CHAPTER-2

LITERATURE REVIEW

2.1 CUPRONICKEL (Cu-Ni) ALLOYS

Copper–nickel (Cu–Ni) alloys are widely accepted materials for application in marine and chemical environments for ship and boat hulls, desalination plants, heat exchange equipment, seawater and hydraulic pipelines, oil rigs and platforms, fish farming cages, seawater intake screens etc. because of their superior corrosion resistance [Agarwal D. C *et al.* (2009) and Aida Varea *et al.* (2012)]. However, this material also has been reported to have failed well before their expected lifetime (Agarwal D.C *et al.* 2002). Investigations had revealed that a majority of these failures occurred when the pipes in question were subjected to widely varying fluid flow rates and were exposed to polluted seawaters.

The two main Cupronickel alloys are 90/10 Cu-Ni (i.e 90% Cu & 10% Ni) and 70/30 Cu-Ni (i.e 70% Cu & 30% Ni) alloys.

2.1.1 PHASE DIAGRAM OF CUPRONICKEL (Cu-Ni) ALLOYS

The effect of Ni alloying on the phase stability of Cu in the Cu-Ni binary phase diagram (CDA Publication TN37, 1986) is shown in Fig.2.1. 90/10 and 70/30 Cu-Ni alloys are Face-Centered Cubic (FCC) structure. Fig: 2.1 shows that the increasing the Ni content from 0% to 100% substantially increases the melting temperature. The Cu-Ni binary phase diagram is isomorphous, which means that there is unlimited solid solubility of Cu dissolved in Ni or Ni dissolved in Cu. Because the Cu-Ni system is isomorphous, the melting temperature range, liquidus and solidus temperatures for 70/30 Cu-Ni alloy are greater than the melting range, liquidus and solidus temperatures for the 90/10 Cu-Ni alloy. Consequently, solidification of 70/30 Cu-Ni weld metal will passes through the mushy zone (liquidus to solidus) and form a single-phase face-centered-cubic dendritic structure in which the dendrite arms are rich in Ni and the interdendritic regions are rich in Cu. Such single-phase microstructures are highly susceptible to solidification cracking, liquidation cracking, and in particular ductility-dip cracking [CDA Publication/ NiDI, (1991), CDA Publication No 94(1992)].

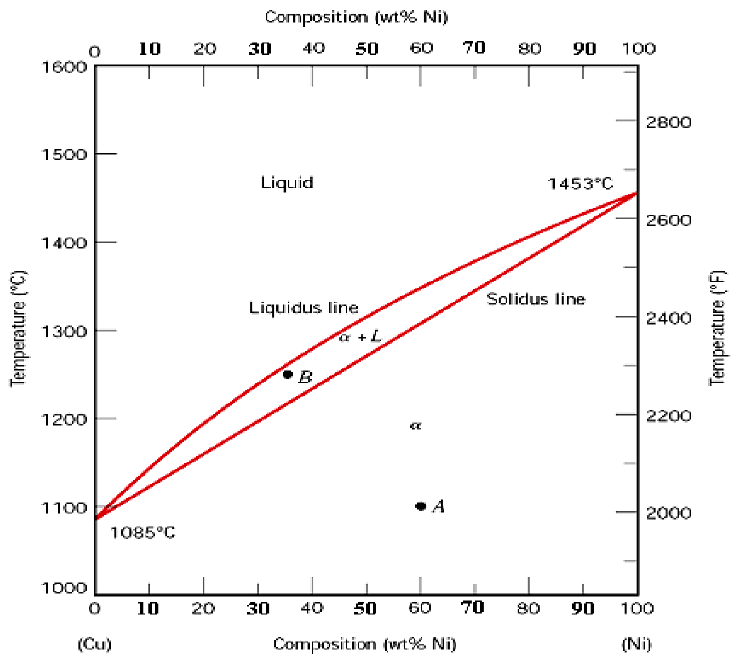

Fig: 2.1 Cu-Ni Binary Phase Diagram

The copper-nickel alloys are single phased throughout the full range of compositions and many standard alloys exist within this range, usually with small additions of other elements for special purposes. Manganese is invariably present in the commercial alloys as a deoxidant and desulphuriser, it improves working characteristics and additionally contributes to corrosion resistance in seawater.

Other elements which may be present singly or in combination are: Iron, added (up to about 2%) to the Cu-Ni alloys and confers resistance to impingement attack by flowing seawater. The initial development of the optimum compositions of the copper-nickel-iron alloys in the 1930s has been described by G. L. Bailey. This work was to meet naval requirements for improved corrosion-resistant materials for tubes, condensers and other applications involving contact with seawater.

Chromium can be used to replace some of the iron content and at one per cent or more provides higher strength.Niobium can be used as a hardening element in cast versions of both the 10% and 30% Nickel alloys (in place of chromium). It also improves weldability of the cast alloys.Silicon improves the casting characteristics of the Copper-Nickel alloys and is used in conjunction with either Chromium or Niobium. Tin confers an improved resistance to atmospheric tarnishing and is used in the electronics industry. It is not recommended for marine applications.Impurity elements such as lead, sulphur, carbon, phosphorus, etc. are the amounts to be found in commercial material have little or no effect on corrosion performance.

Complex castings of Cu-Ni alloys can be made by good foundry practice is provided. The 90/10 composition has a lower melting and pouring temperature than the 70/30 alloy [CDA Publication TN30 (1982), CDA Publication/ NiDI, (1991)].

