3. PROCESS MODELING

3.1 Introduction:
In the preceding chapter literature review on cryogenic treatment effect on various materials, tool wear and tool life models proposed and process parameters optimization using Taguchi’s approach was discussed. Also from the observations of the literature review, the objectives of the proposed work were spelt out.

In order to meet out the objectives in this chapter the tool life, different factors affecting on tool life, an empirical model proposed by F. W. Taylor for calculating tool life as a function of cutting speed used in turning operation, extended Taylor’s equation considering effects of feed and depth of cut alongwith cutting speed are discussed.

Tool wear is a function of process parameters used in turning operation. In the present work a mathematical model for evaluating tool wear of conventionally treated tools due to process parameters is proposed. Similarly a mathematical model for evaluating tool wear of cryogenically treated tools is also proposed. The two models proposed earlier are compared and can be used for evaluating improvement in wear resistance due to cryogenic treatment.

3.2. Tool Life:
Tool life can be defined as the usable time elapsed before the cutting tool has failed to produce acceptable work pieces [62]. Tool life is also defined as useful time elapsed between successive resharpening of the tool.

Tool life of a tool is affected by many factors such as

1. Tool material
2. Tool geometry
3. Work material
4. Cutting fluid
5. Process parameters (Cutting speed, feed and depth of cut)
6. Processes improving life of a tool

A brief discussion of the impact of these factors on tool life is given on next page.
3.2.1 Tool material:

Hardness, red hardness, impact toughness, and wear and abrasion resistance are the major requirements of cutting tool materials. High hardness gives the tool good wear resistance. This decreases toughness of the tool material. For thermal shock resistance, the tool material should have high thermal conductivity and specific heat, a low co-efficient of thermal expansion and high tensile strength.

The variations in the above tool material requirements with cutting temperature are of considerable importance to tool life. Taking hardness as a guide to wear resistance and hence tool life, the effect of cutting temperature on tool material hardness is of major concern. Carbon steels are very sensitive to temperature and they rapidly lose their hardness at low temperatures. Thus, they are used for slow cutting of soft non-ferrous materials, which give low cutting temperatures. The hardness of HSS is affected only slightly till about 600 °C, after which its hardness starts falling rapidly with temperature. Hence HSS can give good performance below 600 °C, even better than cast alloys. Cast alloys show better performance than HSS above 600 °C. Figure 3.1 shows the effect of temperature of cutting zone on hardness of different tool materials. Cemented carbides can retain their hardness at temperatures as high as 1200 °C and hence, can be used at much higher cutting speeds than HSS or cast alloys. However, because of their reduced toughness, they have a greater tendency to chip and fracture under heavy loads and interrupted cutting conditions. Sintered oxides or ceramics can be used at cutting speeds of two or three times than those employed with carbides. But these materials being very hard are extremely brittle and can only be used where shock and vibrations do not occur [2-4].

![Figure 3.1 Effect of Cutting Zone Temperature on Hardness of Tool Materials](image-url)
3.2.2 Tool geometry:
Tool geometry provided to a tool greatly affects its life. If the rake angle provided is larger, then the cutting angle will be smaller and the shear angle will be larger. This reduces the cutting force and power and hence the heat generated during cutting. It means reduced cutting temperature resulting in longer tool life. But increasing the rake angle reduces the mass of metal behind the cutting edge resulting in poor transfer of heat. This can tend to increase the cutting temperature. Also, the cutting edge becomes mechanically weak. There is an optimum value of rake angle, which gives maximum tool life. It has been observed that for small values of clearance angle, an increase in clearance angle results in significant reduced wear rate. But the cutting edge becomes weaker as the clearance angle is increased. The best compromise for clearance angle is approximately $8^\circ$ for HSS tools and $5^\circ$ for carbide tools most of the work materials [2-4].

