

Application of Six Sigma for reduction of “Lack of Fusion” defects in GTAW of nuclear piping installation

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Abstract

Six Sigma is a disciplined data-driven approach for defect reduction through reduction of variation in processes. This paper deals with the application of the Six Sigma methodology in reducing defects in the GTAW process of a nuclear research organization in India. Objective of the study was to explore the possibility of applying Six Sigma in a non-continuous and non-repetitive process like GTAW of ss pipes. DMAIC (Define-Measure-Analyse-Improve-Control) approach has been used to solve the problem of high level of “Lack of Fusion” defect rates. The findings of the study highlight variation in welders’ skill as the root cause for “Lack of Fusion” defects. This research is the first of its kind in implementing Six sigma in GTAW process. Need for ensuring robust weld quality for nuclear safety and the challenge of using the right approach and statistical tools provided the motivation for this study.

Key words: Six Sigma, DMAIC, DPMO, GTAW, Weld Defects, Lack of Fusion, IGCAR. Pareto Chart

I. INTRODUCTION

A. Six Sigma

Six Sigma is a business improvement approach that seeks to find and eliminate causes of defects in business processes by focusing on process outputs that are of critical importance to customers (1). Six Sigma is a powerful breakthrough business improvement strategy that enables companies to use simple and powerful statistical methods for achieving and sustaining operational excellence (2). Objective of Six Sigma is to reduce process variation so that it will result in no more than 3.4 defects per million opportunities (DPMO).

Six Sigma was first developed at Motorola in the early 80s and has since been used beneficially in numerous organizations having repetitive and continuous manufacturing

processes. However, little research has been done in applying Six Sigma comprehensively in a welding process.

Six Sigma uses DMAIC (Define-Measure-Analyse-Improve-Control) methodology for improving existing processes and DMADV approach for designing new processes. This research uses DMAIC methodology for implementing Six Sigma in the GTAW process to reduce “Lack of Fusion” defects.

A1. Five phases of DMAIC methodology:

- **DEFINE** the process and the CTQ issues (Ys) involved.
- **MEASURE** the performance of the processes involved.
- **ANALYSE** the Process Map and data collected to determine the root causes of defects (Vital few Xs)
- **IMPROVE** the target process by designing creative solutions to fix and prevent problems.
- **CONTROL** the improvements to keep the process on the new course

B. IGCAR

Indira Gandhi Centre for Atomic Research [IGCAR], the second largest establishment of the **Department of Atomic Energy** next to Bhabha Atomic Research Centre, was set up at **Kalpakkam**, 80 KMs south of Chennai [MADRAS], in 1971 with the main objective of conducting broad based multidisciplinary program of scientific research and advanced Engineering, directed towards the development of sodium cooled Fast Breeder Reactor [FBR] technology, in India.

This study was carried out at one of their demonstration nuclear plant involving 62 kilometers of stainless steel (ASTM A312 TP 304L) web of nuclear piping welded by GTAW (Gas Tungsten Arc Welding) which will carry highly corrosive nuclear fluid. This paper is the first in the series of studies carried out focusing on “Lack of Fusion” defects.

B.1 GTAW

Gas tungsten arc welding (GTAW), also known as **Tungsten Inert Gas (TIG) welding**, is an arc welding process that uses a non-consumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by an inert shielding gas (argon or helium), and a filler metal is normally used. A constant-current welding power supply produces electrical energy.(4)