Addition of proper rare earth (RE) elements obviously improves the mechanical properties of Cu-30Ni alloy, i.e., the tensile strength, yield strength, and elongation are increased. However, over added rare earth (RE) elements incline to deteriorate the microstructure and mechanical properties. Cu-30Ni alloy with 0.095 wt. % RE content attains preferable mechanical properties (MAO Xiangyang *et al.* 2009).

Earlier investigations reported on changes of microstructure and tensile strength in Cupronickel alloy(Cu-Ni25) material deformed at elevated temperatures between 450-675°C (Sakiewicz. P *et al.* 2011).

2.1.2 PHYSICAL PROPERTIES OF Cu-Ni ALLOYS

The Physical properties of wrought 90/10 & 70/30 Cu-Ni alloys are given in table 2.1.

Table 2.1 Physical properties of wrought 90/10 & 70/30 Cu-Ni alloys [ASM International (1985), Arthur H.Tuthill *et al.* (1987), CDA Publication TN31 (1982)]

Properties	90/10 Cu-Ni alloy	70/30 Cu-Ni alloy
Solidus Temperature	1099ºC (2010ºF)	1170ºC (2140ºF)
Liquidus Temperature	1170ºC (2140ºF)	1240ºC (2260ºF)
Thermal Conductivity	40 W/mºC	29 W/mºC
Coefficient of Thermal Expansion	17.1x10-6 per ºC	16.2x10-6 per ºC
Specific Heat	380 J/kg	380 J/kg
Electrical Resistivity	191 nΩ-m	375 nΩ-m

2.1.3 FABRICATION OF CUPRONICKEL ALLOYS

Hot and cold working techniques may be used for the forming of wrought materials to required shapes though cold working is normally to be preferred. Hot working temperature range for 90/10 and 70/30 are 800°C to 900 °C & 850°C to 950 °C respectively (CDA Publication TN30, 1982). Fusion boundary cracking of 90/10 Cu-Ni alloy plates depends on effects of purity of base metal , weld heat-input and weld metal composition(Norman Stephenson,NiDI,1991). Hereafter, 90/10 Cu-Ni alloy and 70/10 Cu-Ni alloy termed as 90/10 alloy and 70/30 alloy respectively.

2.1.4 RESISTANCE TO CORROSION AND BIOFOULING OF CUPRONICKEL ALLOYS

The 90/10 and 70/30 alloys have good resistance to seawater corrosion and biofouling. For instance, the corrosion resistance of the 90/10 and 70/30 alloys in heat exchangers and condensers are compared to the relative resistance of various alloys to fouling in quiet seawater. If water velocity is accelerated above 1 m/sec, any slight biofouling on metal with good fouling resistance will be easily detached and swept away. On a material that does not have this good fouling resistance, strongly adherent, marine organisms would continue to thrive and multiply.90/10 alloy has the better biofouling resistance.

The corrosion resistance of 70/30 and 90/10 copper nickel alloys and their suitability for many applications can be seen. Some materials with apparently better corrosion resistance may have disadvantages such as lack of resistance to biofouling, lack of availability in the forms required or susceptibility to crevice corrosion. They may also be more expensive and therefore less cost-effective over the required service lifetime. Copper-Nickel alloys do not suffer the stress-corrosion problems associated with some other materials [CDA Publication TN30 (1982), CDA Publication/ NiDI, (1991), Maruthamuthu. S *et al.* (2009)].

The use of Copper-Nickel cladding for ships hulls also demonstrates the value of the material's combined attributes of resistance to corrosion and to marine biofouling (CDA Publication, 1986).

Copper-Nickel alloys for marine use were developed for naval applications with a view to improving the corrosion resistance of condenser tubes and seawater piping. 90/10 and 70/30 alloys are differ in strength and corrosion resistance but 90/10 alloy in extensively used because of economic consideration. In recent years, this has led to sheathing developments particularly for structures and boat hulls (CDA Publication, 1986).

2.1.5 APPLICATIONS OF CUPRONICKEL ALLOYS [CDA Publication TN30 (1982), TN31 (1982) and CDA Publication/ NiDI (1991)]

Some of the applications of 90/10 Cu-Ni & 70/30 Cu-Ni alloys are:

a) Pipelines for handling seawater.
b) Condenser and heat exchanger tubing
c) Seawater intake in marine or land-based
d) Boat and ship hulls
e) Offshore structures - Oil drilling platforms etc.
f) Hydraulic brake tubing for vehicles
g) Hydraulic and instrumentation tubing for marine and offshore use
h) Gas pipelines
i) 90-10 Copper-nickel sheets were cladded on the ‘ARC0 Texas’ oil

tanker as a means to evaluate their effectiveness in corrosion protection and reduced biofouling.

2.2 GAS TUNGSTEN ARC WELDING TECHNIQUES

Automatic AC GTA welding machine having pulsed current (PC) and continuous current (CC) mode using square waveform in the presence of argon as shielding gas is shown in Fig: 2.2 a-b.

