CHAPTER 1

INTRODUCTION
1.1 Introduction:

Drilling is one of the most important and complex manufacturing processes widely used in the manufacturing and other industries. The drilling accounts for more than 40\% of all the machining processes in the automotive and manufacturing sectors. The traditional approach of drilling comprises of generating the hole on the workpiece with the multipoint tool made of hard material. This traditional approach is suitable for making the hole on the solid material which can withstand the cutting forces generated by the cutting tool. The process is economical, versatile though suffered with some limitations in regard with the material thickness, chip formation, generation of heat and large cutting forces, requirement of coolants and large power etc. The traditional drilling is not recommended for the sheet material since the smaller thickness of the sheet material cannot withstand the cutting forces and also there is possibility of tool breakage. Therefore the sheet material drilling is limited to the punching process which can make the hole in the sheet material by pressing the pointed hard tool. This process is also economical and easy to carry out but suffered with many disadvantages such as burr formation, machining or cutting requirement, suitable for small thickness etc.

With the advent of the sheet metal processing technology many sectors such as automotive, structural, fabrication, furniture have become prosperous due to the on demand availability of various grades of sheet materials varying in sizes and thickness. The sheet materials in the form of square tubes, round tubes, I-sections, angles, channels are now days popular for fabrication and the structural work due to high strength and less weight. The processing of sheet material for different applications often require the formation of hole, joining with other parts, making of leak proof joint, etc. Therefore joining of the sheet metal and other forms of the sheet is the basic concern to the most of sheet material processing industries. The methods which are currently popular for joining of the sheet material or tubing or thin sections are J-nuts, weld-nuts, clench nuts, and other threaded inserts. Also the joining of the sheet material by welding is the traditional method and used for attaching the small piece of sheet material which is either drilled or stamped.
The current methods available for joining sheet materials and thin sections have many limitations and have to compromise with the cost and quality. Some of the drawbacks of these traditional techniques are complicated and more manufacturing steps, generation of scrap and wastages of material, requirements of special tools and machines, requirement of skilled labour, problem of waste disposal etc. Therefore the manufacturing industry particular sheet metal working industry is looking for the process which is free from these drawbacks and to carry out the process in most economic and efficient way.

1.1.1 Friction Drilling Process:

The process which uses the frictional energy to form the hole in the sheet material is known as the Friction drilling process. This process is also popular by names such as Thermal drilling, Flow drilling, Form drilling and Friction stir drilling. Conventionally the drilling is carried out in the solid material by rotating the hard multi point drill which removes the material in the form of chips. Opposing to that the friction drilling, instead of removing the material, displaces the material by plastic deformation and forms the hole with bush in sheet material. Therefore it can be seen that this method is non-traditional way of producing the holes in the thin walled workpiece. The holes thus formed on the workpiece has many applications like it can be threaded and used like the nut for joining purpose or it can act as the bearing surface etc.

In the friction drilling process the tool which is conical in nature and has the point, conical and cylindrical regions to indent, form and shape the hole. The tool is generally made of the hard materials like the Tungsten Carbide in Cobalt matrix (WC-Co). The friction drilling process can be carried out on any type of drilling machine or vertical and horizontal machining centers or milling centers which have the capability of controlling the spindle speed and feed and have the sufficient power (above 1.5 KW) and rotational speed (above 1500 rpm) to operate the spindle. In the friction drilling process the tool is operated at the high surface speed and relatively small and constant feed. The workpiece is to be rigidly fixed in the fixture for friction drilling process so that the bending of the drilled portion does not occur. When the process is started the friction drill approaches the work with high axial pressure and is rotating with high surface or tangential speed. Since the tool is fed with high pressure the point
of the tool comes into contact with work material and carries out initial indentation. The point has the conical geometry with smaller length less than 1 mm and wider angle near to 90° which helps to prevent early walking of the tool and indents the work.

The second section of the tool has again conical geometry but is longer (5 mm to 15 mm depending on the size and shape of the hole and thickness of the workpiece) and sharper (30°-40°) than the centre, contacts the indented workpiece. The wall of the indented part slides against the rotating conical part. This sliding under high contact stress generates the frictional heat which raises the material temperature to red hot state which makes the material soft and malleable enough to be formed and perforated. The frictional heat generated is well above the recrystallization temperature (700° C – 900° C for Mild Steel) and grain refinement and plastic deformation can be observed. Since the tool is feeding in the downward direction the most of the material flow plastically along the direction of feed and small amount of material flow opposite to the direction of feed. It is observed for the mild steel that 60-80 percent of extruded material flow along the direction of feed and 20-40 percent of extruded material flow opposite to the feed.

When the third part of the tool that is cylindrical in nature and has the sufficient length (5 mm -15 mm depending on the material thickness, size and shape of the hole) contacts the extruded material, it shapes the downward flown material into the proper cylindrical form and gives the required geometry and dimension to the hole. The frictional contacts and generation of heat are reduced during this phase of operation and material starts cooling rapidly. During this period of operation the downward extruded material takes the form of the bush. Also the recrystallization or grain refinement is observed in the contacting material near to the tool during this phase.