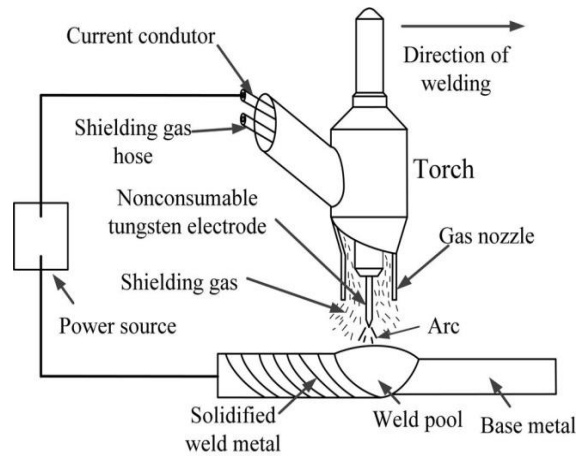


Fig.1 GTAW process setting

GTAW produces exceptionally clean, high quality welds and is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys. The process grants the operator greater control over the weld than competing processes such as shielded metal arc welding(SMAW) and gas metal arc welding(GMAW), allowing for stronger, higher quality welds. However, GTAW is comparatively more complex and difficult to master as it calls for greater skill on the part of the welder, and furthermore, it is significantly slower than most other welding techniques. It is widely used for high quality joints in the nuclear, chemical, aircraft and food industries. In the nuclear piping facility under study, because of the dense web of pipes spanning over an altitude of 10.5 meters and the resulting congestion and abnormal positioning of the welder, call for ambidexterity on the part of the welder.

B.2 Lack of Fusion

Lack of Fusion is a condition where the weld filler metal does not properly fuse with the base metal. This considerably weakens the strength of the weld. IT usually appears in the radiograph as a dark line or lines oriented in the direction of the weld seam along the weld preparation or joining area (Fig.2)

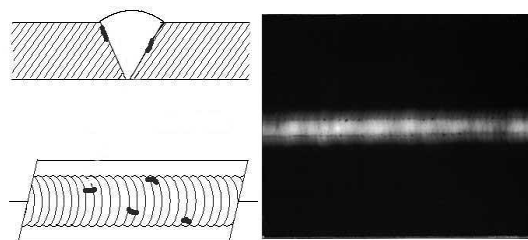


Fig.2 Lack of Fusion - Sketch & Radiography

II. APPLICATION OF SIX SIGMA

A. DEFINE

The process of fabrication of the piping installation was studied and the boundaries of the process under study were established and a high level process map was made as depicted in Fig.3.

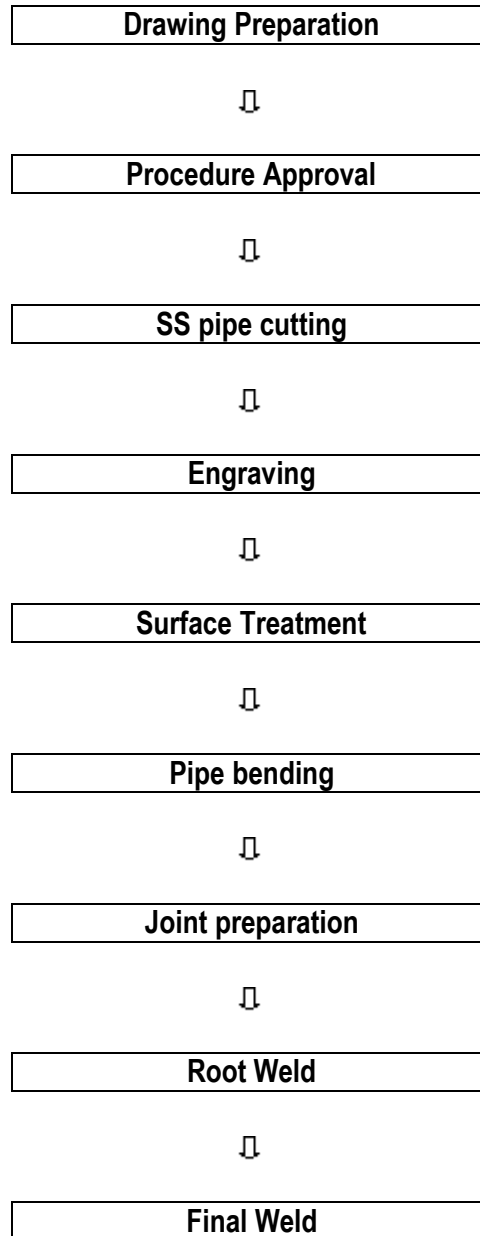


Fig.3 High level process map of piping fabrication

CTQ (Critical To Quality) factors of the process was assessed through discussions with the client / sub-contractor and the Quality Assurance Division. Absence of discontinuity and

non-thinning of material was identified as the CTQ of the nuclear piping facility as the piping will carry corrosive nuclear fluid which can cause further erosion of material easily leading to leakage of nuclear fluid. The criticality of absence of discontinuity further gets accentuated as no repair or maintenance work can be attempted inside the concrete cells housing the fuel piping structure after commissioning of the plant. As the incoming ss pipes are subjected stringent quality assurance checks, material thinning or discontinuities can occur only on account defective weld joints which is done in this process by GTAW, “Defect free GTAW weld joints” were identified as the CTQ of the nuclear piping fabrication.