2.2.1 CONTINUOUS CURRENT GAS TUNGSTEN ARC WELDING (CC GTAW)

Fusion welding generally involves joining of metals by application of heat for melting of metals to be joined. Almost all the CC GTAW processes offers high heat energy required to melt the base material is supplied only during peak currents, which in turn leads to various problems such as burn-through or melt-through, distortion, porosity, buckling, warping & twisting of welded sheets, grain coarsening, evaporation of useful elements present in coating of the sheets, joint gap variation during welding, fume generation from the coated sheets etc. [Praveen P *et al.* (2005) and Ueyama T *et al.* (2005)]

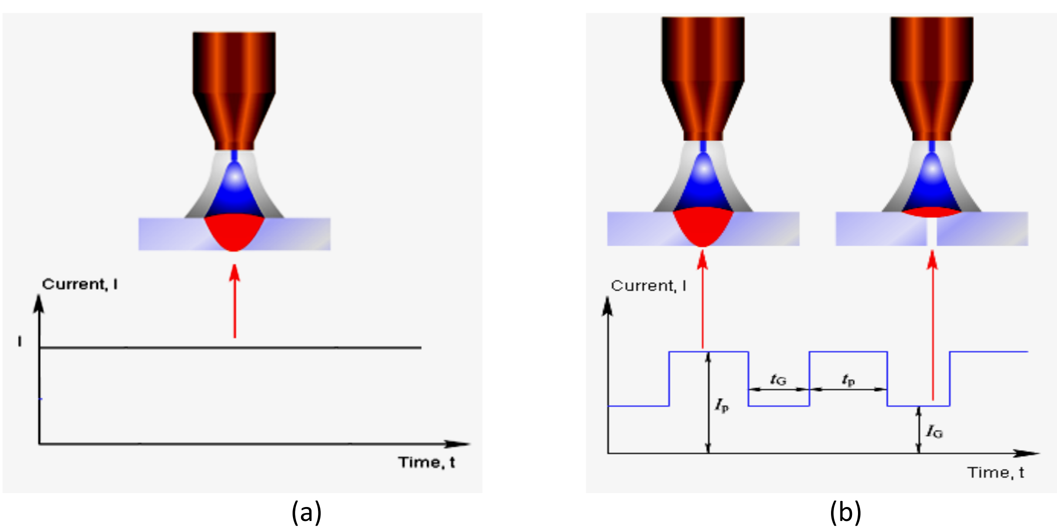

Fig: 2.2 Schematic diagram of (a) CC GTAW (b) PC GTAW

I_{G} = Base or Background Current
I_{P} = Peak Current
t_{G} = Base or Background Time
t_{P} = Peak Time
Frequency = $1 / (t_{G} + t_{P})$
Average Current (I_{avg}) = $(I_P\, t_P + I_G\, t_G) / (t_G + t_P)$

2.2.2 PULSED CURRENT GAS TUNGSTEN ARC WELDING (PC GTAW)

PC GTAW is a variation of Tungsten Inert Gas (TIG) welding which involves cycling of the welding current from a high level to a low level at a selected regular frequency shown in Fig:2.2b (ASM International, 1993). The high level of the peak current is generally selected to give adequate penetration and bead contour, while the low level of the base or background current is set at a level sufficient to maintain a stable arc. This permits arc energy to be used efficiently to fuse a spot of controlled dimensions in a short time producing the weld as a series of overlapping nuggets and limits the wastage of heat by conduction into the adjacent parent material than CC GTAW.

2.2.3 EFFECT OF CC GTAW and PC GTAW

Presently, welding of 90/10 and 70/30 Cu-Ni alloys in ship building industries can be performed adequately only by GTAW which uses ER Cu-Ni 70/30 filler wire.

Gutierrez S.H (1991) conducted a detailed study on Continuous Current Gas Tungsten Arc Welding (CC GTAW) of 70º-80º single V butt Cu-Ni alloys welds results excessive grain size in Fusion Zone (FZ) and Heat Affected Zone (HAZ). This large grain size tends to promote ductility-dip cracking, distortion, hot cracking sensitivity, increase in width of HAZ and residual stresses. Because of the above mentioned problems CC GTAW of Cupronickel alloy welds exhibits inferior mechanical properties.

Earlier many investigations reported on CC GTAW and PC GTAW on other than Cu-Ni alloys such as aluminum alloys, mild steel, stainless steel, titanium alloys and magnesium alloys.

CC GTAW joints had exhibited crack formation, a wide HAZ, porosity, distortion in thin sections, and coarse columnar grain in FZ because of the prevailing thermal conditions during weld metal solidification which often results in the inferior weld mechanical properties and poor resistance to hot cracking were explained [Kou S *et al.* (1986), Sundaresan S *et al.* (1999), KEAR. G *et al.* (2004), Balasubramanian V *et al.* (2008), Rajesh Manti *et al.* (2008), Kumar A *et al.* (2009), Jun Shen *et al.* (2012), and Sundaresan S *et al.* (1999)].

By using PC GTAW joints exhibited fine and more equi-axed grain structures at FZ instead of coarse grains reduced width of the heat affected zone, reduction in grain size leads to improved hardness, control of segregation, reduction in ductility and also exhibited superior mechanical properties and good corrosion resistance than the CC GTAW welds [Kou S *et al.* (1986), Madhusudhan Reddy G *et al.* (1997),Madhusudhan Reddy G *et al.* (1998), Sundaresan S *et al.* (1999), Kishore Babu N *et al.* (2007), Rajesh Manti *et al.* (2008) and Kumar.A *et al.* (2009)].

However, no thorough study has been reported so far on CC GTAW & PC GTAW of 90/10 & 70/30 Cupronickel alloys.