The friction drilling tools are provided with one more section adjacent to the cylindrical part is called as the shoulder. The sole purpose of the shoulder is to remove or shape the upward extruded material. Most of the friction drilled holes are used as the threaded nuts which are used as the leak proof joints. In these applications the upward extruded material is converted in the form of boss or collar so that it can be used as the washer and gives the sufficient rigidity and strength to the joint. The shoulder which is cylindrical and has the bigger diameter than the cylindrical part and
has the flat sides contacts the upward extruded material and shapes it in the form of the boss or collar. In some applications where the boss or collar is not required the shoulder is made in the form of milling cutter to cut and remove the upward extruded material.

The resulting collar and the bush in the friction drilled holes have the lengths well above the three times of the original material thickness. The diameter of the bush is accurately determined by the cylindrical part of the tool. Friction drilling is dry machining process and does not require coolant or oil for machining therefore it is eco-friendly and pollution free process. However for drilling hard materials like stainless steels and others small amount of heat resistant paste is to be applied on the tool before drilling so as material transfer from work to the tool can be prevented. The process does not produce any chips during the machining and it is safe and reliable process. The cycle time is short 10-20 seconds and the tool has long life more than 10,000 holes [1]. The friction drilled holes using the standard geometry friction drilling tool on the workpiece AISI 1015 is shown in the Figure 1.1.

![Figure 1.1: Friction drilled holes on AISI 1015](image)

The process does not disturb the material’s internal structure as a result the formed bush is remarkably strong and can be used for bearing sleeves or, when threaded in a separate process, can provide high torque threaded surfaces with very high pull out strength specifications. Flowdrill process can be used in any application where the material thickness does not provide support for a threaded surface or a sleeve bearing application. When welded or riveted nut or a special inserts are required thermal drilling can be used with improvement in quality and saving of time.
Flowdrill tools can be used on Standard Drilling Machines, conventional or CNC Systems with motor capacities between 1.5 to 3.5 KW and speed of 1500 rpm and above. The Thermal Drilling process produces a bushing formed from the parent material itself. This bushing increases the area available for tapping. So instead of cutting the wall, the material itself is used to form stronger connections.

The methods traditionally used for sheet material connections suffer with drawbacks like material wastage, more cycle time, addition of external elements and results into more weight, costs, and compromising quality. Friction drilling is the best solution to all these problems of joining sheet materials in simple, efficient and most economical way.

1.1.2 Friction Drilling Tool:

Friction drilling tools which are available commercially has the standard geometry and made of tungsten carbide (WC) in a Cobalt (Co) matrix. The friction drilling tool as shown in the Figure 1.2 has the five distinct regions in order to accomplish the friction drilling process effectively. The part which is the point of the tool and like the point of the twist drill is called as the centre or point. This region of the tool is provided with the blunt angle (α) which is of the order of 90°. This blunting of the point helps the tool to avoid early indentation of the workpiece. The second region of the tool which is adjacent to the point is provided with sharper angle. This regions which is conical in nature with the inclusive angle (β) of around 30° – 40° forms the basic component of the friction drilling tool and known as the conical region. When the mechanical indentation accomplished by the point of the tool the conical region comes directly in contact with the indented hole. The high speed tangential movement of the tool causes the frictional heating between the conical region and workpiece. Conical nature of this region facilitates the easy entry and expansion of the hole. The next region which is follows after the conical region toward the shank is cylindrical in shape. The basic objective of this part of the tool is to give the proper shape and size to the extruded material. Therefore the final size and shape of the friction drilled holes are determined by cylindrical region. Next to cylindrical region the shoulder is provided on the friction drilling tool. The shoulder comes into contact with the upward extruded material and either trims or levels the material. Many tools has the shoulder which after contacting with the upward
extruded material levels it and forms the boss which acts as the washer for threaded joints and other applications. The final part of the tool is shank which is designed to hold the tool with standard holders and has the dimension according to the size of the standard holders.

![Friction Drilling Tool Geometry](image)

**Figure 1.2: Friction Drilling Tool Geometry**

1.1.3 **Stages in Friction Drilling Process:**

The friction drilling process which generates the hole by plastic deformation of the material comprises of the distinct stages as shown in Figure 1.3. As the drilling cycle starts the center region of the tool comes into contact of the workpiece. The tool is rotated at high speed and fed axially at the constant feed. When center comes into contact with the workpiece the sufficient heat is not generated and the initial indentation occurs mechanically. Therefore tool experience the rapid increase of thrust force. When tool moves further the conical region comes into contact with the partially indented hole. This workpiece and tool contact along with the tangential speed and vertical feed produces the heat which is sufficient to deform the material plastically. The generation of heat reduces the thrust acting on the tool and workpiece. When the tool contacts the workpiece at the maximum diameter of the conical region the torque increases to its maximum value. At the later stage the
cylindrical region of the tool comes into contact with workpiece and produces the cylindrical bush. Finally the shoulder of the tool makes contact with the upwardly displaced material and converts it into the boss. The last stage is the retraction of tool from the workpiece which completes the friction drilling process.

![Diagram of stages in friction drilling process](image)

**Figure 1.3: Stages in the friction drilling process**

### 1.1.4 Applications:

The friction drilling process produces the hole by plastic deformation of the material. The material thus deformed plastically takes the shape of the bush at the bottom of the hole. Also the material which flows upward converted into the boss by the shoulder of the tool. The bush generated has the length 3 to 5 times the original material thickness. This added thickness of the bush is used as the bearing area or can be tapped to form the threaded hole. The sheet material with the threaded hole efficiently joined with other components with the standard screws or bolts. The process can be carried out on the standard drilling machine, NC or CNC systems with the power capacities above 1.5 KW. The process requires the rotational speed of the spindle above 1000 rpm for the effective use of the friction drilling process. Since the process has many advantages can be used economically for the sheet metal work
where riveting, special inserts and attachments are needed. The process guarantees the high performance assembly with improvement in quality standard and cost cutting. Currently the process finds many applications in structural, fabrication, automotive and furniture industries.

