each trail of the experiment is done twice and the value of the response variable R is noted down. The values of the experiments are noted down and presented in the table 3.3
From the value of the response variable (R), an equation that expresses the response variable in terms of the parameters can be proposed [123, 124].

\[ \text{Response Variable } (R) = C_0 + C_1(A) + C_2(B) + C_3(C) \] \[ \rightarrow \text{eq. 3.2} \]

Where A, B and C are the values of the three parameters. It should be noted here that the values of the parameters to be substituted in the equation 3.2 are -1 & 1 and not the actual values, to get the response variable.

To determine the values of the four co-efficient, the following procedure should be followed. Each co-efficient is generated using the column to which the associated factor is assigned and all four of the average response variable values.

Since \( C_0 \) is the co-efficient corresponding to the average column, its value can be calculated as below:

\[ C_0 = \frac{(1 \times R1) + (1 \times R2) + (1 \times R3) + (1 \times R4)}{4} \]

Similarly \( C_1, C_2 \) and \( C_3 \) can be calculated as below:

\[ C_1 = \frac{(-1 \times R1) + (-1 \times R2) + (1 \times R3) + (1 \times R4)}{4} \]
\[ C_2 = \frac{((-1 \times R1) + (1 \times R2) + (-1 \times R3) + (1 \times R4))}{4} \]
\[ C_3 = \frac{((-1 \times R1) + (1 \times R2) + (1 \times R3) + (-1 \times R4))}{4} \]

From these equations the actual values of the 4 co-efficients can be calculated. Let these values be \( V_0, V_1, V_2 \) and \( V_3 \)

So the final equation for the response variable becomes

\[ \text{Response Variable (R)} = V_0 + V_1 \times A + V_2 \times B + V_3 \times C \quad \rightarrow \text{eq. 3.3} \]

Using the equation 3.3, the value of the response variable for all the possible 8 combinations can be calculated. From these calculated values of the response variable, the combination of the parameters which gave the least/highest value of the response variable will be the optimum combination of the parameters.

**Relative Factor Strength:**

Apart from determining the optimum values of the process parameters considered, Taguchi’s technique also determines the relative factor strength of the parameters. From these values, the parameter which has the highest influence on the response variable can be determined. The absolute value of the factor coefficients, gives the relative factor strength of the corresponding parameter. The parameter which has the highest value of its corresponding co-efficient is the one that has the maximum effect on the response variable. The co-efficient \( C_0 \) should not be considered, because it is not associated with any process parameter.

**Analysis Of Variance (ANOVA):**

When an experiment is repeated at the same parameter values, the results obtained in the form of response variables may not be the
same. This is because of the effect of the parameters that were not considered. These parameters are called noise factors. Some of such parameters are mechanical vibrations, humidity in atmosphere, operator’s skill etc. These untested and hidden parameters combine together and constitute the error in the experiment. An analysis of this noise factor has to be made in order to produce more reliable results. Analysis of variance (ANOVA) is one such approach, which can be used to estimate the effect of the noise factor.

From table 3.3 it can be noted that the values of the response variables on run 1 and run 2 were not the same. So there is an effect of the noise factor on the response variable. The procedure to estimate the noise factor is presented below.

The values of the response variables at each run, for the same set of parameters values are used to determine the noise estimate, using the equation given below.

\[
\text{Noise Estimate} = (\text{Run1} - \text{Run2})^2 / 2 \rightarrow \text{eq. 3.4}
\]

This noise estimate is calculated for all the 4 combinations of the parameters, from which the ‘Average noise factor’ is calculated.

An estimate of the effect of each parameter on the response variables is termed as signal and its magnitude is proportional to its corresponding signal co-efficient \( C_0, C_1, C_2 \) or \( C_3 \). The signal of the factor is calculated as follow:

\[
\text{Signal strength of factor} = (\text{co-eff})^2 \times (\text{total no. of data points}) \rightarrow \text{eq. 3.5}
\]

For any operation the number of degrees of freedom will be equal to the number of data points. In case of replicated experiments,
half of the degrees of freedom are assigned to the noise factor and remaining degrees of freedom are assigned to other factors. So in this case the number of degrees of freedom is equal to 8, out of which 4 are assigned to noise factor and the remaining 4 are assigned to the three process parameters and the average.

Now the signal to noise (S/N) ratio can be calculated for each factor, where the signal is the value calculated from equation 3.5 and the noise is the average noise factor. The results can be tabulated as in table 3.4.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Signal</th>
<th>DF</th>
<th>S/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>( S_{avg} )</td>
<td>1</td>
<td>( S_{avg} / N )</td>
</tr>
<tr>
<td>A</td>
<td>( S_a )</td>
<td>1</td>
<td>( S_a / N )</td>
</tr>
<tr>
<td>B</td>
<td>( S_b )</td>
<td>1</td>
<td>( S_b / N )</td>
</tr>
<tr>
<td>C</td>
<td>( S_c )</td>
<td>1</td>
<td>( S_c / N )</td>
</tr>
</tbody>
</table>