2.3 OPTIMIZATION OF PULSED CURRENT GAS TUNGSTEN ARC WELDING (PC GTAW) PROCESS PARAMETERS BY TAGUCHI METHOD

A scientific approach to plan the experiments is a necessity for efficient conduct of experiments. By the statistical design of experiments, the process of planning the experiment is carried out, so that appropriate data will be collected and analysed by statistical methods resulting in valid and objective conclusions. When the problem involves data that subjects to experimental error, statistical methodology is the only objective approach to analysis. Thus, there are two aspects of an experimental problem: design of the experiment and statistical analysis of the data. These two points are closely related since the method of analysis depends directly on the design of experiments employed. The advantages of design of experiments are as follows:

- Number of trials is significantly reduced.
- Important decision variables which control and improve the performance of the product or the process can be identified.
- Optimal setting of the parameters can be found out.
- Qualitative estimation of parameters can be made.
- Experimental error can be estimated.
- Inference regarding the effect of parameters on the characteristics of the process can be made.

In the present work, the Taguchi method was used to plan the experiments and subsequent analysis was done on the data collected.

2.3.1 TAGUCHI EXPERIMENTAL DESIGN AND ANALYSIS

Dr. Genichi Taguchi's comprehensive system of quality engineering is one of the greatest engineering achievements of the 20Th century. Taguchi methods focus on the effective application of engineering strategies rather than advanced statistical techniques. It includes both upstream and shop-floor quality engineering. Upstream methods efficiently use small-scale experiments to reduce variability and remain cost-effective, and robust designs for large-scale production and market place. Shop-floor techniques provide cost-based, real time methods for monitoring and maintaining quality in production. The better upstream a quality method applied, the greater leverages it produces on the improvement, and the more it reduces the cost and time. Taguchi's philosophy is founded on the following three very simple and fundamental concepts [Ross, P.J (1988), Roy R.K (1990), Ross, P.J (1996), Ross P. J (1996)].

- Quality should be designed into the product and not inspected into it.
- Quality is best achieved by minimizing the deviations from the target. The product or process should be so designed that it is immune to

uncontrollable environmental variables.

- The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

Taguchi proposes an “off-line” strategy for quality improvement as an alternative to an attempt to inspect quality into a product on the production line. He observes that poor quality cannot be improved by the process of inspection, screening and salvaging. No amount of inspection can put quality back into the product.

Taguchi recommends a three-stage process:

a) **System design:** This phase deals with innovative research. Here, one looks for what each factor and its level should be rather than how to combine many factors to obtain the best result in the selected domain (Park C. K et al. 2005).

b) **Parameter design**: The purpose of parameter design is to investigate the overall variation caused by inner and outer noise when the levels of the control factors are allowed to vary widely. Quality improvement is achievable without incurring much additional cost. This strategy is obviously well suited to the production floor [Park C. K *et al.* (2005)**,** Tzeng Yih-fong *et al.* (2006)**].**

c) **Tolerance design:** This phase must be preceded by parameter design activities. This is used to determine the best tolerances for the parameters (Park C. K *et al.* 2005).

2.3.2 TAGUCHI METHODOLOGY

Taguchi methodology for optimisation can be divided into four phases: planning, conducting, analysis and validation. Each phase has a separate objective and contributes towards the overall optimisation process. The Taguchi method for optimisation can be presented in the form of a flowchart, as shown in Fig: 2.3 **[**Khosla A *et al.* (1994), Roy R. K (2001)]:

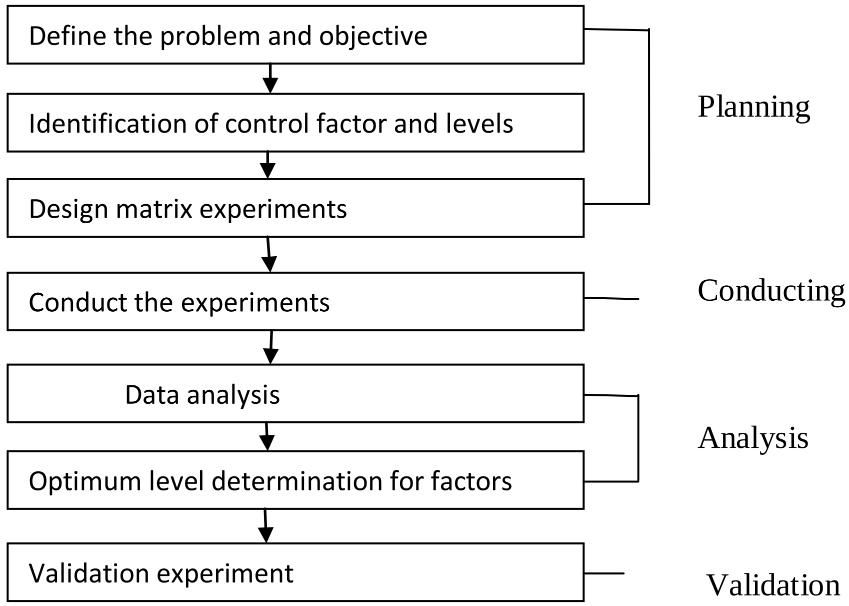

Fig: 2.3 A flowchart of Taguchi method for optimisation

The primary goal is to keep the variance in the output very low, even in the presence of noise inputs. Thus, the processes/products are made robust against all variations.