1.1.5 Advantages:

The friction drilling process provides many advantages over the traditional joining methods presently employed in the sheet metal processing industry. As discussed earlier the friction drilling produces the hole in the sheet material along with the bush the bottom of the hole and boss at the top of the hole. The bush length along the axis of the hole is generally 3-5 times which can be tapped or used as the bearing area. When the threaded friction drilling hole is used for the threaded connections there is no need of using the washer since boss acts as the washer provides sufficient rigidity to the assembly. Therefore the friction drilled holes which are tapped and used as the threaded connections satisfy the pull out strength and torque according to the known standards. The process can be carried out on the CNC vertical or horizontal centers and thus automated very easily. The production steps are simple and less therefore process can be completed within certain seconds. Thus the process is faster and saves lot of machining and labour cost. The friction drilling method can be used to process the materials including Mild and Stainless Steels, Copper, Brass, Aluminum, Titanium and most malleable materials upto 12 mm thickness. The friction drilling process which produces the hole by frictional heating and displacing the material plastically does not produce the chips and also does not require coolant. Therefore the process is clean, environment friendly and safe. The friction drilling process is carried with the tools made of tungsten carbide and has the longer tool life. Moreover the accuracy and consistency of the hole is good and predictable. The friction drilling process which is becoming more popular nowadays is best alternative to costly welding and riveting processes which require special machines, additional components and considerable investments. In the nut shell the friction drilling process is more economical, efficient and precise for the processing of the sheet material for the joining and other purposes.
1.1.6 Disadvantages:

With having many advantages over other processes the friction drilling process has certain limitations. The process is basically recommended for thin and hollow workpieces having thickness upto 12 mm. The material deformation is plastic in friction drilling process due to the generation of the frictional heat therefore the process creates the heat affected zone. The process is not suitable for hard and brittle material since the cracking of the bush known as the petal formation may occur. The workpiece should be properly cleaned and free from grease, plastic coating. Also some of the sheet materials which are hardened and galvanized are difficult to process by this method.

1.2 Modeling of Thrust force and Torque in friction drilling process:

The force model based on the contact area between tool and workpiece for the prediction of the thrust force and torque is developed by Scott F. Miller and et. al. [1]. In this study it is assumed the uniform pressure is acting on the workpiece. This pressure is estimated by the yield stress of the rigid plastic workpiece material. Also two coefficients of friction $\mu$ and $\mu_a$ acting in the tangential and axial directions are defined. In the tangential direction, the workpiece is sliding on the fast rotating tool surface at higher surface speed without lubricant compared with relatively slow movement along the axial direction. This results in relatively high coefficient of friction $\mu$ acting along the tangential direction.

Following four assumptions are made to simplify the force model.

- The tool is perfectly sharp at the tip and all corners. Five parameters that define the perfect tool are the length of the centre region $(h_n)$, length of the conical region $(h_c)$, length of the cylindrical region $(h_l)$, angle of centre $(\alpha)$ and angle of conical region $(\beta)$. These parameters are shown in the figure 1.4.
- The deformation of the workpiece is negligible.
- The coefficients of friction are independent of temperature and speed and do not change during the friction drilling process.
- No displaced work-material contributes to the force modeling, i.e., only the overlapping area between the tool and undeformed steel sheet is used in the force modeling.
Figure 1.4: Geometry of the Friction Drilling Tool

For the Tapered conical and center region [Figure 1.5 (a)] the thrust force and torque is given as:

\[ F = \pi P \tan \left( \frac{\theta}{2} \right) \left( h_3^2 - h_1^2 \right) + \mu_a \pi P \tan \left( \frac{\theta}{2} \right) \left( h_3^2 - h_1^2 \right) \]  
\[ T = \mu P \tan \left( \frac{\theta}{2} \right) 2\pi \frac{1}{\cos \left( \frac{\theta}{2} \right)} \left( h_3^2 - h_1^2 \right) \frac{h_3^3 - h_1^3}{3} \]  

For the cylindrical area [Figure 1.5 (b)] the thrust force and torque is given as:

\[ F = \mu_a P 2\pi R h_3 \]  
\[ T = 2\pi \mu P R^2 h_3 \]  

Where;

- \( h_n \) = Length of the centre region,
- \( h_c \) = Length of the conical region ,
- \( h_l \) = Length of the cylindrical region,
- \( h^* \) = Length of conical region from vertex of cone.
- \( \alpha \) = Half angle of centre
- \( \beta \) = Half angle of conical region
- \( h_1 \) and \( h_2 \) are heights shown in the figure 1.5 (a)
- \( h_3 \) height of Cylindrical Region;
R Radius of the cylindrical Region

θ is the angle either α or β depending on center or conical region.

P Uniform Pressure acting on the tool

The theoretical computations of the thrust force and torque for the friction drilling process in the ductile material can be computed using the equations (1.1), (1.2), (1.3), (1.4). This model explains the variations of thrust force and torque in the friction drilling process.