B. MEASURE

The objective of Measure phase is to comprehend the “Base line performance” of the process by collecting and analysing data on current defects and their frequency of occurrence. GTAW weld quality is assessed through Non-Destructive Testing methods such, as visual Examination, radiography, liquid Penetration examination, pneumatic testing. Data on defects were collected from the Welding Inspection Reports (WIR) and Radiography reports of a sample of 10316 weld joints. There are nine possible defect categories that occur in GTAW pipe welding. Terminology, abbreviation and frequency of occurrence of these defects are given in Table-1. Base line sigma level was established by calculating DPMO (Defects per Million Opportunities) and by reading the corresponding sigma level from the sigma level table. DPMO was calculated using the formula (1).

$$DPMO = \frac{\text{Number of defects}}{\text{No. of weld Joints} \times \text{No. of categories of defects}} \times 1,000,000 \quad (1)$$

As there were 9 possible GTAW defect categories (Table 1) and as there were 439 defects that have been encountered in the chosen sample weld joints of 10316 for the study the DPMO was calculated to be 4728 and the corresponding Sigma Level was read from the table and the Base Line Sigma Level was established as 4.1 sigma which offers ample scope for improvement. This process could be improved to 6 sigma level after reducing all the defect categories to lowest possible level.

Table 1: GTAW Weld defect Categories

S. No.	Weld defects	Abbreviation	Number
1	Lack of Fusion	LF	132
2	Tungsten Inclusion	TI	61
3	Under Cut	UC	46
4	Lack of Penetration	LP	43
5	Excess Penetration	EP	22
6	Distortion	DIS	2
7	Oxidation	OXI	93
8	Porosity	POR	35
9	Concavity	CON	4

In order to identify vital few defect categories from the trivial many, defect categories were prioritized using a Pareto chart based on the sample data (Fig.4).

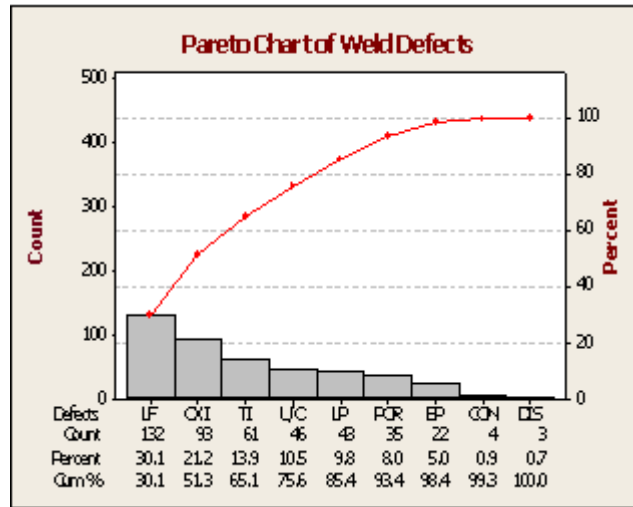


Fig.4.Pareto chart of GTAW defects

As it could be seen from the Pareto chart, it is the “Lack of Fusion” that has the highest occurrence accounting for 30% of the total defects. Hence, it was decided to target “LF” for improvement through further data collection and analysis.

After zeroing in on LF, all possible potential causes of LF were identified through a brain storming session with all the process owners and the QAD officers and the same are depicted in the “Cause and Effect diagram” (Fig.5) also known as ‘Fish Bone diagram.

