2.1 FRICTION WELDING PROCESS

The first successful application of this process is welding of metals which were reported from Russia in 1956. Earlier this process has been used for joining thermoplastic polymers. In this process one of the pieces to be welded is rotated and the other is made to rub the first one under the axial load resulting in increased friction which helps in heat generation and joining of the two pieces when the pieces are subjected to rest under an enhanced axial load, the joint made by this friction welding method is similar to the ones produced by electrical resistance butt welding process of flash and upset welding [1]. Filler metal, shielding gas or flux is not required by this friction welding method [2]. This process is not only used for welding cylindrical pieces like tube or rod but, it can also be used to weld in case if one of the components to be welded is symmetrical in shape and can be easily rotated.

2.2 TYPE OF FRICTION WELDING PROCESS

Friction welding processes are classified into following [3]

a) Energy Based classification

b) Relative motion classification
2.2.1 ENERGY BASED CLASSIFICATION

2.2.1.1 DIRECT DRIVE OR CONTINUOUS

Continuous drive process is a variant where power or energy is provided by an infinite duration source and maintained for a preset period [3].

2.2.1.2 STORED ENERGY

The process variant where the energy for welding is supplied by the kinetic energy stored in a rotating system or fluid storage system [3].

2.2.1.3 HYBRID SYSTEM

It is the combination of some of the features of both the above method [3].

2.2.2 RELATIVE MOTION BASED CLASSIFICATION

2.2.2.1 ROTATIONAL

It is a method in which one component is rotated relative to and in contact with the mating face of another component [3].

2.2.2.2 LINEAR OSCILLATION

In this method, one component is moved in a linear oscillating motion relative to and in contact with the mating face of another component [3].
2.2.2.3 ANGULAR OSCILLATION

In this method, one component is moved in angular oscillating motion about a common component axis relative to and in contact with the mating face of another component [3].

2.2.2.4 ORBITAL

In this method, one component is moved in a small circular motion relative to and in contact with the mating face of another component either with components rotating about its own central axis or with components rotating in the same direction about their own axes and at the same speeds but with their axes displaced [3].

2.3 ADVANTAGES OF FRICTION WELDING PROCESS [4]

- Friction welding is environmentally friendly process as it does not generate fumes, gases or smoke.
- Friction welding is suitable for quantities ranging from prototype to high production.
- As friction welding is a solid state process, possibility of porosity and slag inclusions are eliminated.
- Welding of unequal cross sections can be done by friction welding process.
- It allows choosing of either manual loading or optional automated loading.
Dissimilar materials which are normally not compatible for welding can be friction welded.

- Friction welding is consistent and repetitive process.
- It consumes low energy and low welding stress.
- It reduces raw material cost with bi-metal applications.
- It reduces maintenance cost.
- It reduces machining labor, which in turn increases capacity and reduces perishable tooling cost.
- It reduces cost for complex forgings or castings.
- Self-cleaning action of friction welding reduces or eliminates surface preparation cost or time for some material combinations.
- In case of friction welding, joint strength is equal to or greater than parent material.
- It creates a narrow heat affected zone.
- It has accurate control over post welds tolerances.
- It is highly precision and repeatable process.
- No flux or filler metals or gases are required in case of friction welding.
- Create cast or forge like blanks, without the expensive costs of tooling and the minimum quantity requirements.
- Friction welded joint can withstand high temperature variation.
2.4 APPLICATIONS OF FRICTION WELDING PROCESS

Figure 2.1 Nuclear Power Plant

Figure 2.2 Bi-Metallic Joint (Aluminum to SS304)

Figure 2.3 Aluminum-SS (Copier Fuser Roller)

Figure 2.4 Motor shaft
Figure 2.5 Light Weight propeller shaft with Al-Steel Joint

Figure 2.6 Airbag Inflator

Figure 2.7 Anode anchors

Figure 2.8 Transition Joint for Nuclear Reactor (Al alloy and Steel)
Figure 2.9 Cu-Al connector

Figure 2.10 Aircraft application (Ignition assembly) – Al 6061 – SS 304

Figure 2.11 Aerospace applications

(Transition Joint Al alloy to SS 304)
2.5 VARIABLES IN DIRECT DRIVE FRICTION WELDING PROCESS

The variable in friction welding can be divided into two groups [5-20].