**Figure 1.5**: Two basic areas for contact between the tool and workpiece in friction drilling force modeling [1]

1.3 **Heat Generation and Heat Transfer in Friction Drilling Processes:**

In metal forming processes, both plastic deformation and friction contribute to heat generation. Approximately 90 to 95% of the mechanical energy involved in the process is transformed into heat [13]. In some continuous forming operations such as drawing and extrusion, performed at high speeds, temperature increases of several hundred degrees may be involved [14]. Heat generation is also significant in forgings produced in high-speed equipment such as mechanical press, screw press, and
hammer. A part of generated heat remains in the deformed material, another part flows into the undeformed/less-deformed portion of the material where temperature is lower, while still an additional part may flow into the tooling [11].

The temperatures developed during the Friction Drilling influence Plastic Flow, Drilling Time, tool life, as well as microstructure and properties of the Drilled Hole. With the finite element based process modeling, the heat generation during deformation and heat transfer before, during, and after deformation can all be calculated in a computer. To ensure accurate heat transfer calculation, correct workpiece and tool interface heat transfer coefficient must be known. Using accurate process modeling, the influence of tool speed, contact time, and heat transfer in friction Drilling can be evaluated. In Friction Drilling, the magnitudes and distribution of temperatures depend mainly on:

- The initial workpiece and die temperatures.
- Heat generation due to plastic deformation.
- Friction at the workpiece/tool interface.
- Heat transfer between the workpiece and tool and between the workpiece and the environment (air or lubricant and coolant, etc.).

In Friction Drilling, the average instantaneous temperature in the deforming workpiece, $\theta_A$, can be estimated by:

$$\theta_A = \theta_W + \theta_D + \theta_F - \theta_T - \theta_R - \theta_C$$  \hspace{1cm} (1.5)

Where,

- $\theta_W$ is the initial workpiece temperature,
- $\theta_D$ is the temperature increase due to plastic deformation,
- $\theta_F$ is the temperature increase due to interface friction,
- $\theta_T$ is the temperature drop due to heat transfer into the tool and workpiece,
- $\theta_R$ is the temperature drop due to radiation to the environment, and
- $\theta_C$ is the temperature drop due to convection to the environment.

### 1.3.1 Thermal Analysis of Friction Drilling Process:

In any sliding operation, most of the frictional energy input generally used up in plastic deformation which is directly converted to heat in the material close to interface. Contact between two bodies can be approximated as a single contact or as multiple contacts. During high contact stress situation, the real area of contact (Ar) is
close to that apparent area of contact (Aa) and essentially single contact occurring during sliding. In the process of heat generation due to sliding the analysis can be carried out by considering either high speed sliding or low speed sliding which can be determined by calculating dimensionless number known as the Peclet number L [12].

\[ L = \frac{V}{l} \frac{l}{k} \]  

(1.6)

Where,

- \( V \) is the characteristic velocity
- \( l \) = characteristic length or radius (for \( FD = d/2 \))

Putting \( l \) in above equation we will get,

\[ L = \frac{V}{2} \frac{d}{k} \]  

(1.7)

If

- \( L > 10 \), high speed category
- \( L < 0.5 \), low speed category
- \( 0.5 < L < 10 \), approximate transition curve can be used.

Peclet number for high contact stress i.e. for single asperity condition \((Ar/Aa \approx 1)\) can be calculated as:

\[ L = \frac{V}{l} \frac{l}{k} \]  

(1.8)

Where;

- \( V \) is the characteristic velocity
- \( l \) = characteristic length or radius (for \( FD = d/2 \))

\[ L = \frac{V}{2} \frac{d}{k} \]  

(1.9)

Peclet number for low contact stress i.e. for single asperity condition \((Ar/Aa < 1)\) can be calculated as:

\[ L = \frac{V_p}{l} \frac{l}{k} \]  

(1.10)

Where,

- \( V_p \) = Velocity of particle on asperity 1 with respect to asperity 2 which is equal to \( V/2 \)
- \( l \) = Average contact radius equal to \( 3d_{max}/8 \)
\[ k = \text{Thermal diffusivity of material in mm}^2/\text{s} \]
\[ d_{\text{max}} = \text{Maximum contact diameter} \]

Putting the value of \( d \) in equation following relation is obtained,

\[ L = \frac{3Vd_{\text{max}}}{16k} \]  \hspace{1cm} (1.11)

Since the Peclet no. for all the three regions are above 10, therefore the friction drilling is the high speed sliding process and hence the analysis should be carried in by the following way.

I. **Thermal Analysis of considering single area of contact (Ar/Aa \( \approx \) 1) and high speed (L>10):**

Assumptions:

1. Single contact is considered.
2. Frictional heating is liberated uniformly over the contact area.
3. Heat only goes into the solids with no loss of heat from the surface.
4. Heat transfer occurs by conduction of heat and convection and radiation effects are neglected.
5. Partition of heat is not considered since (L \( >> \) 1)
6. Moving Circular source of heat with diameter 2l is considered.