3.2.3 Work material:
As the hardness of the work material increases, the power consumption and temperatures increase. Tool wear gets increased, resulting in shorter tool life. Impurities or hard constituents present in the work material increases tool wear. Micro-structure of the work material is very significant since there is a great variation in hardness of the micro-constituents of an alloy. Out of the various micro-constituents of C.I. and steel, free graphite and ferrite are the softest constituents and martensite is the hardest with spheroidite and pearlite coming in between. Scales and oxide layers on the work piece being quite abrasive, have an adverse effect on tool life. In such cases, the material should be cut below the oxide layer or below the work hardened zone. Pure metals tend to adhere to the tool surface and give high friction and high wear rates resulting in shorter tool life [2-4].

3.2.4 Cutting fluid:
Cutting fluid can be used as a coolant or a lubricant depending on machining process, tool material and work material. It is required to select an appropriate cutting fluid to be used in the machining process, which will help in improving the life of the tool [2].
3.2.5 Process parameters:
The process variables, cutting speed, feed and depth of cut play an important role in
determination of tool life of a tool, since they control the rate of metal removal and the
production rate.
The cutting speed has the greatest effect on tool life followed by feed and depth of cut,
respectively [2,4,68,69,71]. Effect of these parameters on tool life can be explained in terms
of tool-work piece interface temperature. It has been seen that the tool life is a direct
function of cutting temperature, irrespective of the cutting conditions. These process
parameters monitor the temperature of cutting zone, which regulates the wear of the tool.
This causes the changes in the life of the tool [4].

3.2.6 Processes improving life of a tool:
One of the processes which are used to improve life of a tool is cryogenic treatment. Efforts
are being made to understand effect of cryogenic treatment on tool material properties.
Cryogenic treatment was carried out for various steel materials as discussed in chapter 2 and
the effects of the treatment are found to be encouraging. In present study effect of cryogenic
treatment on T42 tool steel is being studied and results of the pilot experiment carried out
indicated improvement in wear resistance, ultimately resulting in improvement in tool life.
Hence, it can be said that tool wear is also dependent on cryogenic treatment parameters.

3.2.7 Model proposed:
As discussed in above section tool life, in turn tool wear depends on tool material, work
material, tool geometry, cutting fluid, process parameters and processes improving life of a
tool. If turning operation is carried out having same tool material, work material, tool
geometry and cutting fluid, the tool life can be said to be dependent upon process parameters
used. The tool life also will get affected if the tool material is provided with treatments such
as coating or cryogenic treatment etc. Mathematical models taking these aspects into account
are proposed in following sections starting from the basic empirical model proposed by F. W.
Taylor for calculating tool life of a tool for given cutting speed, tool and work combination.
3.3 Mathematical Modeling:

3.3.1 Taylor’s tool life equation:

Tool life criteria are
i) Total destruction of the tool
ii) A fixed size of the wear land on the tool

In case of wear of the tool, face (crater) wear or flank wear can be considered as parameter to find out tool life. Normally flank wear land is used as a measure of tool life in case of HSS tools. If the flank wear land $V_B$ is more than 0.6 mm then tool life is said to be over [61].

It has been found experimentally by F.W. Taylor that tool life is primarily a function cutting speed. He has established an empirical relationship between cutting speed and tool life. This relationship is given as [2-4]

$$V (TL) ^ n = C \quad (1)$$

where $V$ is cutting speed in m/min, $TL$ is tool life in min, $n$ is exponent of the curve between cutting speed and tool life and $C$ is constant, which is taken as cutting speed for one minute tool life. The curve between tool life and cutting speed is as shown in Figure 3.2(a). When plotted on log-log scale it is a straight line as shown in Figure 3.2 (b).

![Cutting speed Vs Tool life](image.png)

Figure 3.2 (a): Tool Life Versus Cutting Speed on Linear Scale
3.3.2 Extended Taylor’s equation:

In Taylor’s equation tool life is considered as affected only by cutting speed. Other process parameters are neglected. It is observed that the feed and depth of cut also affect on wear of the tool, i.e. on tool life. These factors also contribute to wear of the tool. Hence tool life can be said to be function of cutting speed, feed and depth of cut and can be mathematically expressed as

\[ TL = f(V, f, d) \]

An empirical relationship between these factors is established and is known as extended Taylor’s equation [3,4]

\[ V (TL)^n f^x d^y = C_1 \]  \hspace{1cm} (2)

Where V is cutting speed in m/min, TL is tool life in min, f is feed in mm/rev, d is depth of cut in mm, n is exponent of the curve between cutting speed and tool life, x is exponent of the curve between feed and tool life, y is exponent of the curve between depth of cut and tool life and C_1 is constant dependent on work material.