- Machine
- Non machine

The machine variables include

- RPM
- Friction pressure
- Friction time
- Forging pressure
- Forging time

The non machine variables include

- Material type to be welded
- The part configuration
- The size

2.6. DIRECT DRIVE WELDING PARAMETERS

2.6.1 ROTATION SPEED

Rotational speed provides the necessary relative velocity at the faying surfaces. Its magnitude depends upon the metal being welded and for steels [9]; the tangential velocity for both solid and tubular work piece should be in the range of 75-110 m/min. Tangential speeds lower than 75 m/min results in excessive torque with
consequential clamping problems, non-uniform up-set and tearing of metals at the joint. Friction welding machines for production purposes, handling 50 to 100mm diameter work pieces, usually operate at speeds varying between 90 to 200 m/min.

High rotational speeds are useful for welding but axial pressure and heating time must be carefully controlled to avoid overheating of the weld zone particularly for welding quench hardenable steels, to control cooling rate and possible cracking [9].

In dissimilar metal welds, low rotational speed can minimize the formation of brittle intermetallic compounds; however in general for controlling weld quality, rotational speed is not considered as critical parameter.

N. Ozdemir [10] investigated mechanical properties of friction welded joints between AISI 4340 steel as a function rotational speed.

### 2.6.2 Friction Pressure

The applied axial pressure controls the power require for machine, the axial shortening of the work piece, and the temperature gradient in the weld zone. The specific pressure depends upon the joint configuration and the metal being welded. It can be use to compensate for heat loss to a larger body as in the case of tube-tube plate welds. Applied pressure should be high enough during the heating phase so as to keep the faying surfaces in close contact to
avoid oxidation. Joint properties may often be improved if the applied pressure is increased at the end of the heating phase.

For making sound welds in mild steels the heating pressure used is unusually 30-60 N/mm² while the forging pressure may lie in the range of 75-150 N/mm², and the commonly used values are 55-130 N/mm². However, higher forging pressure is required for high hot strength alloys like, nickel base alloys and stainless steels. If preheating effects is required then the axis pressure of 20 N/mm² is applied initially for a short period which is then raised to the normal heating pressure.


2.6.3 FRICTION TIME

Friction time is controlled depending upon whether a fixed preset time is allowed for heating or the extent of the axial upset is to be within the specified limits [14]. Excessive time limits productivity and results in wastage of material; while insufficient time may result in uneven heating as well as entrapment of oxide resulting in unbounded areas at the interface. The duration of welding for a 25mm diameter bar, as already mentioned, should be from 5 to 7 seconds at the rotational speed of 1000 rpm.
Kimura Masaki, Otsuka Yosuke, Kusaka Masahiro and Seo Kenji [14] studied effects of friction time and friction pressure on tensile strength of welded Joint for medium and High Carbon Steel by low heat input friction welding method.

2.6.4 UPSET PRESSURE

Upset Pressure is important since it controls the metal deformation, and hence, the extent of metal consolidation and flow both at the interface and in the adjacent heat affected zone. Thus, the upset pressure must be sufficiently high to produce an effective pressure weld but not so great as to develop excessive deformation and adverse reorientation of the adjacent parent material. The application of forging pressure is often beneficial because it helps to break up and refine the heated metal in the interface and adjacent heat affected zone and further benefits are obtained since non metallic inclusion can be favorably broken up as hot metal is squeezed out radially.

Horie Hiroshi, Wenzhi Huang, Nakamura Mitsuru, Kowata Toshinori, kitagawa Masayoshi, KIM Chang-Gyu [21] studied Effects of upset conditions on friction welding characteristics of spheroidal graphite cast iron to mild steel.

2.6.5 UPSET TIME

The upset time should be applied for suitable duration [21-22]. Excessive upset time leads to excessive deformation of material and
lower upset duration leads to ineffective removal of non metallic inclusions.

### 2.7 FACTORS WHICH INFLUENCES THE FRICTION COEFFICIENT

According to I. V. kragel’skiy and I. E. Vinogradova [23] the following is the list of nine factors which have influence on friction coefficient:

- The nature of the material and presence of films on friction surfaces (oxides, lubrication, contamination)
- Finish of the surface and roughness.
- The area of contact surface, coefficient of overlapping and character of the contact between bodies.
- The magnitude of normal pressure force.
- The temperature of the friction surfaces.
- The rigidity and elasticity of the friction surfaces.
- The relative speed of motion of the friction surfaces.
- The speed of application of the load.
- The duration of contact without movement.