2.3.3 IDENTIFICATION OF PROCESS PARAMETERS

The parameters that identify the output response, before conducting the experiment are as follows:

1. Peak current (Amps)
2. Base current (Amps)
3. Pulse frequency (Hz)
4. Welding speed (mm/min)

2.3.4 NUMBER OF LEVELS DECIDED

After deciding the process parameters, the number of levels for each variable was decided. The selection of number of levels depends on the trend in which the parameter influences the output response.

2.3.5 LEVEL SETTINGS

In this investigation, four levels for each process parameter are considered. Table 2.2 shows the control factors and levels.Two major tools used in the Taguchi method are the orthogonal array (OA) and the signal to noise ratio (S/N ratio).

Table 2.2 Typical L16 orthogonal array for 4 levels of each 4 factors

No. of experiments	Factor 1	Factor 2	Factor 3	Factor 4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	2	1	2	3
6	2	2	1	4
7	2	3	4	1
8	2	4	3	2
9	3	1	3	4
10	3	2	4	3
11	3	3	1	2
12	3	4	2	1
13	4	1	4	2
14	4	2	3	1
15	4	3	2	4
16	4	4	1	3

2.3.6 SELECTION OF ORTHOGONAL ARRAY

In this study, full factorial experimentation with 4 factors and 4 levels for each factor would require $(\text{level})^{\text{parameter}}$ i.e $4^4 = 256$ number of experiments. But on applying L16 orthogonal arrays, only 4 columns and 16 rows are required i.e. result is obtained with 16 experiments. Those arrays have sufficient degrees of freedom to handle four-level process parameters. Sixteen four-level (L16) experiments were required to study the PCGTAW parameters using Dr. Taguchi's L16 orthogonal array. "Minitab" software was used for designing the matrices for each experiment in random order. And hence maximum information was extracted from minimum number of experiments.

2.3.7 S/N RATIOS AND MSD ANALYSIS

Taguchi recommends the use of signal to noise ratio (S/N) as it opposes simple process optimizing process parameters. The rationale is that while there is a need to maximize the mean (signal) in the sense of its proximity to nominal value, it is also desirable to minimize the process variations (noise). The use of S/N accomplishes both objectives simultaneously (Kumar A *et al.* (1996).

The S/N ratio is expressed in decibels (dB). Conceptually, the S/N ratio (η) is the ratio of signal to noise in terms of power. In other words, it represents the ratio of sensitivity to variability **[**Raymond H. M *et al.* (1992)**,** Taguchi G *et al.* (2005)**].** Higher the S/N ratio, better is the quality of product. The idea is to maximize the S/N ratio, thereby minimising the effect of random noise factors, which have significant impact on the process performance **[**Palanikumar K (2006), Zeydan M (2008)**].**

In order to evaluate the influence of each selected factor on the responses, the S/N ratio for each control factor should be calculated. The signals indicated that the effect on the average responses and the noise were measured by the influence on the deviations from the average responses, which would indicate the sensitiveness of the experiment output to the noise factors.

The appropriate S/N ratio must be chosen using previous knowledge, expertise, and understanding of the process. When the target is fixed and S/N ratio is trivial or absent signal factor (static design), it is possible to choose the S/N ratio depending on the goal of the design (Phadke M.C, 1989). S/N ratio selection is based on Mean Squared Deviation (MSD) for analysing repeated results. MSD expression combines variation around the given target and is consistent with Taguchi's quality objective (Anawa E. M et *al.* 2008). The relationships among observed results of MSD and S/N ratios are as follows (Eq. 2.1 to 2.4) [Ross P. J, (1996), Roy R. K (2001) , Taguchi G *et al.* (1987)].

$$MSD = ((Y_1-\bar{Y})^2 + (Y_2-\bar{Y})^2+\ldots\ldots\ldots (Y_n-\bar{Y})^2) / n \quad \text{... For nominal is better} \quad \text{... (2.1)}$$

$$MSD = (Y_1^2 + Y_2^2 +\ldots\ldots\ldots+ Y_n^2) / n \quad \text{... For smaller is better} \quad \text{... (2.2)}$$

$$MSD = ((1/Y_1^2) + (1/Y_2^2) +\ldots\ldots\ldots+ (1/Y_n^2)) / n \quad \text{... For larger is better} \quad \text{... (2.3)}$$

$$S/N = - 10 \text{ Log (MSD)} \quad \text{... For all characteristic} \quad \text{...(2.4)}$$

Taguchi defines three categories of quality characteristics in the analysis of S/N ratio, i.e. the lower-is-best, the larger-is-best and the nominal-is-best. In this study, the S/N ratio was chosen according to the criterion of the larger-the-better, in order to maximize the response. The S/N ratio for each process parameter was computed based on S/N analysis (Eq.2.3). Regardless of the category of the quality characteristics, larger S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of process parameter is the level of highest S/N ratio.

2.3.8 OPTIMISATION

The optimal values for these experimental factors are to be determined. Optimal factor values depend on the process objective. The optimisation methods available in “MiniTAB” Statistical software Release 15 used, include general full factorial designs (designs with more than two-levels), and Taguchi designs.

2.3.9 FINDING THE OPTIMAL SET

Based on the response values found from the specific experiments defined by the orthogonal array, an optimal solution can be obtained. This is done using the factor plots in the Taguchi DOE approach.

Factor plots show data points of response versus level of each factor in the optimisation search space. The responses corresponding to one level of a factor are taken average. The average responses of all factor levels are used in factor plots. From these plots, the set of levels of each factor that gives optimal solution can be found. This is explained further with an example in Chapter 5.