Equation 2 can be also be written as

\[ TL = \frac{(C_1)^{1/n}}{V^{(1/n)} f^{(x/n)} d^{(y/n)}} \]
which can be further written as

$$ TL = a_0 \cdot V^{a_1} \cdot f^{a_2} \cdot d^{a_3} $$  \hspace{1cm} (3)

where $a_0 = (C_1)^{1/n}$, $a_1 = - (1/n)$, $a_2 = - (x/n)$ and $a_3 = - (y/n)$ are constants.

### 3.3.3 Mathematical model to evaluate wear of a non cryo tool:

There are various methods to determine tool life data. As suggested by Taylor, if wear land is considered to be constant, the wear-land curves as shown in Figure 2.6 can be extrapolated to determine tool life [1,4]. An equation can be written for tool life in terms of wear using these curves as [1]

$$ TL = \frac{w_1 - w'}{k_w} $$  \hspace{1cm} (4)

where $w_1$ is wear land failure criterion, $w'$ is the wear land intercept found experimentally and $k_w$ is wear land growth rate.

Tool wear $w$ and cutting time $t$ mathematically can be expressed [1] as

$$ w = w_0 + mt $$  \hspace{1cm} (5)

where $w_0$ is initial wear, $m$ is slope of wear time curve and $t$ is cutting time.

Since an increase in wear is dependent on the given cutting conditions [1], tool wear can be expressed as

$$ w = w_0 + a_0 \cdot V^{a_1} \cdot f^{a_2} \cdot d^{a_3} \cdot t^{a_4} $$  \hspace{1cm} (6)

where $w$ is tool wear, $w_0$ is initial wear, $V$ is cutting speed in m/min, $f$ is feed in mm/rev, $d$ is depth of cut in mm, $t$ is cutting time in min, $a_0, a_1, a_2, a_3$ and $a_4$ are constants.

If machining time is constant, then tool wear can be said to be function of process parameters $i. e.$ cutting speed, feed and depth of cut

\[ w = f (V, f, d) \]

A mathematical model for tool wear as a function of process parameters is proposed as

$$ w = a_0' \cdot V^{a_1'} \cdot f^{a_2'} \cdot d^{a_3'} $$  \hspace{1cm} (7)

where $w$ is tool wear, $V$ is cutting speed in m/min, $f$ is feed in mm/rev, $d$ is depth of cut in mm, $a_0', a_1', a_2'$ and $a_3'$ are constants, which can found out experimentally.
By using equation 7 effects of process parameters on wear of tool can be evaluated for a tool work combinations for a given setup.

In terms of logarithmic form equation 7 can be written as

$$\log w = \log a_0' + a_1' \log V + a_2' \log f + a_3' \log d$$  \hspace{1cm} (8)

The wear of the conventionally treated tools shall be treated as of non cryo tool, which is denoted as $w_{\text{noncryo}}$. Hence equation 7 can be reproduced as

$$w_{\text{noncryo}} = a_0' \cdot V^{a_1'} \cdot f^{a_2'} \cdot d^{a_3'} \hspace{1cm} (9)$$

By using equation 9 effects of process parameters on wear of non cryo tool can be evaluated for a tool work combination for a given setup.

This is the mathematical model proposed for evaluating tool wear of a non cryo tool for constant machining time due to the selected process parameters.