Some factors which are predominant in friction welding are:

- The nature of the material and pressure of surface films.
- The rigidity and elasticity of the friction surfaces.
The relative speed of motion and temperature of the friction surfaces.

The magnitude of the normal pressure force.

Research has proved that the coefficient of sliding friction does not stay constant. It varies not only with the change in natural pressure, but also change in some other factors [24]. In case of sliding friction of steel on steel the friction coefficient may vary from 0.1 to 1 and higher, depending upon the condition existing during friction process. Since dry friction is a complex physical phenomenon which depends upon many factors, and in which the mechanical destruction of the material is combined with the interaction of molecular fields. Under such condition one cannot describe friction by one parameter constant for a given pair of materials [25].

2.7.1 EFFECT OF THE RELATIVE SPEED ON THE FRICTION COEFFICIENT

Some scientists feel that the friction coefficient increases with speed; other cites that the friction coefficient decreases with speed and finally there are investigations that prove the independence of the friction coefficient from the speed of sliding [26-28]. Such contradictions cannot be explained by errors, since most of the experiments were conducted with great accuracy. The result of the experiments were influenced by the condition under which they were carried out, i.e. one cannot investigate by taking the influence of speed of sliding alone, without considering the influence of other
parameters on the friction coefficient. This is confirmed, the general equation for determining the friction coefficient is [29]

\[ f = (a + bv) e^{-cv} + d \]  

(2.1)

It can be notice from the equation that with an increase in the speed \((v)\) the friction coefficient either increases or decreases steadily, or passes maximum, or stay constant, depending upon the numerical relationship of the coefficients \(a, b, c\) and \(d\) of the above equation. The value of the coefficient depends upon the unit pressure, properties of the bodies, the hardness of the bodies, and other factors, that must be determined for pair of materials under working conditions.

![Figure 2.12 Dependency of the friction coefficient upon the speed of sliding for various pressures](image)

1- Small Unit Pressure  
2 & 3- Average Unit Pressure  
4- Considerable Unit Pressure

Figure 2.12 Dependency of the friction coefficient upon the speed of sliding for various pressures [based on equation (2.1)]

It is known, however, that the position of the curve maximum (as shown in Figure 2.12) is a function of the magnitude of the unit
pressure and the hardness of each of materials. The maximum the unit pressure the greater is the hardness of the material.

The deficiency of equation (2.1) is that the friction coefficient is determined only as a function of speed without considering other parameters of friction process, such as pressure. Future research faces the task of finding dependency of the friction coefficient upon the speed of sliding, unit pressure and other factors.

2.7.2 INFLUENCE OF TEMPERATURE FIELD ON THE FRICTION COEFFICIENT AND PHENOMENON OF SEIZING

During friction process, the temperature of contiguous friction surface does not remain constant; it varies within the friction surfaces. This is due to the fact that the energy utilized for overcoming the friction forces is first generated in the form of heat on the physical contact surfaces. At these points, temperature peaks of short duration may occur, causing the sudden increase in the temperature of the micro projections. Because of an intensive dissipation of heat with in the body to the surrounding medium the temperature might drop quickly in shorter intervals. However, during initial period of process the average temperature of the friction surface will continue to increase.

The deformation of uneven surfaces, absorb certain portion of energy during friction process and also generates heat. Heat
generation is not limited to the surface of the point of contact during the friction process [29]. The heat generating surface can be referred as a layer having a certain thickness. A temperature field is created during friction process within the limits of this layer, this field has a hemispherical shape; at certain body depth, the isothermic surfaces of the individual point begin to form a uniform temperature as shown in Figure 2.13. At present, the necessary scientific means for calculation of friction temperature fields are not yet available.

It is important to emphasize here that the distribution of the temperature along the depth “x” of the body is determined by a diminishing function as shown if Figure 2.14. The temperature of the bodies increases, resulting from heat generation produced by friction which in turn introduces changes in the friction process. Thus, lubricants change their properties with heating to up to 200-300° C, so that the marginal friction existed before the dry friction. In most of the cases this change is connected with an increase in the friction coefficient, friction forces, and heat generation energy.

