Pareto Analysis of Non-Conformances Observed During the Fabrication of Rocket Engines and Suggestions to Prevent their Occurrence

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Abstract

The background of this paper is to find out the predominant types of defects that occurs during the fabrication of pump fed rocket engines. Pump fed rocket engine which works on gas generator cycle is used in operational launch vehicles. The number of non-conformances are to be reduced to improve the reliability of the engine. The non-conformances reported during fabrication of twenty numbers of the engine realised over a period of four years are classified under different heads. Pareto analysis was carried out and found that the non-conformances due to weld shrinkage (process limitation), operator mistakes (human error) and free condition ovality (raw material) are the pre-dominant ones. The suggestions for process improvement leading to reduction in non-conformances per engine are also highlighted in this paper.

Keywords
Rocket engines, Fabrication, Pareto analysis, Non-conformances and Weld shrinkage.

1. Introduction
Pump fed rocket engine which works on gas generator cycle is used in operational launch vehicles. The major sub-assemblies of the engine are Engine On & off valves, Gas generator, Turbo pump, Main injector, Combustion chamber & Nozzle assembly, Thrust regulators, Mixture ratio regulators and POGO correctors.

Each engine consists of 355 types of fabricated components. The fabrication process involves machining, forming, welding, heat treatment, surface treatment, match machining, wear resistant coating, etc. On an average forty two non-conformances are reported per engine. As part of continuous improvement as well as to increase the reliability, there is an urgent need to reduce the number of non-conformances (N.Cs). Hence, finding out and resolving the predominant factors contributing for the N.Cs are of utmost importance to improve the reliability of the engine. In the present study N.Cs noticed during the fabrication of twenty numbers of engines realised over a period of four years are classified under different heads. Pareto principle is applied to find out the predominant N.Cs which needs immediate action to reduce the number of N.Cs as part of continuous quality enhancement and to reduce the lead time for NC processing and assessment. This paper also suggests the improvements that can be incorporated to avoid the predominant non-conformances so that the no. of N.Cs per engine can be reduced to a target value of less than ten numbers.

Rejection of a component leads to loss of machine and man hours, loss of expensive aerospace quality raw materials and increase in lead time of fabrication. Increase in the number of NCs leads to loss of man-hours and money for analysing the NCs, a risk of taking a wrong decision on NC which may be catastrophic during the mission and fatigue to inspectors leading to possible non-reporting of an NC.

1.1 Objectives
The main objective is to find out the predominant type of N.Cs during the fabrication of pump fed rocket engine.

2. Literature Review
Italian economist Vilfredo Pareto in the 19th century noticed that approximately 80% of Italy's land was owned by 20% of the population. He then carried out surveys on other countries and found to his surprise that a similar

distribution exist. Joseph M. Juran developed the concept of Pareto principle, named after the Italian economist and generalized its application from wealth distribution to many other areas, particularly quality.

Yakovenko and Silva (2007) analysed income data from the US Internal Revenue Service from 1983 to 2001, and found that the income distribution of upper class follows Pareto's principle. Pressman and Roger S (2010) discovered that in general the 80% of a certain piece of software can be written in 20% of the total allocated time. Conversely, the hardest 20% of the code takes 80% of the time. Miloșan et al. (2019) found that 20% of the causes of work accidents accounts for 80% of the total work accidents in manufacturing industry. Alison P. Galvani and Robert (2005) found that during epidemics super-spreading conforms to the 20/80 rule, where approximately 20% of infected individuals are responsible for 80% of transmissions. Singh and Katheria (2022) applied Pareto analysis to control denier variation to save excess weight of woven fabric used in FIBC.

In manufacturing, the 80/20 rule can be applied from raw material to sales and everywhere in between Husain et al. (2021) analysed the production of gears for the transmission system of 4-wheeler automobile with the help of Pareto analysis and found that more than 80 % rejection and rework are due to defects like Forging Problem, Dent and Fall Down. Heena Sharma and Dr. N.M Suri (2017) categorized the defects in LV Electrical Panels during in-process and at final stage using Pareto analysis and found that 27% rejections are due to poor welding. Polak et al. (2015) evaluated the cut quality of Hydro abrasive metal cutting by Pareto method and Abhay et al. (2014) studied the reasons for rejection of forging of cam shaft gear in a leading forging industry and found that furnace issues and die crack are the predominant ones. Joshi and Jugulkar (2014) analysed the reasons for rejection of castings from an industry using Pareto analysis and found that flash, mould shifting and buckling are the major factors contributing for rejections. Mathew et al. (2013) studied the defects that come in Integral Axle Arms using Pareto analysis and it was found out that 83.33% of the total rejections were due to un filling and lap. Borowiecki et al. (2011) carried out another case study on the defects in sand castings and found that 70% of defects has three reasons: sand holes, porosity and slag inclusions. Ahmed and Ahmad (2011) found out that 37% of defects occurred during the lamp manufacturing is single lead in wire using Pareto analysis.