In terms of logarithmic form equation 9 can be written as

$$\log w_{\text{noncryo}} = \log a_0' + a_1' \log V + a_2' \log f + a_3' \log d$$  \hspace{1cm} (10)

3.3.4 Mathematical model to evaluate wear of a cryo treated tool:

Also from the literature review discussed in chapter 2 and results of pilot experimentations discussed in section 4.3 of chapter 4, it is found that if cryogenic treatment is provided to a tool steel the wear decreases and, hence it can be said that tool wear is a function of cryogenic temperatures assuming constant soaking time for the treatment alongwith other process parameters for constant machining time. It can be mathematically expressed as

$$w_{\text{cryo}} = f (V, f, d, T_c)$$

where $w_{\text{cryo}}$ is wear of a cryo treated tool.

A mathematical model for tool wear as a function cryogenic temperature and process parameters is proposed as

$$w_{\text{cryo}} = b_0' \cdot V^{b_1'} \cdot f^{b_2'} \cdot d^{b_3'} \cdot T_c^{b_4'} \hspace{1cm} (11)$$

where $w_{\text{cryo}}$ is wear of a cryo treated tool, $V$ is cutting speed in m/min, $f$ is feed in mm/rev, $d$ is depth of cut in mm, $T_c$ is cryogenic treatment temperature in °C and $b_0'$, $b_1'$, $b_2'$, $b_3'$ and $b_4'$ are constants, which can found out experimentally. By using equation 11 effects of cryogenic
treatment temperature along with process parameters on wear of a cryo treated tool can be evaluated for a tool work combinations for a given setup.

**This is the mathematical model proposed for evaluating tool wear of a cryo tool treated for constant machining time due to the selected cryo temperature and process parameters.**

In terms of logarithmic form above equation can be written as

\[
\text{i.e. } \log w_{\text{cryo}} = \log b_0' + b1' \log V + b2' \log f + b3' \log d + b4' \log Tc \quad (12)
\]

### 3.3.5 Mathematical model to evaluate wear resistance improvement due to cryogenic treatment:

Equation 9 can be used to evaluate wear of the conventionally treated tool due to process parameters such as cutting speed \(V\) in m/min, feed \(f\) in mm/rev and depth of cut \(d\) in mm. Equation 11 can be used for evaluating wear of the tool due to cryogenic treatment temperature \(T_c\) in °C and process parameters such as cutting speed \(V\) in m/min, feed \(f\) in mm/rev, and depth of cut \(d\) in mm. If the process parameters used in turning operations using a conventionally treated and a cryo treated tool are same, then the difference between these two equations can be used to find out reduction in wear i.e. wear resistance improvement due to cryogenic treatment temperature. Wear resistance improvement due to cryogenic treatment temperature can be mathematically given as

\[
w_{\text{imp}} = w_{\text{noncryo}} - w_{\text{cryo}} \quad (13)
\]

\[
w_{\text{imp}} = a_0' \cdot V^{a1'} \cdot f^{a2'} \cdot d^{a3'} - b_0' \cdot V^{b1'} \cdot f^{b2'} \cdot d^{b3'} \cdot T_c^{b4'} \quad (14)
\]

Equation 14 can be used to find out wear resistance improvement of a cryo treated tool by cryogenic treatment temperature over a conventionally treated tool.

Equation 9 is a proposed mathematical model for evaluating tool wear of a conventionally treated tool due to process parameters. Further a mathematical model for evaluating tool wear of a cryo treated tool due to cryogenic treatment temperature and process parameters is given by equation 11. **As per the objectives of the proposed research work a mathematical model for evaluating wear resistance improvement of cryo treated tools is given by equation 14.**
As flank wear land is used as a measure of tool life in case of HSS tools, hence this percentage in wear resistance improvement of the tool due to cryogenic treatment can be considered as improvement in tool life of the tool.

Thus mathematical models for tool wear as a function of process parameters and cryogenic temperature alongwith process parameters are proposed in this chapter. In order to find out the constants of the models experiments are required to be performed.

The tool material selection, procurement, pilot experimentations, work material selection, experimental setup, selection of process parameters, selection of process optimization technique, carrying out main experimentations, measurement of tool wear, validation of experiments etc. are discussed in forthcoming chapter. Micro structural observations of the microstructures taken by SEM and hardness measurement of the conventionally treated and cryo treated samples are also presented in the next chapter, i.e. Chapter 4 on Experimentation.