Certain scientists assume that the character of the friction process is determined not only by the temperature on the friction surface but also by the temperature gradient normal to this surface [29]. The gradient of mechanical properties always corresponds to the temperature gradient as it is known that in metals the mechanical properties, particularly the strength, depend on the temperature.
When the strength increases from the surface to the depth of the body, the mechanical gradient is positive, and then the friction caused failure of the surfaces. With a negative strength gradient a deep failure occurs and the thickness of the heat generating layer is increased. It is probable that this has an influence on the phenomenon of binding (seizing).

![Figure 2.13 Temperature field of the surface layer during friction](image)

Figure 2.13 Temperature field of the surface layer during friction

![Figure 2.14 Temperature distributions at depth (x) of the surface layer](image)

Figure 2.14 Temperature distributions at depth (x) of the surface layer

Many different hypotheses exist for understanding the nature and mechanism of seizing. I. E. Vinogradova, for example refers to the Boyden hypothesis, according to which seizing is connected with melting and subsequently crystallization (during cooling of metal). Also several other hypothesis are mentioned which have been
analyzed by the author. A more broad review of the different opinions on the seizing phenomenon may be found in the monograph by A. P. Semenov [30]. Nevertheless, it must be admitted that as yet there is no theory that can explain the nature of seizing in a satisfactory manner.

I. E. Vinogradova has the following to say: “admitting the predominant role of temperature in initiation of seizing process, it cannot be disregarded in this connection that the influence of pressure as a factor determining the area of actual contact surfaces and the number of seizure centers. According to observation, the relation of the actual to the nominal contact surface determines the change from friction to the process of seizing, in case if the actual contact surface is sufficiently large”.

The above conclusion can be logically applied to metals that are normally less plastic. It can be assumed from the above case that the temperature does not have any direct influence on the formation of the seizing centers; the comparatively high temperature simply brings the contiguous surface to a state of sufficient plasticity. Thus, in formation of seizing centers temperature can be considered as a major factor.

The possibility of seizure during friction and consequently during welding of metals and allows is acknowledge by several authors [31-34].
2.7.3 THE INFLUENCE OF THE FINISH OF THE FRICTION SURFACES AND THE DEGREE OF THEIR CONTAMINATION ON THE FRICTION COEFFICIENT

Depending on the finish of the surfaces the friction coefficient for same pair of materials varies to a considerable degree. An increase in the friction coefficient is observed between very smooth surfaces, as a result of an increase in the force of the molecular interaction between these surfaces. An increase in friction coefficient is also observed between rough finished surfaces when compared to the friction coefficient for the same material with a smooth finish. This is because of the fact that larger micro-projections provide stronger interlocking of the surfaces and, it results in a greater friction force. The degree of contamination of contiguous surfaces has a considerable influence on the friction process. Films of various lubricants adsorbed by these surfaces contribute to the lowering of the friction coefficient and decrease the intensity of heat generation during friction.

The thickness of oxide films, also influence the friction coefficient. As a rule, thick oxide films being softer increases the friction coefficient and thin but hard oxide films further decreases the friction coefficient.

The formation of seizing center leads to a considerable quantitative change in the process, which is reflected by the friction coefficient. The formation of seizing connection between two friction
surfaces result in the creation of a tangential resistance force which avoid the relative movement of these surfaces even without normal pressure.

At the beginning before the start of seizing process no other force exist expect friction, the rotation of one with respect to other is resisted only by the moment of the exterior friction forces. After the removal of the axial load the permanent connection i.e., interlocking between the end sections disappears. At the end of the process, after the formation of permanent connection the resistance to such rotation cannot be explained by exterior friction force (the permanent connection between end sections does not disappear even after the removal of axial load). This is how the strength of details is determined when testing them in torsion. Thus, in the friction welding process, the exterior friction is super ceded at the end of the process by phenomena connected with the strength and interior forces of the material.

These changes taking place in the welding process must be connected with the formation of unit seizure center, since they form the basis for the creation of a permanent connection in joints of mechanisms and machines that are subjected to friction forces as well as in friction welding. The seizure centers are first created locally and then it spreads over the entire friction surface.
2.8 INFLUENCE OF SURFACE CLEANLINESS

In friction welding of dissimilar materials such as aluminum alloys to steel cleanliness plays a very important role in achieving good quality of weld and it is extremely important to clean the faying surface properly when these weld combinations are used for critical applications. The metallic surface consists of micro unevenness, roughness and the layers of oxides as shown in Figure 2.15.