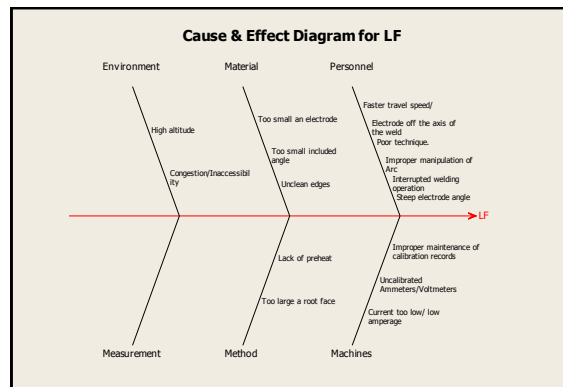


Fig.5 Cause and effect Diagram of LF

B.1 Root Cause Analysis

Root cause analysis was done to identify the significant few causes from among the exhaustive list of causes depicted in the Cause & Effect diagram. The causes were evaluated by their

probability of occurrence in the fabrication environment at IGCAR, given the effective and exacting Quality Assurance Plans backed by well defined and tested procedures for GTAW parameters and every other connected activity and the stringent incoming and stage inspections during fabrication. Probability of occurrence of the different causes were estimated through an opinion survey among the experts of GTAW at IGCAR on a rating scale of 1-10, where 10 was “most likely”, 5 represented “may have an influence but not likely to be root cause” and 1 was “least likely root cause”. Using the probability rating, it was decided to consider the following causes having a score of “7 and above” as significant root causes of LF.

- a) Congestion & inaccessibility
- b) Welders’ Experience in GTAW
- c) Welders’ Qualification
- d) Migration from SMAW
- e) Working at high altitude
- f) NB of pipe
- g) Welding position

There are totally 35000 weld joints in the demonstration plant. It was decided to collect data from the Weld Inspection reports and the radiography reports of weld joints on all the above variables from a sample of 10316 weld joints using systematic sampling method in order to give due representation to all the 4 altitude ranges. Data on welders’ experience, qualification and migration status were collected from welders’ database.

C. ANALYSE

Under this phase, data was gathered on all the above variables from records and the same were analysed using Chi-square and ‘two proportion test’ to confirm the statistical significance of association between these variables and the LF defects. These data have also been presented graphically for visual confirmation. Data tables, Outputs of statistical tests and the charts are given below for all the seven root causes shortlisted.

C1. Altitude of weld joints

The nuclear piping facility spans over an altitude of 10.5 meters. In order verify the psychological effect of working at heights analysis was done to test the influence of altitude on LF defects.

Table 2 : Lack of fusion by Altitude

Sl. No.	Altitude in meters	LF (Nos.)	Total weld Joints	LF (%)
1	-2.5 - <0	18	1156	1.6
2	> 0 - 4.5	62	4680	1.3
3	>4.5 - <7.5	33	2604	1.3
4	>7.5- <10.5	19	1876	1.0
5	Total	132	10316	1.3