Pareto principle has a wide range of application in areas like Production Engineering, Production control, Quality control, Education, Inventory management, Software engineering, Economics, Sports, Hospital management, Occupational health and safety, etc.

3. Method selected for study

Pareto method is selected for the present study based on extensive literature review, wide range of applicability and this is the best method to identify areas to be focusedfor quality improvement. Pareto Principle says that, for many events, roughly 80% of the effects come from 20% of the causes. It would be wise to concentrate on the 'vital few' causes rather than the 'trivial many' causes. The most important benefit of using Pareto chart analysis is that it helps to highlight the important factors in a scenario where there are a large number of factors to be considered. A Pareto chart is a type of chart that contains both bars and a line graph, where individual values are represented in descending order by bars, and the cumulative total is represented by the line. Vertical axis shows the frequency of occurrence and the cumulative frequency.

4. Case study

Pump fed earth storable rocket engine which works on gas generator cycle is used in all operational launch vehicles of ISRO. All the components are fabricated as per the configuration controlled drawings and process plans at industries in India. An average of 42 hardware NCs are being reported for each engine from industries as hardware NCs. After case by case analysis, the disposition for the non-conformance will be any one of the following: Accept as it is, accepted with a suitable mating part such that assembly / functional tolerances are within the specified limit, re-work or reject. This decision is based on combination of following factors: type of deviation (i.e dimensional, geometrical tolerance, visual), extent & direction of the deviation, whether the dimensional deviation will affect the assembly or functioning of the engine or visual remark is in critical zone etc.

835 NCs reported from 20 set of engine components fabricated from a single industrial consortium are considered for the present study. Based on the detailed discussions with the fabrication team and data collected from Cause and Preventive Action (CAPA) sheets for each NC, the total NCs are classified under 11 heads as shown in the fishbone diagram, (Figure 1).

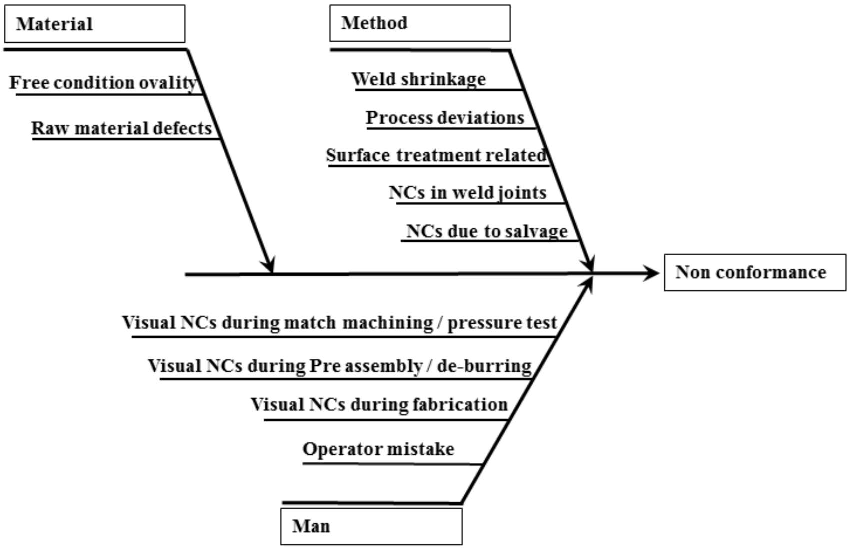

Figure 1. Fish bone diagram for Non-conformances observed during rocket engine fabrication.

Table 1 shows the criteria for classification of non-conformances. Table 2 shows the classification of 835 Non-conformances in 20 engines according to the criteria shown in Table 1.

Table 1. Criteria for Classification of Non-conformances for rocket engine fabrication

No.	**Classification of NCs**	**Process characteristics / information**
1	Raw material defects	Pores and inclusions, mainly in aluminium castings for elbow, clamps and filter elements.
2	Free condition ovality	Ovality comes after machining of higher size Aluminium alloy components like Valve body, Skirt, Pump covers, Pogo corrector body, etc.
3	Weld shrinkage	Dimensional deviation occurred after welding, mainly in sheet metal components like thrust chamber and turbine casing assembly.
4	Process deviations	Dimensional deviation due to wrong process likemore drill depth, hole size enlargement, etc.
5	Surface treatment related	Mainly visual and coating thickness NCs after anodisation of aluminium components
6	NCs in weld joints	Mainly pores opened out to surface in the weld joints after subsequent machining in main injector and POGO correctors.
7	NCs due to salvage	Dimensional NCs with respect to drawing dimension, purposefully made to suit with the mating part to achieve assembly / functional tolerances
8	Operator mistake	Wrong offset given in CNC program, Thread tapping NCs, wrong engraving, uneven chamfer, co-ordinate change of wire locking hole, etc.
9	Visual NCs during fabrication.	Tool diggings marks, scratch marks, thread chatter, etc occurred during fabrication process.
10	Visual NCs during pre-assembly / de-burring	Line marks and scratch marks during assembly and disassembly as part of pre- assembly operations.
11	Visual NCs during match machining / pressure test	Line marks and scratch marks during assembly and disassembly as part of match machining and proof pressure test.