![Figure 2.15 surface contamination on typical metal surfaces](image)

Considerable amount of work is published related to oxidation of finished surfaces of metals. It is observed that degreasing and machining of metal faying surfaces is essential for obtaining good quality weld [35-48].

Korsnov [49] found that if weld cleaning is done long time before welding, exhibits lack of bond due to presence of oxides and other contaminations. Shi and Zhang [50] have reported that the rust on the faying surfaces reduces the impact strength. Ohashi et al [51-52] al studied the behavior of oxide layers for aluminum, copper, iron and
stainless steel 304. A.S. Gel’man and M.V. Bolshakov [53] studied the influence of oxide films on joint formation in the pressure welding of metals.

2.9 PROBLEMS ASSOCIATED WITH WELDING OF DISSIMILAR MATERIALS

Two of the most common dissimilar joints produced using the friction welding processes are:

- Copper to aluminum and
- Aluminum to steel or stainless steel.

In case of joining such materials, surface preparation is required prior to joining, because of oxidation of the aluminum surface. A dry machining or chemical etching of the aluminum is preferred. As mentioned previously, a majority of the deformation (material loss) occurs in the aluminum, especially on the aluminum to steel joint or aluminum to copper joint.

Primarily, in electrical industry joining of aluminum to ceramic is performed by attaching steel to ceramics using an aluminum interlayer. This is performed by first welding the steel to the aluminum, followed by bimetal joint to the ceramic. The use of an interlayer for such application is common generally, when two incompatible materials require joining. The interlayer materials are selected on the basis of their formability and compatibility with the two parent material. The welding chart shown in Figure 2.16 shows
the compatibility (Weldability) of similar and dissimilar material combinations.


Mumin Sahin [56] studied Joining of high-speed steel and medium-carbon steel using friction welding process.


Interdiffusion of each element at the weld interface between aluminum and stainless steel are studied by Okita et al [62] by using transmission electron microscope (TEM) with an energy dispersive spectroscopy (EDS) analysis attachment.
Enjo [63] studied diffusion welding of copper to aluminium. Aristosshi M et al [64] studied friction welding of oxygen free copper to pure aluminium.

![Weldability chart for Friction Welding Process](image)

**Figure 2.16** Weldability chart for Friction Welding Process

### 2.10 DEFECTS IN FRICTION WELDING

Defects which can encounter during the friction welding process are as follows [65]:

- Lack of bonding,
- Cracks,
- Non-metallic inclusions, and
- Intermetallic phase accumulation
2.10.1 LACK OF BONDING

In this type of defect there is insufficient bonding between the faying surfaces, shown in Figure 2.17.

![Figure 2.17 Lack of bonding in a friction welded joint](image)

This is caused by low rotational speed or due to improper preparation of interface surfaces or due to insufficient heating time (friction time). This defect can be prevented by improved surface preparation and by optimizing the welding variables.

2.10.2 CRACKS

Cracks are encountered in some specific zones, given as follows:

- Within the heat affected zone or its marginal area.
- At the sharp edged transitional area to weld flash
- Inside weld flash, in axial direction
- Internally on the faying interface

The cracks in the heat affected zone or in its marginal area are caused by the formation of coarse carbides in these zones. Remedial action involves affecting the quality of carbides by preheating the work piece to reduce the cooling rates after welding.
Cracks at the sharp edge transitional area to weld flash as shown in Figure 2.18 are caused by the use of high forge pressure. Thus, this can be prevented by reducing the forge pressure and adjusting the weld variables is another step for prevention of these types of defects.

![Crack at the sharp edge transitional area to weld flash](image1)

Figure 2.18 Crack at the sharp edge transitional area to weld flash

Cracks inside the weld flash, in axial direction as shown in Figure 2.19 are also caused by high forge pressure and because of generation of insufficient high heat during the process. By increasing the rotational speed and by controlling the weld cycle time to generate sufficient heat before applying the final forge pressure.

![Crack inside the weld flash](image2)

Figure 2.19 Crack inside the weld flash

Internal crack occurred during the welding of dissimilar component materials shown in Figure 2.20, can be removed by
controlling the behavior of intermetallic compounds at the faying surfaces.

2.10.3 NON-METALLIC INCLUSION

Solid inclusions of non-metallic forging matter in contact area lead to defect in friction welding, known as non-metallic inclusion, as shown in Figure 2.21.