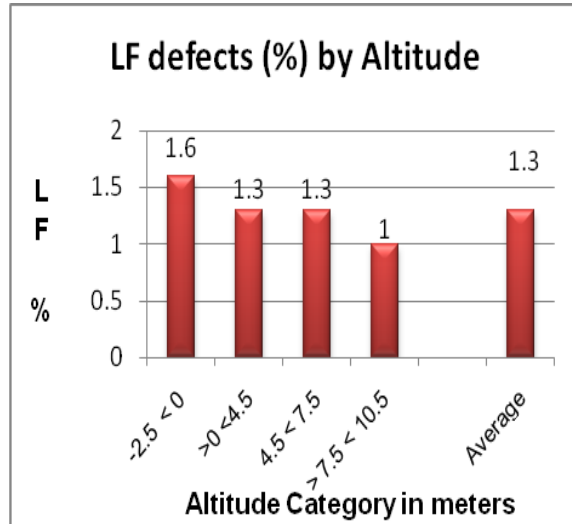


Fig.6 Bar Chart of LF defects by Altitude

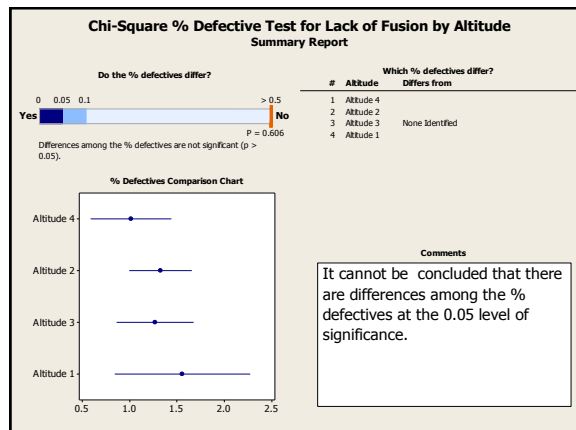


Fig.7 Chi-Square test for LF by Altitude

As the 'P' value is 0.606 which is greater than .05, it cannot be concluded that the differences among the % LF defectives of weld joints between different altitudes are statistically significant.

C2. Pipe size

Nuclear piping structure involves many NB sizes of ss pipes. But 6NB, 15 NB, 20 NB and 25 NB pipes are predominant. The difference in LF defect rates was tested using Chi-Square.

Table 3 : LF defects by pipe size

Sl.No.	PIPE NB	LF (Nos.)	Total weld Joints(No.)	LF (%)
1	8	54	5172	1.0
2	15	62	4759	1.3
3	20	6	143	4.2
4	25	10	208	4.8
5	40	Nil	7	0
6	50	Nil	25	0
7	150	Nil	2	0
	Total	132	10316	1.3

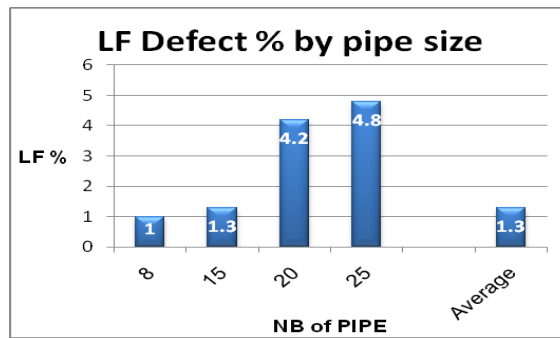


Fig.8 LF defects % by pipe size

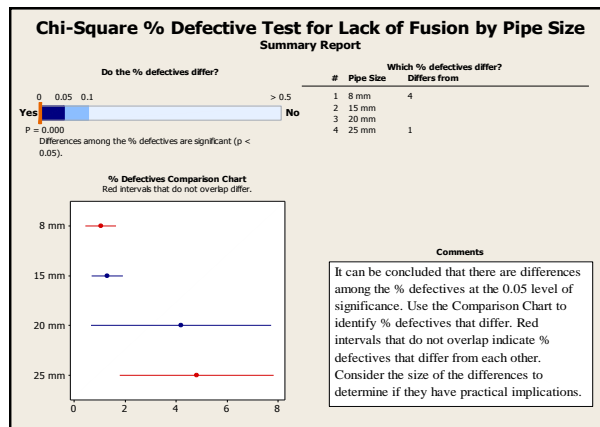


Fig. 9 Chi-Square test for LF by Pipe Size

As the 'P' value is 0.00 it can be concluded that there is association between pipe size and quantum of LF defects. The % of LF defects in 25 mm is significantly greater than the % of LF defects in 8mm.

C3. Welding position

Pipe welding involves 5 different positions of welding namely 1G, 2G, 3G, 5G and 6G. Some of the welding positions call for high level of dexterity and skill on the part of the welders and hence the possible causal relationship with the quantum of LF defects was tested.

Table 4 : LF defects by welding position

Sl.No	Welding Position	LF (Nos.)	Total Weld Joints	LF (%)
1	1G	NIL	31	0
2	2G	103	7087	1.5
3	3G	NIL	3	0
4	5G	25	2633	0.9
5	6G	4	562	0.7
6	Total	132	10316	1.3