From the values of the S/N ratio, an estimate can be made regarding the effect of noise factor on the significance of the parameter. ‘Fisher tables’ or ‘F tables’, designed by Sir Ronald Fisher, can be used to determine the significance level of the parameters. Fisher proposed many tables, each of which is associated to the number of degrees of freedom of the numerator. Since the number of degrees of freedom of the process parameters is 1 in the current context, the corresponding F-table is shown in table 3.5.
Table 3.5: F Table for one degree of freedom for signal

<table>
<thead>
<tr>
<th>Denominator DF</th>
<th>Trip value at significance level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95%</td>
</tr>
<tr>
<td>1</td>
<td>161.4</td>
</tr>
<tr>
<td>2</td>
<td>18.51</td>
</tr>
<tr>
<td>3</td>
<td>10.13</td>
</tr>
<tr>
<td>4</td>
<td>7.71</td>
</tr>
<tr>
<td>5</td>
<td>6.61</td>
</tr>
</tbody>
</table>

The denominator of the S/N factor (i.e. the noise factor) has 4 degrees of freedom. So the 4th row of the F table is relevant for the current case. If the calculated S/N value in table 3.4 exceeds the corresponding trip value shown in table 3.5, then the signal is significant by the corresponding percentage; i.e. if a parameter is significant by 99%, then the effect of noise factor is 1% on the performance of that parameter on the response variable.

ANOVA is carried out based on some assumptions, which are listed below:

1. The expected values of the errors is zero
2. The variances of all the errors is equal to zero
3. The errors are independent of each other
4. The errors are normally distributed.

3.3 Finite Element Analysis:

Finite element analysis (FEA) is technique for predicting the response of structure and components to environmental factors such as forces, heat vibrations etc. FEA is based on the idea of building a complicated object with simple blocks, or dividing a complicated object
into small and manageable pieces. The application of this simple idea can be found in every day life and in engineering as well. A building is constructed by assembling the blocks, steel and wooden pieces together, which is a very simple example of the above statement. Another example is the calculation of the area of a circle. Decompose a circle into triangles, as shown in figure 3.36.

![Figure 3.36: Circle decomposed into triangular elements](image)

The area the circle, which is decomposed in triangles, will be a summation of the areas of all the triangles, when the angle $\theta_i$ tends to very small value.

Area of one triangle: $S_i = \frac{1}{2} R^2 \sin \theta_i$

Area of the circle: $S_N = \text{Sum of all triangles} = \sum_{i=1}^{N} S_i$

$= \frac{1}{2} R^2 N \sin \left(\frac{2\pi}{N}\right)$

$= \pi R^2 \quad \text{as } N \to \infty$

So any complicated or smooth object can be represented as a summation or combination of small elements. The behavior of each of these simple elements can be determined easily and can be aggregated to determine the behavior of the actual object. This concept is the foundation of finite element analysis.
3.3.1 Introduction to finite element analysis:

Finite element analysis was initially developed by R. Courant, in 1943, to obtain solutions for vibrating systems. By early 70’s, FEA could be processed by expensive mainframe computers, which could be owned by only aeronautics, automotive, nuclear and defense industries. Later, with rapid decline in computer costs and further development in the FEA capabilities, it became part of most of the industries.

In FEA, a model of the structure or component is designed. This model is then subdivided into a mesh of finite sized elements of simple shape. Triangular and quadrilateral shapes are used for 2-D analysis, tetrahedrons and hexahedrals are used for 3-D analysis. The behavior of these elements under the working conditions is modeled by forming quadratic equations. These equations handle the displacement, stress, strain and many other characteristics. After applying the appropriate symmetric and boundary conditions, the solution for these equations can be derived.

FEA can be used to improve the cycle time of a product, by using virtual testing instead of physical prototypes for design validations. This is depicted in figure 3.37.
3.3.2 Procedure for finite element analysis:

The basic steps involved in finite element analysis are listed below:

1. Preprocessing
2. Analysis
3. Post-processing

3.3.2.1. Preprocessing: In this step the user builds a model of the part or structure to be analyzed. This model is programmed to contain the structural properties which define how the actual component reacts to certain loading conditions. This model is then subdivided into a number of discrete sub-regions called elements. These elements are connected at discrete points called nodes. Some of these nodes will have fixed displacement; some will be restricted from moving; some will be carrying prescribed loads. Most of these tasks can be done by using CAD software, which can be then loaded onto the FEA platform.
3.3.2.2. Analysis: The data prepared in the preprocessor is fed as input for analysis. In this step, numerous linear and non-linear algebraic equations (equation 3.6) are built and solved.

\[ K_{ij} u_j = f_i \rightarrow eq. 3.6 \]

In equation 3.6, \( u \) is the response or behavior (like displacement, expansion etc) and \( f \) is the applied action (like applied force, temperature etc) at the nodal points. \( K \) is the property of the material tested. The formation of the \( K \) matrix is dependent on the type of problem.