There are a number of underlying assumptions and checks associated with the Taguchi method. The comparison of average responses in factor plots is based on the assumption that no significant interactions exist between factors. This assumption stems from the definition of orthogonality and mainly ensures that the effect of one factor level on the response is minimally dependent on the level of other factors. The validity of the interaction assumption can be checked using interaction plots which also employ the average response of factor levels.

It is important to note that using physical experiments, DOE method accounts for noise factors. In this work, computer experiments were used, hence the response value for a given input set was considered free of noise since repeated tests were identical.

2.3.10 THE PREDICTIVE EQUATION

As explained previously, the Taguchi approach provides optimal set of factor levels. The response of a combination of factor levels need not be the original set of orthogonal array. This can be determined by means of a predictive equation using the average response of all experiments in the array and the average of individual factor levels. The equation is given by

$\bar{Y}_{predicated} = \bar{Y}exp + (\bar{Y}_{PC} - \bar{Y}exp) + (\bar{Y}_{BC} - \bar{Y}exp) + (\bar{Y}_{PF} - \bar{Y}exp) + (\bar{Y}_{WS} - \bar{Y}exp)$ ………..…. (2.5)

where $\bar{Y}_{predicated}$ is the predicted response; $\bar{Y}exp$ represents the total average response of experiments in the array, and $\bar{Y}_{PC}$, $\bar{Y}_{BC}$, $\bar{Y}_{PF}$, $\bar{Y}_{WS}$ are the average responses for a level of significant factors PC, BC, PF, WS respectively.

A necessary condition for the predictive equation is additivity. The predicted value of the response calculated by equation (2.5) needs to be compared to the response obtained from actual experiment. According to Sen and Yang **(**Sen P *et al.* 1998)**,** if the differences between predicted and actual responses lie within 10%, then the condition of additivity is valid and the assumption of insignificant interaction between different factors is maintained. From significant factor interactions, multiplicative terms should be added to the equation.

2.3.11 ANALYSIS OF VARIANCE (ANOVA)

It is often useful to know which factors in a given set of experiments have more effect on the overall response or on the performance of a system. The analysis of variance (ANOVA) provides adequate criteria to quantitatively assess the effect of different factors.

Table 2.3 is a sample of the ANOVA Table used for analysis. Correction factor, Total sum of squares ,Sum of squares on each factor, mean square errors and percent contribution of each factor on the overall response are calculated using Eq. 2.6 to 2.16 **[**Sugiono *et al.* (2012), Yash Mehta (2012)**].**

Correction factor (CF) = T^2 / N……………………………………………………. (2.6)

where T is the sum of observations

N is the number of experiments

The total sum of squares uses the sum of deviations in the orthogonal array from the total mean of the array and is calculated as

Total sum of squares $SS_T = \sum_{i=1}^{N} Y_i^2 - CF$ ………………………………………….... (2.7)

where N is the total number of experiments (=16), Y_i is the mean response of the i^{th} row in the orthogonal array (i.e. mean response of an experiment); CF is correction factor (i.e T^2/N)

Similarly, the sum of squares of each factor is calculated. This calculation for Peak Current (PC) is given in equation (2.8) as

$SS_{PC}=[\sum (PC_{L1})^2/n_{PCL1} + \sum (PC_{L2})^2/n_{PCL2} + \sum (PC_{L3})^2/n_{PCL3} + \sum (PC_{L4})^2/n_{PCL4}] - CF$……………………………………………………………………………….(2.8)

where PC_{L1} is the mean response of factor PC for a given level L1, n_{PCL1} is the number of experiments for each level of factor PC (=4) , CF is correction factor (i.e T^2/N)

Degree of freedom of factor PC (DF_{PC}) = number of levels of factor PC -1………..…(2.9)

Total Degree of freedom (DF_T) = Total number of experiments (N) – 1…………… (2.10)

Degree of freedom error (DF_E) = $DF_T - (DF_{PC} + DF_{BC} + DF_{PF} + DF_{WS})$……………...(2.11)

Sum of squares error (SS_E) = $SS_T - (SS_{PC} + SS_{BC} + SS_{PF} + SS_{WS})$…………………….(2.12)

Mean square of factor PC (MS_{PC}) = SS_{PC} / DF_{PC}……………………………………(2.13)

Mean square error (MS_E) = SS_E / DF_E …………………………………………… (2.14)

F ratio of factor PC (F_{PC}) = MS_{PC}/ MS_E …………………………………………… (2.15)

The percent contribution of each factor on the overall response is determined by the ratio of the individual sum of squares of a factor to the total sum of squares as given by equation (2.16) for factor PC as

% contribution of factor PC = $(SS_{PC} / SS_T) \times 100$ ………………………………… (2.16)

Greater the effect of a factor, higher is its contribution. By studying the contributions, the experimental space can be refined by eliminating factors with relatively low contributions and by placing more emphasis on significant factors in subsequent investigations.