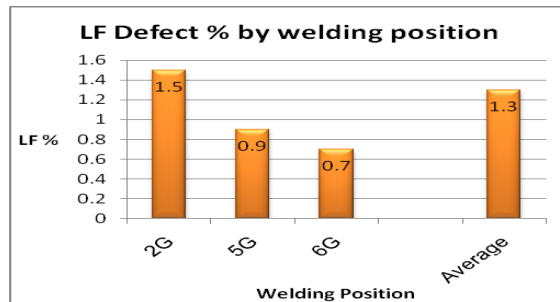


Fig.10 Bar chart of LF defect % by welding position

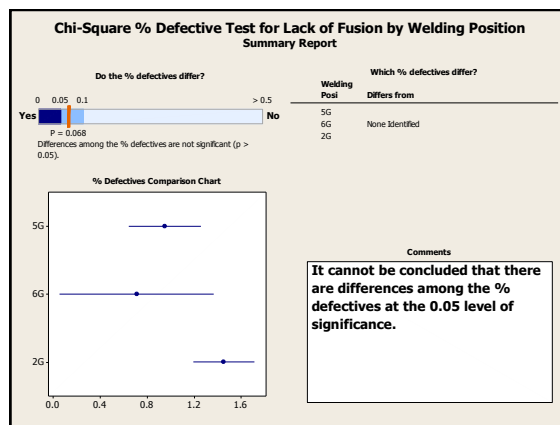


Fig.11 Chi-Square test for LF by welding position

As the 'P' value is 0.68 which is greater than .05 it cannot be concluded that there is an association between welding position and quantum of LF defects.

C4. Educational Qualification of welders

Welders with 10th qualification and ITI qualification are performing the GTAW welding at the Nuclear piping facility. Analysis of the LF defects caused by welders with 10th and ITI qualifications revealed a significant association between qualification and quantum of LF defects as seen from the table No.5 and the result of the two proportion test. (Fig.12)

Table 5: LF defects % by Qualification of welders

Sl. No.	Qualification	LF (Nos.)	Total Weld Joints(Nos.)	LF (%)
1	10 th	92	4634	1.9
2	ITI	40	5682	0.7
3	Total	132	10316	1.3

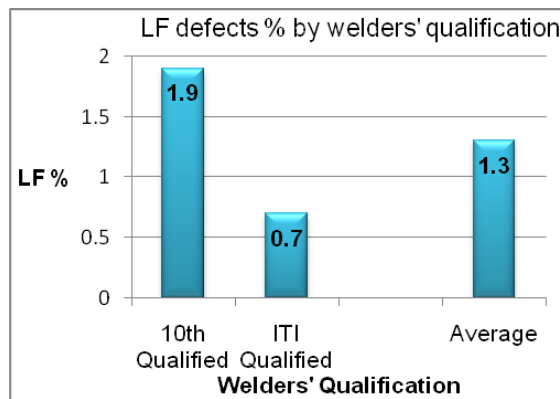


Fig.12 LF defects % by welders' qualification

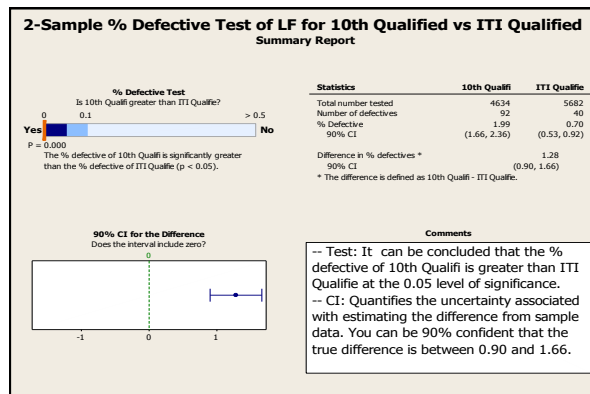


Fig.13 Two sample proportion test of LF by Qualification

C5. Experience of welders in GTAW

Experience perfects a person’s skill in any process. In GTAW it is more so as the weld quality largely depends on the ‘welder technique’ such as correct angle or manipulation of the

electrode/welding gun when standard welding parameters, Joint preparation procedures and standard fabrication practices are ensured.

Table 6 and Fig.14 give the analysis of LF% by experience category of the welders. It could be seen that welders with less than 4 years experience in GTAW have caused over 5 times the LF defects caused by welders with longer experience.