Table 2. Classification of 835 nos. of Non-conformances in 20 engines

No.	Classification of Non-conformances	Frequency	Percentage	Cumulative Percentage
1	Weld shrinkage	180	22	22
2	Operator mistake	162	19	41
3	Free condition ovality	146	17	58
4	Raw material defects	130	16	74
5	Visual NCs during fabrication	50	6	80
6	Process deviations	49	6	86
7	Surface treatment related NCs	48	6	92
8	Visual NCs - Pre assembly / de burring	24	3	94
9	Visual NCs – pressure test/ match machining	21	3	97
10	NCs in weld joints	20	2	99
11	NCs due to salvage	5	1	100

5. Generating the Pareto chart

Non-conformances reported for twenty engines fabricated at an industrial consortiumwere classified as shown in section 2. Pareto chart is prepared as shown in Figure 2 as a bar chart with frequency on the Y-axis and types of NCs on the X-axis. The cumulative percentage is also plotted as a line curve. The percentage contributions of each type of non-conformances are shown in Table 2.

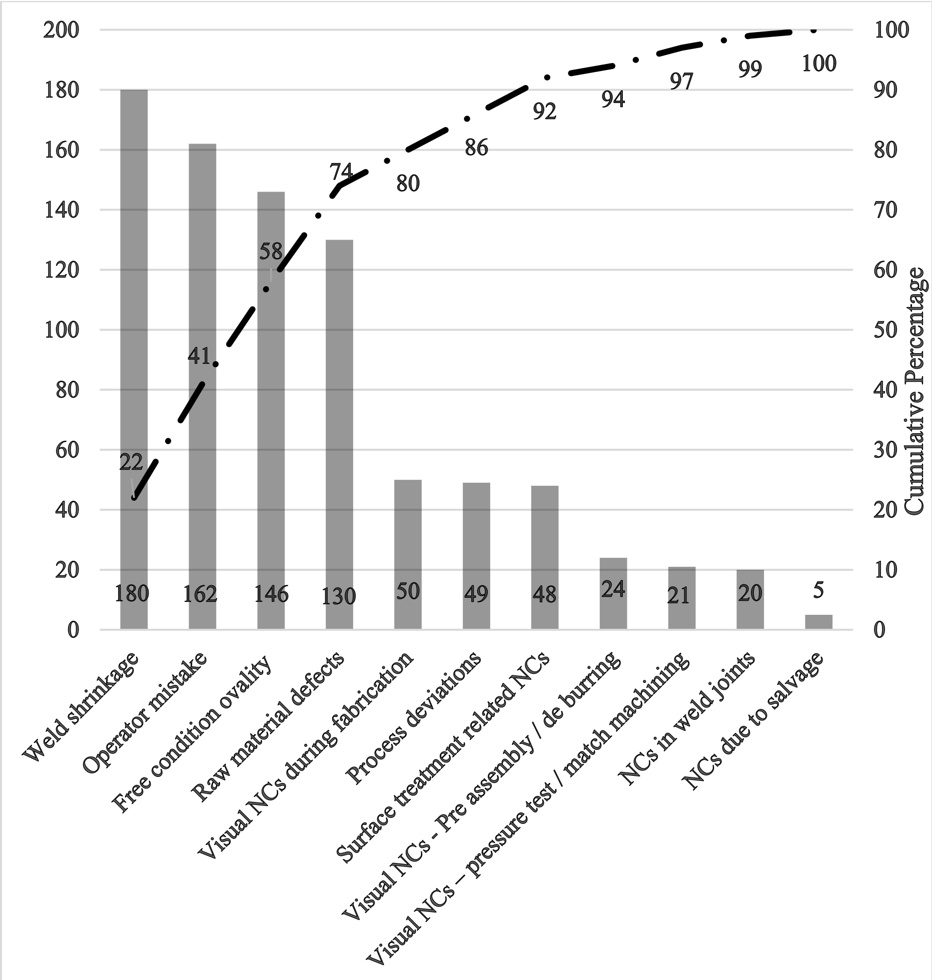

Figure 2. The Pareto Chart for the Types of Non-conformances reported during the fabrication of 20 rocket engines

6. Results and discussions

Out of the eleven types of non-conformances, four numbers are found to be the predominant ones. The four types of non-conformances due to weld shrinkage, operator mistakes, free condition ovality and raw material related issues are the predominant ones which cumulatively contribute to 74% of total NCs observed based on the Pareto chart given above. It is also observed that the next six causes result in 25% of total NCs and last one contribute to only 1% of total NCs. Therefore, the predominant four causes contributing to majority of the non-conformances which is identified by Pareto analysis merits further study and immediate corrective measures to reduce the number of non-conformances to less than ten numbers per engine.