Thermal analysis is based on the classical equations for heat conduction in a homogeneous isotropic solid [15]. In the thermal analysis, the transient temperature field \( \theta \) is a function of time \( t \) and the spatial coordinates \( (x, y, z) \), and is determined by the three-dimensional nonlinear heat transfer equation. [12]

\[
\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} = \frac{1}{\alpha_t} \frac{\partial \theta}{\partial t} \]  \hspace{1cm} (1.12)

For a single asperity contact the rate at which frictional heat is liberated \( q \) in watt per unit area at the interface is given by [11],

\[ q = \mu P_a V \]  \hspace{1cm} (1.13)

The approximate equation for maximum temperature rise for high sliding condition is given by [12]

\[ \theta_{\text{max}} = \frac{1.6q}{\rho C_p V \left( \frac{V l}{\alpha_t} \right)^\frac{1}{2}} \]  \hspace{1cm} (1.14)

Putting equation 1 in equation 2
\[ \theta_{\text{max}} = \frac{1.6 \mu P_a}{\rho C_p \left( \frac{V I}{\alpha} \right)^{\frac{1}{3}}} \]  \hspace{1cm} (1.15)

Also the surface temperature of workpiece can be calculated by considering the partition of heat i.e. actual heat transferred to the workpiece,

\[ \theta_w = \left( \frac{k_w}{k_w + k_{\text{tool}}} \right) \theta_{\text{max}} \]  \hspace{1cm} (1.16)

Where,

- \( q \) is the heat liberated in W/m\(^2\)
- \( \mu \) is the coefficient of sliding friction
- \( P_a \) is the pressure in N/m\(^2\)
- \( \rho \) is the mass density in Kg/m\(^3\)
- \( C_p \) is the specific heat in J/g K
- \( \alpha \) is the thermal diffusivity in m\(^2\)/s
- \( V \) is the speed in m/s
- \( l = d/2 \) is the contact radius in m

II. \textbf{Thermal Analysis of considering Low contact stress Condition (Ar/Aa << 1) and high speed (L > 10):}

In this type of contact situation neither the contact nor the heat generation is uniform. At any instant, contact is between a numbers of pairs of contacting asperities. The load per asperity, size of contact, location of asperity and duration of contact varies from point to point and from time to time. Contacts grow, shrink and disappear and this process goes on. As some contacts disappear, others are continuously formed. There are three levels of temperature rise in multiple asperity sliding contacts

- Maximum asperity contact temperature or Flash temperature \( \theta_f \).
- Average surface temperature \( \theta_a \)
- Bulk temperature \( \theta_b \)

Low contact stress condition can be divided into two classes as:

A. Both surfaces are of more or less equal roughness. The contact is made between pairs of tips of asperities and each asperity acts as slider for the other. The centre of the contact moves at approximately half the sliding velocity with respect to each asperity.
B. One surface is much rougher than the other so that the asperities of the rougher surface can be identified as the slider and the smoother surface is assumed to be stationary.

A. **Both surfaces are of more or less equal roughness:**

The rate at which frictional heat is liberated at the interface is given by

\[ q = \mu \varphi_a V \frac{A_a}{A_r} \]  

For plastic contact, the ratio of areas can be formulated as

\[ \frac{A_r}{A_a} = \frac{P_a}{H_s} \]  

Where,

- \( q \) = heat produced in W/m²
- \( A_a \) = Apparent area of contact
- \( A_r \) = Real area of contact
- \( P_a \) = contact pressure in N/mm²
- \( H_s \) = surface hardness of the softer material N/mm²

\[ q = \mu \varphi_a V \frac{H_s}{P_a} \]

\[ q = \mu VH_s \]  

Also the maximum contact \( \theta_{f_{\max}} \) is correlated to the maximum contact diameter and the thermal properties. Based on the number of computer runs for several materials with large variations in thermal and mechanical properties having different surface roughnesses at different interferences which provide a large variation in contact diameter and at different sliding velocities, the following relationship [12] holds good.

\[ \frac{\theta_{f_{\max}} \rho C_p V}{q} = 0.95 \left( \frac{V d_{\max}}{k} \right)^{\frac{1}{2}} \]  

This equation indicates that the flash temperature rise is proportional to the square root of the velocity. By modifying equation 1.20 the equation obtained is

\[ \theta_{f_{\max}} = 0.95 \frac{\mu H_s}{\rho C_p} \left( \frac{V d_{\max}}{\alpha_s} \right)^{\frac{1}{2}} \]  

Also mean temperature can be calculated as [12]
\[ \bar{\theta} = \frac{2}{3} \theta_{f_{\text{max}}} \]  

(1.22)

Where,

\[ \theta_{f_{\text{max}}} = \text{maximum contact(flash) temperature}^0\text{C} \]
\[ \rho \ C_p = \text{Volumetric specific heat} \ j/\text{m}^3 \ 0\text{C} \]
\[ \rho = \text{mass density} \ \text{Kg/m}^3 \]
\[ C_p = \text{Specific heat} \ J/\text{Kg} \ 0\text{C} \]
\[ H_s = \text{Surface hardness of the softer material} \ \text{N/mm}^2, \text{which may be equal to} \]
twice that of bulk hardness (H).

**B. Sliding of rough surface on smooth surface:**

Asperities in the rough smooth surfaces form contacts and unlike rough-rough surfaces, the size of the contact does not change and the contacts can be continuous during sliding, unless the contact results in a wear debris generation. Asperities in the rough smooth surfaces can be identified as slider and the smoother surface is assumed to be stationary. Asperity contacts are assumed to be either square or circular and to move across a stationary semi-infinite body. The steady state temperature rise for circular asperity contact is given by equation 1.21 and 1.22.