Table 6 : LF defects % by experience of welders

Sl. No.	Experience	LF (Nos.)	Total Weld Joints (Nos.)	LF (%)
1	>10 yrs.	2	316	0.63
2	>8-10 Yrs	16	2789	0.57
3	>6-8 Yrs.	21	2895	0.73
4	4- 6 Yrs.	10	1878	0.53
5	< 4 yrs	83	2438	3.4
6	Total	132	10316	1.3

It is more evident in the bar chart of LF defects by Experience category of welders.(Fig.15)

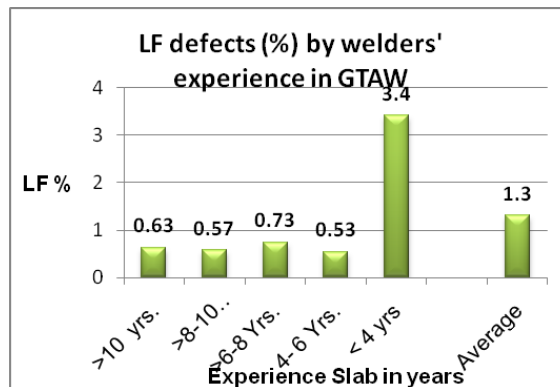


Fig.15 LF defects % by welders' experience

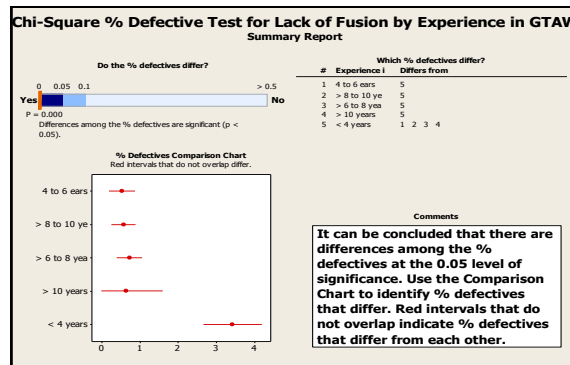


Fig.16 Chi-Square test for LF by experience

Chi-Square test also confirms that difference in % of LF defects between welders with less than 4 years and all other welders with longer years of experience is statistically significant.

From the analyses the following factors emerge as the root causes for LF defect in GTAW as there is a strong association between them and the quantum of LF defects.

- a) Congestion and inaccessibility of weld joints and the consequent abnormal positioning of the welder
- b) Variability in welders' skill as manifested in their educational qualification and experience in GTAW
- c) Pipe size denoted by its NB, as occurrence of LF defect is 3.5 times the average % of LF in the weld joints involving 20 and 25 NB pipes.

D. IMPROVE

Improve phase of Six Sigma aims at finding solutions for the root causes identified in the Analyse phase. The following solutions have been offered to the nuclear research organization for reducing the LF defects in their GTAW process and improving the sigma level from 4.1 sigma.

- a) Welders with a minimum experience of 4 years in GTAW should be engaged.
- b) GTAW welders with Technical qualification have to be engaged and those with non-technical qualification are to be avoided.
- c) Welders' performance qualification has to be carried out in a condition which Simulated production condition with heavy congested net work of SS pipes at worst possible elevation to test welders' ability to make sound weld deposit in realistic site conditions.
- d) Simulated condition for performance qualification should have 20 and 25 NB SS pipes predominantly.

E. CONTROL

Real difficulty in Six Sigma application is the sustenance of the improved performance. After implementing the above suggestions and realizing the reduction in LF defects level, in order to sustain the improvement, it has been suggested to standardize the welder engagement procedure by incorporating the revised welder eligibility criteria in terms of Experience and Qualification in the contract specifications / and to monitor the same when new welders are inducted in to the team or when new contractors are introduced.

LF defect percentage has to be monitored on a monthly basis using C charts to ensure and sustain the reduced LF defect level.

F. CONCLUSION

This paper has presented the phase-by-phase application of the DMAIC methodology in GTAW at the SS piping facility of a nuclear research organization for their demonstration plant for reducing 'Lack of Fusion' (LF) defects. The outcome of the study confirms the suitability of Six Sigma and its DMAIC methodology in a non-continuous and non-repetitive activity like GTAW process. By implementing the suggested improvement strategies while fabricating the functional plant, the organization can benefit from considerable reduction in LF defects and the

resulting improvement in safety & reliability and savings through reduction of rework and avoidance of project overruns.

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