Table 2.3 Analysis of Variance (ANOVA)

Source	Degree of freedom (DF)	Sum of squares (SS)	Mean Square (MS)	F-Test (F)	% of contribution
PC	DF_{PC}	SS_P	SS_{PC} / DF_{PC}	MS_{PC}/ MS_E	(SS_{PC} / SS_T) x 100
BC	DF_{BC}	SS_B	SS_{BC} / DF_{BC}	MS_{BC}/ MS_E	(SS_{BC} / SS_T) x 100
PF	DF_{PF}	SS_P	SS_{PF} / DF_{PF}	MS_{PF}/ MS_E	(SS_{PF} / SS_T) x 100
WS	DF_{WS}	SS	SS_{WS} / DF_{WS}	MS_{WS}/MS_E	(SS_{WS} / SS_T) x 100
Residual	DF_E	SS_E	SS_E / DF_E		
Total	DF_T	SS_T	SS_T / DF_T		

2.3.12 VERIFICATION

The final step is to predict and verify the improvement of the response using the optimal level of the welding process parameters. In addition, to verify the satisfactoriness of the developed models, minimum three confirmation experiments were carried out using new test conditions at optimal parameters conditions, obtained using the Design Expert software (MiniTAB).

Earlier reports explained on the optimisation of PC GTAW process parameters on other welds such as aluminum alloys, titanium alloys and magnesium alloys by Taguchi technique for predicted optimum tensile strength of welds [Balasubramanian M *et al.* (2008), Balasubramanian M *et al.* (2009), Kumar A *et al.* (2009)], in the present investigation an attempt has been made to determine the optimum levels of PC GTAW process parameter through the Taguchi parametric design approach. The results indicate that the PC, BC, PF & WS are the significant parameters in deciding the tensile strength of Cu-Ni alloy welds.

Many research papers reported on the application of Taguchi design in the PC GTAW of different materials. However, no research has been conducted on Cupronickel alloys and PC GTAW parameters using Taguchi design.

Earlier reports explained on the optimisation of LBW process parameters on other than Cu-Ni alloys such as aluminum alloys (Bappa Acherjee *et al.* 2011), FSW process parameters (Elangovan. K *et al.* 2008) and turning cutting machine process parameters (Jitendra Verma *et al.* 2012) by Taguchi method.

In the present work Taguchi's parameter design approach was used to study the effect of PC GTAW process parameters on the various responses of 90/10 Cu-Ni alloy welds.

2.4 INFLUENCE OF PULSED CURRENT GAS TUNGSTEN ARC WELDING (PC GTAW) PROCESS PARAMETERS ON MECHANICAL PROPERTIES AND MICROSTRUCTURES OF 90/10 AND 70/30 Cu-Ni ALLOY WELDS

Ishikawa diagram (cause and effect diagram) **(**Factory Management and the Asian Productivity Organisation, 1982) was constructed as shown in Fig: 2.4 to identify the PCGTAW process parameters that influence the quality of welds. The process parameters namely pulse frequency, peak current, base current and welding speed play a major role in deciding the weld quality.

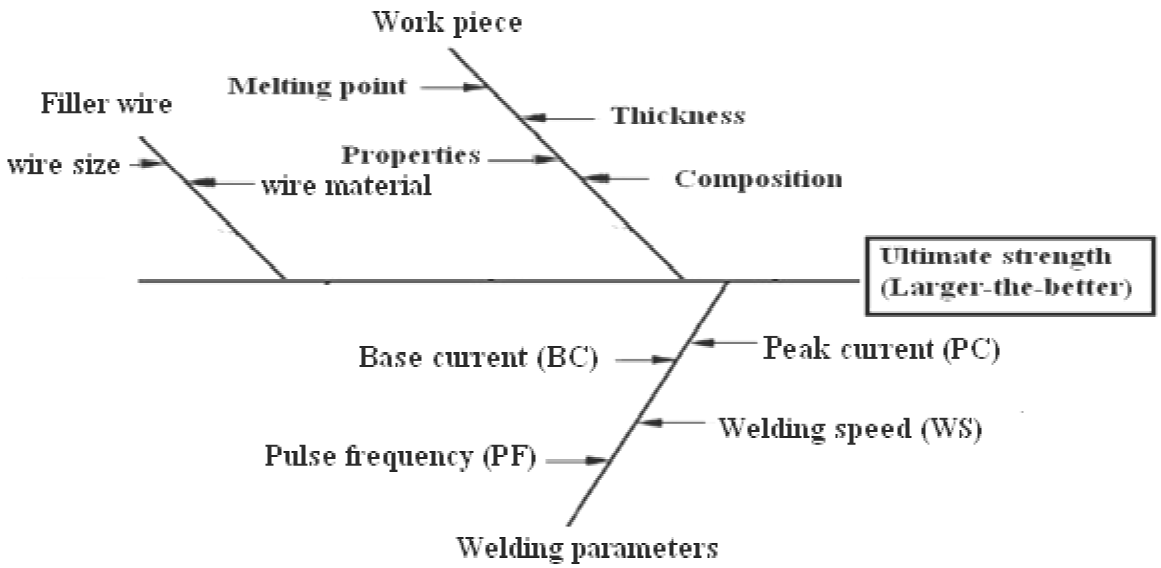

Fig: 2.4 Ishikawa Cause and Effect Diagram for PCGTAW process

Heat input is a very important factor which affects the bead geometry, mechanical properties and metallurgical properties of weld. Hence, heat input was also calculated and included in the study. The heat input per unit length is proportional to voltage and current and inversely proportional to the welding speed. In CCGTAW process, heat input was calculated from the continuous current, whereas in PC GTAW process, the heat input was calculated from the mean current (Im). The equation for the mean current is given as (Cornu J, 1988).