There are various types of analysis that can be performed, which are listed below:

- Structural
- Vibrational
- Fatigue
- Thermal
- Fluid flow
- Electromagnetic
- Acoustic

Table 3.6 lists some of the analysis types, along with their response, applied action and properties.
Table 3.6: Action and response variables of analysis types

<table>
<thead>
<tr>
<th>Analysis Type</th>
<th>Property (K)</th>
<th>Response (u)</th>
<th>Action (f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural (Elastic)</td>
<td>Stiffness</td>
<td>Displacement</td>
<td>Force</td>
</tr>
<tr>
<td>Thermal</td>
<td>Conductivity</td>
<td>Temperature</td>
<td>Heat source</td>
</tr>
<tr>
<td>Fluid</td>
<td>Viscosity</td>
<td>Velocity</td>
<td>Body force</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>Dielectric permittivity</td>
<td>Electric potential</td>
<td>Charge</td>
</tr>
</tbody>
</table>

3.3.2.3. **Post-processor:** The results of the analysis step are presented in this step, like displacement stress, strain, temperature, frequency etc. A typical post-processor displays colored contours representing stress levels on the model. Graphical representation of the model, over time, temperature, load etc can be obtained in this phase. If the results from the post processor report the failure of the component, the modal has to be redesigned or the loads should be adjusted, such that the design is safe and sound at the prescribed loading conditions. The procedure of FEA is depicted in figure 3.38.

![Figure 3.38: Procedure for finite element analysis](image-url)
3.3.3 Advantages and disadvantages:

The advantages and disadvantages of finite element analysis are discussed here.

**Advantages:**

1. Complex components and structures can be easily handled. This is the key advantage for the success of this analysis. A rich family of elements makes it more convenient.
2. A very wide variety of problems can be handled, which are listed in the above sections.
3. Complex restraints can be handled, which facilitates in solving indeterminate structures.
4. Complex loading and constraints can be applied
5. Components or structures involving multiple materials can be analyzed simultaneously.

**Disadvantages:**

1. Only approximate solutions can be obtained.
2. Mistakes made by users, which are very common in modeling and application of constraints, may be fatal. These mistakes are generally committed in selection of wrong elements type, application of force on wrong nodes, usage of inconsistent units etc.
3. A powerful computer and reliable software is needed for accurate solutions.
4. Input and output data is enormous and tedious to prepare and intercept.
3.3.4 Application of FEA to Burnishing:

Finite element analysis has many advantages, if used accurately. To leverage these merits, burnishing process was modeled and analyzed using FEA. The main reasons for choosing FEA over other techniques are:

- It facilitates exact modeling of the process.
- It is very user friendly in modifying the model and varying the forces and constraints.
- The output obtained includes vast number of results, like deformation, stress etc.

The analysis of burnishing process can be done either manually or by using commercially available software. To eliminate manual errors and to obtain results at a quick pace, commercially available FEA software ANSYS 10.0 was used for this work. This software was used because of its versatility, user friendliness and author's hands-on experience on the software.

The steps involved in modeling and analysis of burnishing process using ANSYS 10.0 are explained below.

1. Selection of preferences: The preferences for filtering the GUI are set in this step. The individual disciplines to show the GUI was selected as ‘Structural’. ‘h-method’ was selected as the discipline option.

2. Preprocessor: The element type was chosen as ‘Tetrahedral 10 node 92’, because it has the quadratic displacement behavior and is well suited to model irregular meshes. This element has plasticity and
creep capabilities. This element is defined by ten nodes having three
degrees of freedom at each node. Figure 3.39 shows the 10 node
tetrahedral SOLID92 finite element.

![Figure 3.39: SOLID92 10 node tetrahedral finite element](image)

Linear isotropic properties of the material (Young’s modulus and
Poisson’s ratio) are specified, the values of which are presented in
table 3.7.

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Young’s Modulus</strong></td>
<td><strong>Poisson ratio</strong></td>
<td></td>
</tr>
<tr>
<td>Mild steel</td>
<td>210</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>70</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Brass</td>
<td>110</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>118</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

The component is then modeled as per dimensions, 40 mm
diameter and 30 mm length. Only one quarter of the component is
modeled to as to view the internal details of the component after FEA.
The model is then meshed using the mesh tool, by specifying the
element type defined earlier, figure 3.40 shows the component after meshing.

![Figure 3.40: FEA model (after meshing)](image)

Symmetry boundary conditions were applied on the surfaces on the three vertical flat edges, as shown in figure 3.41. Displacement constraints are applied on the horizontal flat surface, because the work piece’s movement is arrested on that surface. This is shown in figure 3.42.

![Figure 3.41: Symmetry boundary condition - FEA](image)
The nodes that carry the burnishing force, applied by the tool, are identified, on the circumference of the model. The force is then applied along the Y axis, as structural load on the identified nodes.

3. Solution: The type of analysis is set to ‘Static’. The finite element model is then solved. If the solution converges, which mean the applied loads does not cause failure of the component; a message of successful completion of the solution is presented to the user.

4. General postprocessor: The results of the analysis can be viewed and analyzed. The results which are of high importance for this study are stress in the direction of application of force (compressive stress).