**1.3.2 Analysis of Temperature increase due to plastic deformation:**

In order to understand the forces and stresses involved in metal forming processes it is necessary to (a) become familiar with the concept of flow stress and (b) start with the study of plastic deformation under conditions where a simple state of stress exists. For studying the plastic deformation behavior of a metal it is appropriate to consider homogeneous or uniform deformation conditions. The yield stress of a metal under uniaxial conditions, as a function of strain, strain rate, and temperature, can also be considered as the “flow stress.” The metal starts flowing or deforming plastically when the applied stress (in uniaxial tension without necking and in uniaxial compression without bulging) reaches the value of the yield stress or flow stress. The flow stress is very important because in metal forming processes the loads and stresses are dependent on (a) the part geometry, (b) friction, and (c) the flow stress of the deforming material. The flow stress of a metal is influenced by:

- Factors unrelated to the deformation process, such as chemical composition, metallurgical structure, phases, grain size, segregation, and prior strain history
Factors explicitly related to the deformation process, such as temperature of deformation, degree of deformation or strain, and rate of deformation or strain rate.

Thus, the flow stress, $\bar{\sigma}$, can be expressed as a function of the temperature, $\theta$, strain, $\varepsilon$, the strain rate $\nu$, and the microstructure, $S$. For a given microstructure, i.e., heat treatment and prior deformation history:

$$\bar{\sigma} = f (\theta, \varepsilon, \nu, S)$$  \hspace{1cm} (1.23)

In hot forming of metals at temperatures above the recrystallization temperature the effect of strain on flow stress is insignificant and the influence of strain rate (i.e., rate of deformation) becomes increasingly important. Conversely, at room temperature (i.e., in cold forming) the effect of strain rate on flow stress is negligible. The degree of dependency of flow stress on temperature varies considerably among different materials. Therefore, temperature variations during the forming process can have different effects on load requirements and metal flow for different materials.

To be useful in metal forming analyses, the flow stresses of metals should be determined experimentally for the strain, strain rate, and temperature conditions that exist during the forming processes. The most commonly used methods for determining flow stress are the tensile, uniform compression and torsion tests. At cold forming temperatures, $\bar{\sigma}$ increases with increasing $\varepsilon$ and reaches a saturation stress at values of $\varepsilon$ larger than 0.8 or 1.0.

At constant strain rate $\nu$, flow stress increases first, and then decreases because of internal heat generation and thermal softening. In all tests, the test temperature is not constant in a strict sense. Because of plastic deformation, a temperature increase, $d\theta$, takes place. This can be estimated as [11]:

$$d\theta = \frac{\beta \varepsilon \bar{\sigma}}{c \rho}$$  \hspace{1cm} (1.24)

Where,

$\beta$ is a conversion factor, (fraction of deformation work converted into heat usually $\beta = 0.95$)

c is the heat capacity in J/K and

$\rho$ is density of workpiece kg/m$^3$
Most materials, when tested at room temperature in the work hardening range, are not affected by moderate strain rates; hence, the speed of loading need not be controlled too closely. Approximate stress-strain relationships for a limited region of strain can often be given by exponential equation of the form:

\[ \sigma = K\varepsilon^n \]  

Where, 

- $K$ is stress at $\varepsilon = 1.0$ and is called strength coefficient and
- $n$ is the strain hardening exponent and is the slope of a log-log plot of this equation

For strain rate sensitive process this equation can be modified as 

\[ \sigma = K\varepsilon^n \exp \left[ \frac{mQ}{R_g T} \right] \]  

Where,

- $Q$ is the apparent activation energy joules per mole
- $R_G$ is a constant equal to 8.32 mole\(^{-1}\)K\(^{-1}\) and
- $T$ is the absolute temperature.

1.4 Modeling of tool wears in Friction Drilling Process:

1.4.1 Friction drilling tool wear mechanisms:

Microscopy of the tool surface, augmented by energy dispersive X-ray analysis, suggest that adhesive, oxidative, and abrasive wear all occur to some extent during friction drilling; however, it is difficult to determine their proportional contributions [9]. They are described in their proposed order of importance namely:

I. Adhesive wear:

In friction drilling, most material transfer is observed to be from the workpiece to the tool. Work-material adhesion to the tool during machining is a familiar phenomenon [2]. Due to the high temperature of the process, the Co matrix in the tool material will soften, be removed from the tool, and lose hard WC particles embedded in the matrix. Adhesive wear arises from the strong adhesive forces created whenever atoms come into intimate contact. When these adhesive forces are greater than the shear strength of either bulk material, a break is likely within one of the materials [12].
II. Oxidative wear:

Oxidation was detected on the tool by EDS X-ray. High temperature increases potential for oxidation in normal atmospheric air. Oxidative wear occurs when a reaction with oxygen produces an oxide layer on the surface of the tool. This is likely to happen after every hole drilling when the tool has a fresh surface under high temperature. The removal rate and wear of the oxide layer are important to determine the contribution of oxidative wear.

III. Abrasive wear:

The circular grooves in the tool conical and center regions suggested abrasive wear. This is the form of wear which occurs when the hard particles of WC, that were dislodged due to adhesive wear, slide on the surface of the tool and plough grooves into it. This is the three-body wear with the three bodies being the tool, workpiece, and dislodged WC particles.