:

$$Im = \frac{Ip \times Tp + Ib \times Tb}{Tp + Tb} \qquad \text{.......(2.17)}$$

Heat input (HI) is calculated using Eq. 2.18 (J. Cornu, 1988):

$$HI = (Im \times V \times \eta) / S \qquad \text{.......(2.18)}$$

where

Ip = Pulse current, Amps

Ib = Base current, Amps

Tb = Base current duration, milli seconds

Tp = pulse current duration, milli seconds

S = welding speed, mm/s

V = mean voltage, V

η = efficiency of the welding process.

For PC GTAW process, arc efficiency was taken as 60 % **(**Cornu J, 1988)**.** During the experiment, voltage was found to vary from 17 V to 19 V. Hence, a mean voltage of 18 V was taken for the heat input calculation. A constant optimum welding speed of 2.5 mm/s was used for the welding parameters namely PC, BC & PF.

Earlier reports explained on the influence of PC GTAW process parameters on mechanical properties and microstructures of welds other than Cupronickel (Cu-Ni) alloy welds such as aluminum alloys (Padmanaban G *et al.* 2011), in the present investigation an attempt has been made on influence of PC GTAW process parameters on mechanical properties and microstructures of 90/10 & 70/30 Cu-Ni alloy.

2.5 EFFECT OF LASER BEAM WELDING (LBW)

Laser beam welding is a high energy density welding process. The term LASER stands for Light Amplification by Stimulated Emission of Radiation. The light beam has one wavelength and is in–phase which could be considered, as a unique source of thermal energy, precisely controllable in intensity and position for metal joining. For welding, the laser beam must be focused to a small spot size to produce a high-power density. This controlled power density melts the metal.

A laser beam is commonly produced by one of three types of laser, which are: Ruby laser, Nd-YAG laser and CO2 (Carbon Dioxide) laser. CO_2 laser beam welding with a continuous wave is a high energy density and low heat input process. The result of this is a small heat-affected zone (HAZ), which cools very rapidly with very little distortion, and a high depth-to-width ratio for the fusion zone [Anawa E. M *et al.* (2008)].

Earlier reports explained on the effect of CO_2 Laser beam welding processing parameters namely laser power and welding speed on mechanical properties other than Cupronickel (Cu-Ni) alloy welds such as magnesium alloys, titanium alloys, stainless steel alloy, aluminum alloys, nickel alloys and, dissimilar metals of Cu and Ni welds. It was reported an improvement in mechanical properties & microstructures by using different laser welding speeds [Madhusudhan Reddy G *et al.* (1997), Jae-Do Kim *et al.* (1998), Tzeng Y.F *et al.* (2000), Gandham Phanikumar *et al.* (2004), Phanikumar G *et al.* (2005), El-Batahgy A *et al.* (2009), Lakshminarayanan A. K *et al.* (2009), Myung Kyun Park *et al.* (2009), Jong-Do Kim *et al.* (2010), Reed C.B *et al.* (2000), Marya M *et al.* (2001), Kabir A.S.H *et al.* (2010), Sindhu R A *et al.* (2010), Daxin Ren *et al.* (2011), Hui-Chi Chen *et al.* (2011), Paulraj Sathiya *et al.* (2011), Seyed Mahdi Hamidinejad *et al.* (20120, Mohammad M. Hailat *et al.* (2012) and Santillan Esquivel A *et al.* (2012)]

There was no evidence observed from the earlier investigations on the use of LBW for joining Cupronickel (Cu-Ni) alloys.

2.6 PITTING CORROSION

Corrosion is the gradual destruction of material, usually metals, by chemical reaction with its environment. This means electrochemical oxidation of metals in reaction with an oxidant such as oxygen. Rusting, the formation of iron oxides, is a well-known example of electrochemical corrosion. This type of damage typically produces oxide(s) or salt(s) of the original metal.

Pitting corrosion, or pitting, is a form of extremely localised corrosion that leads to the creation of small holes in the metal. Under certain specific conditions, particularly involving chlorides (such as sodium chloride in sea water) small pits can be formed on the surface of the metal.

Potentiostat software based Gill AC electrochemical system (Fig. 4.15) was used to make potentiodynamic polarisation tests to study the pitting corrosion behavior of the BM, CC GTAW, PC GTAW & LBW of both the 90/10 and 70/30 Cu-Ni alloy welds.

Specimens exhibiting relatively more positive corrosion potential Ecorr (or less negative potentials) were considered to have better pitting corrosion resistance (Venugopal A *et al.* 2012).

Earlier reports explain on pitting corrosion behavior on Base Metal of Cupronickel alloys and report that Cu-Ni alloys are good corrosion resistance material [Gilbert, P (1982), El Domiaty A *et al.* (1997), Mathiyarasu J *et al.* (1999) & (2001), Waheed A. Badawy *et al.* (2005), Agarwal D.C *et al.* (2009), LIN LeYun *et al.* (2009), Aida Varea *et al.* (2012)]. However, this material also was reported to have failed well before their expected lifetime (Agarwal D.C *et al.* (2002). Investigations had revealed that a majority of these failures occurred when the pipes in question were subjected to widely varying fluid flow rates and were exposed to polluted seawaters.

Earlier investigations reported, on pitting corrosion behavior of PC GTAW, & LBW of titanium and aluminum alloy welds, a fine and more equi-axed grain structure at FZ of welds and showed an increase in pitting corrosion resistance [Senthil kumar T *et al.* (2007), Venugopal A *et al.* (2012)].

There was no evidence observed on pitting corrosion behavior of PC GTAW & LBW of Cupronickel alloys (Cu-Ni) welds.