During the forging stage the inclusions are entrapped. These inclusions may include scale, rust, cutting solution, drawing grease, etc. on the faying surfaces. These defects may also be caused by soiled center bore in the work piece. Cleaning of forging surfaces and the central bore is the solution for prevention of this defect.
2.10.4 INTERMETALLIC PHASE ACCUMULATION

Intermetallic phase accumulation formation and depletion with contact area is shown in Figure 2.22. Incorrect welding variable and dissimilar component material are main reasons for its occurrence. The preventive measures include optimization of welding variables like rotational speed, cycle time and forge pressure and proper selection of component materials.

![Figure 2.22 intermetallic phases inside contact area](image1)

![Figure 2.23 intermetallic phases along contact area](image2)

Carbides, oxides and nitrides may also accumulate in the bonding zone along the contact area as shown in Figure 2.23. This is cause by improper material preparation. Prevention of such occurrence includes greater homogeneity of component material being welded; proper selection and adjustments of welding variables to achieve the desire weld joint.
Sudarshan and Murty [66] have studied intermetallic layer formation at the weld interface of aluminum alloys and stainless steel. Won-Bae Lee, Luek-saeng, seing [67] studied, effects of intermetallic compound on the electrical and mechanical properties of friction welded copper-Aluminum bimetallic joints during annealing. H. Ochi, K Ogawa, Y. Yamomoto, G Kawai and T Sawai [68] studied the formation of intermetallic compounds in aluminum alloy to copper friction welded joints and their effect on joint efficiency.

2.11 FINITE ELEMENT ANALYSIS OF FRICTION WELDING PROCESS

Finite element analysis helps in predicting temperature distribution, stresses, strains, deformations that takes place during friction welding process.

The finite element processes helps better understanding of the friction welding process and it provides very important information without conducting the practical experimentation, which saves time, cost and resources.

Several research papers are published on Finite Element Analysis of Friction Welding in the past [68-79]. C.J. Cheng [72] presented transient temperature distribution during friction welding of two similar materials in tubular form. K.Wang and P. Naggapan [73] have analyzed transient temperature distribution in inertial welding of

2.12 FRICTION STIR SPOT AND REFILL FRICTION STIR SPOT WELDING PROCESS

Friction stir spot welding (FSSW) was invented in 1991 by the welding institute (TWI). It was developed by GKSS a German company. In friction stir welding process, a rotating tool is plunged into a material under high force to create weld.

Refill friction stir spot welding process is a similar to friction stir spot welding except in refill friction stir spot welding; material is refilled back into the void by the withdrawing tool.


2.13 INTRODUCTION TO DESIGN OF EXPERIMENTS

Design of experiments is generally used to collect the pattern of observation. A series of test are conducted by changing the input variable and thus the effect of these change on predefined output are accessed.

Dr. R. A. Fisher laid foundation for DOE in 1920’s and successfully applied them in agricultural research. His approach towards DOE differs in two fundamental aspects from classical approach [92]. Firstly, he emphasizes on obtaining an accurate estimation of magnitude of experimental errors. Secondly, he emphasizes on including as many factors as possible whose effects are to be estimated in the same experiment.

The main advantages of his approach are:

- With a smaller number of observations higher efficiency is achieve.
Information pertaining to the extent to which factors interact is given, that is the way in which the effect of one factor is affected by the other factors.

Design of experiment has been used in the industry for the improvement of the process. Researchers have contributed to the growth of subject and its applications. The optimization techniques for their application in chemical and allied industries were proposed by G. E. P. Box (1978-87). G. Taguchi (1978-80) has developed technique for robust product design and their application in the automotive and electronic industries. Based on the experimental situation different statistical designs are proposed. The most flexible of them is Orthogonal array Design [93]. This approach is easy and versatile in the assessment of factors and analysis and it is almost similar to excellent reproducibility of experimental results. Both simple and complex experiments can be easily designed and analyzed with the help of linear graph associated with orthogonal array. The linear graph was developed by Taguchi (1959) and theoretical results associated with orthogonal array were developed by Rao (1947).

2.13.1 DEFINITION OF DESIGN OF EXPERIMENT

DOE is a systematic approach for investigation of system or process. A series of structured tests are conducted and purposeful
changes are made to the input variables of the process so as to observe and identify the reason for change in output response [94-99].