1.4.2 Modeling of Adhesive wear in friction drilling process:

Adhesive wear occurs when two nominally flat solid bodies are in sliding contact, whether lubricated or not. Adhesion or bonding occurs at the asperity contacts at the interface and these contacts are sheared by sliding, which may result in detachment of a fragment from surface and attachment to the other surface. As the sliding continues, the transferred fragments may come off the surface on which they are transferred and be transferred back to the original surface or else form loose wear particles. Some are fractured by repeated loading and unloading action resulting in formation of loose particles [12]. Archard’s [16] equation of wear is given as:

\[ V = \frac{k L x}{H} \]  

(1.27)

Where,

\( V \) is volume of the wear in m³
\( k \) is the wear co-efficient (dimensionless)
\( L \) is the applied load in N
\( X \) is the sliding distance in M
\( H \) is the Hardness of the surface being worn in Pa
This equation generally considered to give amount of wear removed from softer of the two sliding surfaces. However this equation can also be used to calculate wear from harder surface by considering its hardness. The wear co-efficient k is usually interpreted as the probability that transfer of material fragments occurs or wear particles are formed to a given asperity encounter. The value of k is $10^{-8}$ to $10^{-4}$ for mild wear and $10^{-4}$ to $10^{-2}$ for severe wear.

Rate of wear depth can be calculated as

$$dt = \frac{k P v}{H}$$  \hspace{1cm} (1.28)

Where,
- P is the Pressure in Pa
- v is the sliding velocity in m/s
- dt is rate of wear = d/t
- d is the wear in mm

Since the flow pressure or yield pressure under combined normal and shear stress is lower than that under a static normal load therefore P can be taken as

$$P = \frac{H}{\left(\alpha + \mu^2 \frac{1}{2}\right)}$$  \hspace{1cm} (1.29)

Where,
- $\alpha$ is the constant about 9
- $\mu$ is the co-efficient of friction

This equation for hardness may be used in Archard’s equation.

Putting in equation (1.27)

$$V = \frac{k L x}{p \left(\alpha + \mu^2 \frac{1}{2}\right)}$$  \hspace{1cm} (1.30)

Rabinowicz [17] has suggested that average diameter of loose wear particles is

$$d = 60000 \frac{W_{ad}}{H}$$  \hspace{1cm} (1.31)

Where,
- $W_{ad}$ is the work adhesion in Nm
- H hardness in Pa

The size of particles in metallic contacts typically ranges from submicrons to tens of microns.
1.4.3 Calculation of Adhesive wear coefficient of friction drilling tool:

In the friction drilling process the tool made of Tungsten Carbide slides past the workpiece with high speed both tangentially and axially. The two bodies remain in contact during the process which exhibits the frictional heat generation. There is fare chance of adhesion between asperity contacts at the tool workpiece interface. The continuous sliding of the tool past the workpiece causes asperity contacts to be sheared. The shearing of the asperities due to sliding contacts, fragments of material from the workpiece is deposited on the tool. The adhesion wear of the tool and the workpiece in the friction drilling process can be modeled using the modeling explained in section 1.4.2.

Let $k_{ad}$ is the wear co-efficient of tool and it can be calculated as:

$$k_{ad} = \frac{V_t \cdot H}{L \cdot x} \quad (1.32)$$

Also,

$$V_t = \frac{W_t}{\rho \cdot t}$$

$L = PdA$ and $x = Vdt$

Where,

$W_t$ is the weight of the material removed from the tool in Kg

$\rho$ is the mass density of the tool in kg/m$^3$

$V_t$ is the volume of material removed from the tool in m$^3$

$t$ is the time

$$k_{ad} = \frac{w_t \cdot H}{\rho \cdot PdA \cdot vdt} \quad (1.33)$$

Now in friction drilling process the load will vary as the contacts change and thermal conditions change i.e. co-efficient of friction will vary according to the temperature conditions. In the tool wear study of friction drilling tool [2] it is observed that the wear of different regions are different therefore it can be said that wear coefficient will be different for centre, conical and cylindrical region. Also the effect of varying coefficient of friction can be considered by using different co-efficient of friction for centre, conical and cylindrical region i.e.

$$P = \frac{H}{\left(1 + \alpha \mu^2 \right)^{\frac{1}{3}}} \quad (1.34)$$
Where,

\[ \alpha \text{ is constant about 9,} \]
\[ \mu \text{ is the co-efficient of friction} \]

Therefore the final equation can be modified as:

\[
K_{ad} = \frac{w_i}{\rho_i} \left( \frac{1}{d} + \frac{\alpha \mu^2}{d} \right) \quad (1.35)
\]

1.5 Need and significance of study:

Applications of the sheet materials in the manufacturing and other industries are ever growing due to the economical and technical benefits of the sheet materials. In sheet metal working joining of the sheet material with other parts is cumbersome, time consuming and costly affair. The method used presently for sheet material joining suffered with many drawbacks. There is always motivation for the process which makes sheet material joining and drilling more economical and reliable. The friction drilling process due to its easiness in operation and less time consuming and producing joints with good strength and rigidity is recently becoming quite popular in the industries. The friction drilling process is simple, safe and pollution free and offers many advantages over other processes. Due to this process many researchers shown their interest in this process and carried out the work using different materials. The most of the research so far carried out is concentrates on mechanistic modeling, finite element modeling, and tool wear mechanism in the friction, drilling process, microstructure alteration in this process etc. The process is suitable for most of the materials including the fabrication and furniture where the use of Steel Square and Round pipes are prevalent and demanding due to economical benefits. In all these applications the quality and integrity of the joints made by the friction drilling process play an important role on the performance of the final product. Also the manufacturing feasibility is major concern in these industries which has utmost importance while selecting the process and its parameters.