The process can be visualized as the combination of method, machine, people and other resources which convert some input into an output that has one or more noticeable responses. The performance of the process and system can be studied by experiment. Figure 2.24 shows the model which represents the process or system. Some of the process variables $X_1, X_2, X_3, \ldots, X_p$ are controllable, where as other variables $Z_1, Z_2, Z_3, \ldots, Z_q$ are uncontrollable (based on purpose of a test they can be controlled).

Following are the objective of the experiments:

- To determine which friction welding variables are most influential on the response $y$. 

Figure 2.24 Model of process
To determine where to set the influential x’s so that changeability in y is small.

To determine where to set the influential x’s so that y is always near the desired nominal values.

To determine where to set the influential x’s so that the effects of the uncontrollable variables \( Z_1, Z_2, Z_3, \ldots, Z_q \) are minimized.

It can be observed from the above points that experiments involve several factors. The main objective of conducting the experiment is to determine the influence of friction welding factors on the output response (tensile strength, upset, temperature) of the system. i.e. the process affected minimally by external sources (the z’s).

2.13.2 BASIC PRINCIPLES

Statistical design of experiment refers to the process of planning the experiment in order to collect the suitable data that can be analyzed by statistical method, resulting in valid and objective conclusion. The statistical approach to experimental design is necessary to get meaningful conclusion from the data. The two aspects to solve any experimental problem are statistical analysis of data and design of experiment. In both of the approaches the method of analysis depends directly on the design employed [101].

The three basic principle of experimental design are

- Replication
Randomization

Blocking

2.13.2.1 Replication

Replication means repetition of the basic experiment. It consists of two significant properties. First, the experimenters are allowed to obtain the estimation of experimental error. This estimate of error can be used as the basic unit of measurement for finding whether the observed differences in the data are really statistically different. Second, if the sample mean (e.g., y) is used to estimate the effect of a factor in the experiment, replication permits the experimenter to obtain more precise estimate of this effect.

For example, if $\sigma^2$ is the variance of an individual observation and there are n replicates, the variance of the sample mean is [102]

$$\sigma^{2/y} = \sigma^2/n$$ (2.2)

2.13.2.2 Randomization

It means that both the allocation of the experimental material and the order in which the individual trials or runs of the experiment are to be conducted are randomly determined. Statistical technique requires that the observations to be independently distributed among the random variables. It usually makes this assumption valid.
The influence of extraneous factor can be prevented by properly randomizing the experiment.

2.13.2.3 BLOCKING

Block is a design method used to improve the precision with which comparison compares among the factors of interest. Blocking is used to eliminate or reduce the variability transmitted by from nuisance factors.

2.13.3 THE DESIGN OF EXPERIMENT PROCESS

The design of experiment process is divided into three main phases that includes all the experimentation approaches [103]. The three main phases are:

- The planning phase
- The conducting phase
- The analysis phase

2.13.3.1 THE PLANNING PHASE

It is the most important phase for the experiment which provides the expected information. The experimenter will gain some information from any experiment; this information can be in positive sense or in negative sense. The positive information is an indication of which factor and which levels leads to improve the performance of the
product or the process. Whereas, negative information is an indication of which factor does not lead to improvement.

2.13.3.2 THE CONDUCTING PHASE

This phase is the second most important phase as the test results are collected in this phase. If the experiments are conducted in well planned manner, the analysis is much easier and more likely to provide positive information concerning factors and levels.

2.13.3.3 THE ANALYSIS PHASE

In analysis phase the positive or negative information regarding the selected factors and levels is generated. The analysis phase is the more important in terms whether the experiment successfully yields a positive result or not, however it is the most statistical in nature of the three of the DOE by wide margin.

Almost all designed experiments require certain number of combination of factors and levels to be tested for observing the results of those combinations. The Taguchi approach relies on the assignment of factors in specific orthogonal array to determine those test combinations. Taguchi is not the first to utilize an orthogonal array or equivalent approach to experimentation. All Latin square, Greco-Latin
square, or Yates algorithm experiments are based on the same approach.

2.13.4 ORTHOGONAL ARRAY EXPERIMENTATION

When the objects have already been investigated to a certain extent, optimization would begin. This would give the clear idea of the optimization parameter, the factors, the responses, and the best condition for conducting a process and nature of the responses.

Taguchi’s approach relies the assignment of factors in specific orthogonal array to determine those test combination (i.e. combination of factors and levels). Orthogonal array is a set of Latin square constructed by Taguchi to lay out the design of experiments. By using this Latin square, an orthogonal array of standard procedure can be used for number of experimental situations.

A full factorial experiment is one in which all possible combination of the factor levels are realized. The number of experimental trials (‘N’) for a full factorial experiment is therefore given as \( N=s^n \), where ‘s’ is number of levels for each factors and ‘n’ is the number of factors. If more number of factors is involve in the experiment the number of trials for full factorial experiment becomes high and hence in actual case conducting this many trials become impractical. Therefore, to minimize the number of trials to be conducted an orthogonal array is used, which are highly fractionalized.
factorial layout. The concept of linear graphs associated with orthogonal array is introduced by Taguchi for orthogonal array to meet the requirement for different practical situations [99-104].

![Linear Graphs](image)

**Figure 2.25 Linear Graphs**

Linear graphs used in design of experiments are shown in Figure 2.25. Friction welding process is considered as an example. The optimization of the process parameter begins after the investigation of the object is done. This involves factors such as rpm, friction pressure, friction time, upset pressure and upset time. If full factorial experiment is considered for above process, as the number of factors is five and the number of levels selected for each factor is three, the number of trials to be conducted is $3^5$. Whereas 27 trials are sufficient for finding out optimum weld parameters using orthogonal array system. $L_{27}$ table is selected for five factor at three level each. The columns of the table indicate the factors (i.e. rpm, friction pressure, friction time, upset pressure and upset time) and the rows of the table indicate trials (i.e. 1, 2, 3,.., 27) with a different combination of individual factors. During the initial designing stage orthogonal array
ensures the proper investigation of factors as well control of the factors which influence the quality of the product. In this way, orthogonal array assure the consistency of design carried out by different experiment. The result obtained by orthogonal array is analyzed to achieve the following objectives:

- To estimate the contribution of individual factor influencing the quality of the product in initial design phase itself.
- To predict, the response of the friction weld parameters under optimum condition.
- To achieve the optimum condition for the friction welding process so that the quality characteristics can be maintain.

2.13.5 STATISTICAL MODELING AND DATA ANALYSIS

A statistical model can be regarded as the realization of an underlying physical system, particularly the probabilistic mechanism that governs the system.

This model contains a deterministic component that describes the relationship between input i.e. friction welding parameters and output variables such as tensile strength, upset, weld interface temperature. Researchers can extract the information from the data by organizing it and by numerically calculating it for useful purpose.

Residual analysis is done to check the structure and to validate the model.
2.13.6 ANOVA

R. A. Fisher has developed a method, the Analysis of Variance or ANOVA. This is a statistical technique used for analyzing the data from the experiment. This technique uses the decomposition of variance in the experimental data into variance due to source identified through underlying model that is assumed (typically a linear and additive model). The analysis of variance table is constructed based on analysis of effects [a]. The various effects of factors and their interaction are then compared and tested against the residual error and are presented in the ANOVA table.

2.13.6.1 USE OF GRAPHS

Graphs are the effective way to present an immediate vivid perception of the information in the data. Some of the common types of graph used by statistical data analysis are as follow.

- **MAIN EFFECT PLOTS**

  The main effect plot is drawn by linking the average of observations at each level of a factor by a line. The change in the level is observed from shape of the line. Steep line is related to a significant one. The main effect plots of all factors are placed together in one graph for comparison of their relative magnitudes.
**INTERACTION PLOTS**

Interactions are effects that are definite on two or more factors. Interactions are defined as components wise product of the corresponding main effects. These plots are used to graphically show the joint effect. They reflect the joint effects of factors on response.

They display the average of observations at each level combination of the two factors and connect the averages by lines. Number of lines in the interaction plot is the same as number of levels in this factor. By comparing the shape of these lines, more insight into the interactions can be obtained. Lines of similar shape, indicates no interaction, while different ones indicates the existence of interaction.

**SCATTER PLOTS**

These plots are often seen in residual analysis. They are used to explore the relationship between two variables by representing each paired observation of these two variables as point in plane.

**2.13.7 RESIDUAL ANALYSIS**

It is the difference between the observed response and fitted response. Residual analysis is perform to detect problem in the data sheet or fitted model. If data have been collected on any variables that might possibly affect the response, residual should be plotted against these variables [94-98]. A visual check of scatter plots, such as residual against time index, residual against factors or residual against fitted response is performed by residual analysis. Residual
analysis answers the question such as if all the important effects are captured or if there exist extreme or unreasonable values in the data set.