The friction drilling process which is considered as the replacement for welding, riveting in the sheet material industry for joining the parts is found to be affected by the selection and control of the process parameters. The main factors which affect the process are workpiece and tool material, the size and shape of the friction drilling tool, the cutting conditions, the behavior of the machine tool and the
control parameters, operator skill etc. The analysis of these elements is indispensable in order to obtain the quality performance from the process. Also there is need to design the process which is more robust and less prone to errors and defects during the process. Therefore the study and analysis of this process considering all the factors individually and combined is the need of the day.

In today’s manufacturing scenario the economic advantage from the product can be gained when the process operates at the optimum performance level. The optimum performance from the process can be achieved when all the control parameters which affects the process are selected properly and with prior analysis. This demands the study and analysis of the process parameters and finding out the optimal parameter setting which is used for carrying out the process effectively. The process parameter selection also involves the study of the internal and external elements of the process which may directly or indirectly affect the process. There is need to make the process more robust and error free. In order to improve the performance of friction drilling process, it is essential to optimize the process parameters, which will help in reducing cost while achieving the required geometrical tolerance. The friction drilled holes are generally tapped in order to use it as the threaded joints. The friction drilled holes can be tapped using the cutting tap or form tap. Due to the small wall thickness of the friction drilled holes the cutting tap is not recommended for the process since it removes the material in the form of fine chips and forms the grooves. Whereas the form taps does not remove the material and form the ridges by displacing the material plastically. The use of the cut tap or form tap has many benefits and limitations associated with them. The comparative assessment of the cut tap and form is needed in order to select the proper tapping method. Also the parameters selection during the tapping process considering the cutting condition is viable and needed.

Nowadays the use of the artificial neural network (ANN) for the study and analysis of the machining processes in the manufacturing industries is common and popular phenomenon. The ANN offers many advantages which includes analysis and modelling of the processes which is useful for intelligent monitoring of the automatic processes. Much work has been done by the researchers using the ANN to study various machining processes but no attempt has been made to study the friction drilling process. Therefore considering the need and importance of the intelligent
control system, in this study an attempt is made to model the process using ANN for controlling the thrust force, torque and surface roughness which has much impact on quality and reliability of the friction drilling process.

1.6 Objectives of Study:

Friction drilling is a nontraditional machining process with many advantages but the capability of this process is not fully utilized in commercial application due to the lack of study and awareness about the process. The process parameters selection and their effect on the quality of hole needs to be addressed. Experimental investigations involving in depth study of commercially available tool has to be done. The thread formed on the friction drilled holes and its strength needs to be investigated. The metallurgical aspects of friction drilled holes like hardness of bush, heat affected zones have to be studied. Taking into account all above considerations following objectives were defined. The material selected to carry out the experimentations is AISI 1015 which is the mild still commonly available and has the many application in the fabrication, furniture and automotive industries.

- Experimental set up for the friction drilling process.
- Setting up of online thrust and torque monitoring dynamometers.
- Study the effect of process control parameters viz. Material Thickness to tool dia. Ratio (T/D ratio), Rotational Speed (N), Feed (f) on responses.
- Analytical and Mathematical Modeling of Friction drilling process.
- Measurement of Thrust Force, Torque, Surface roughness, Dimensional Error, Circularity Error, and Cylindricity Error of friction drilled holes.
- Analysis of individual responses using Analysis of Variance (ANOVA) and Taguchi methods.
- Mathematical formulations of individual responses in terms of inputs factors using the regression analysis.
- Multi attribute decision making of friction drilling process considering measured responses using Analytical Hierarchy Process and TOPSIS (Technique for Order Preference by Similarly to an Ideal Solution) method.
- Modeling and analysis of friction drilling process by Artificial Neural Network (ANN) for intelligent monitoring and control friction drilling process.
- Measurement of Temperature, Heat Affected Zone (HAZ), Bush Length and Hardness.
- Experimental Investigation in Friction Drilling to investigate the effect of process parameters on Bush Length, Temperature, and Heat affected zone, Hardness and Microstructure.
- Multi-objective optimization of Bush length, Temperature and Heat affected zone using Grey Relation Grade analysis method.
- Microstructure analysis of friction drilled holes and heat affected zone near to hole.
- Experimental investigations and characterization of internal thread forming and thread cutting process on friction drilled holes.
- Comparative assessment and analysis of the thread forming and thread cutting process for the friction drilled holes using the Taguchi method.
- Formulation of decision model for the ranking of attributes of the threading process based on Analytical Hierarchy Process (AHP) and Relative Reliability Risk Index (R3I) method.

1.7 **Methodology Adopted:**

In this work the experimental investigations of the friction drilling process has been carried out with the aim of improvement of the quality and reliability of the friction drilled holes and the process. Following methodology is being utilized for effective planning and conduction of this research.

- Statement and definition of the problems concerning the friction drilling process and clear understanding and identification of the area of research.
- Statements regarding the objectives and aims of the research.
- Selection of proper workpiece material, tool material, machine tool and working conditions.
- Experimental setup, Conduction of trial experiment and design of experiments.
- Collection and measurement of data.
- Data Analysis and development of mathematical model.
- Optimization and conduction of confirmation experiments.
- Data modeling using the ANN and comparative assessment with statistical analysis.
- Process Characterization and metallurgical studies.
- Interpretation and conclusions from the experimental studies.