6.1 Non-conformances due to weld shrinkage

As per the Pareto analysis the most predominant factor (22 % of NCs) is the non-conformance caused byweld shrinkage. These types of non-conformances are noticed in major welded components namely Combustion chamber & Nozzle assembly, turbine casing assembly and POGO corrector assembly.

Combustion chamber & Nozzle assembly and turbine casing assembly is fabricated from sheet metal by forming and TIG welding. These results in an average of nine nos. of NCs in each engine and are repetitive in nature.Causes identified are due to inadequacies in holding & welding fixtures and these are to be modified suitably to prevent these types of non-conformances. Machining from a higher thickness sheet after forming and welding can also be considered as a solution for combustion chamber & nozzle assembly realisation. However, this option is comparatively costlier. A common cause observed is that a few tolerances specified in drawings seem to be highly impossible to achieve in sheet metal works which involves welding and forming. Such tolerances are to be studied and modified based on its criticality in engine operationand previously cleared maximum deviated values which have successfully flown earlier. A few repetitive non conformances noticed in

Combustion chamber & Nozzle assembly due to weld shrinkage are highlighted in Table 3. Out of 20 engines maximum and minimum variations are shown in the Table.

Table 3. Details of repetitive dimensional NCs noticed in Combustion chamber & Nozzle assembly

No.	Dimensions	Noticed in (numbers)	% variation as per drawing	% Variation noticed with respect to nominal	Possible correction
1	Convergent end diameter	20	+0.04	-0.01 to +0.08	Acceptable limit to be re-specified based on successful usage in flight and process capability.
2	Convergent start diameter	20	+0.04	-0.02 to +0.07	
3	Total length	17	±0.07	-0.12	
4	Divergent exit ovality	14	±0.20	+0.26	Welding and fixturing process to re looked.
5	Pump outlet interface adaptor diameter	12	+0.08	-0.02 to 0.10	

To avoid NCs due to welding in POGO correctors which are now realised by machining multiple forgings and welding together, a fully machined version of POGO corrector is recommended.

6.2 Non-conformances due to operator mistake

As per the Pareto analysis 19 % of non-conformances observed are due to various types of operator mistakes. On further study it is found that 40% of such non-conformances are due to the entry of wrong offset value in the CNC program. Other operator mistakes includes wrong thread tapping, wrong engraving, wrong machine settings, using worn out tools, uneven chamfer, co-ordinate change of wire locking hole, etc.

After studying the processes, five points for improvement are suggested below to prevent the NC occurrence.As a corrective measure, offset values entered by the operator are to be re-verified by the supervisor using a setup checklist before proceeding for machining. First off inspection is to be strictly implemented in industries before proceeding for batch production. In most industries, it is noticed that the employees are changing regularly. Hence proper training and qualification should be mandated for the employees by the industries before entrusting them in realising flight hardware. Conducting awareness programs from LPSC side at more frequent intervals will also help the industry employees to understand the criticality of the work. Once a mistake occurs, publishing the NC and its preventive measure at a common place (notice board) in the workshop to prevent others doing the same mistake is to be followed.

6.3 Non-conformances due to free condition ovality

As per the Pareto analysis 18 % of non-conformances are due to free condition ovality. This is mainly occurring in Aluminium alloy components of higher sizes having thin cross sections namely valve body, valve skirt, pump covers, injector flange, POGO corrector tibia, rings of higher sizes, etc. The specified drawing dimensions will be achieved within the tolerance in the machine with the fixture in place. But once fixture is removed, this non-conformance will occur.

Based on the achieved values so far, the dimensions to be obtained in the machine with the fixture in place are to be fixed so that once fixture is removed the dimensions will be within the drawing specification. Stage machining with sufficient natural ageing can be introduced. In certain cases where thickness is less, possibility of relaxing the tolerance based on criticality and previously accepted dimensions can be studied.

6.4 Non-conformances due to issues in Raw Material

As per the Pareto analysis, 16 % of non-conformances are due to raw material issues. Raw materials are cleared in-house and are issued to the industry for fabrication. Non-conformances are generally noticed in aluminium castings like, elbow, clamp and filter elements. Non-conformances like pores opened up after machining, lack of stock for machining due to distortion as a result of heat treatment after casting are commonly reported.

The acceptance criteria of castings (prior to machining) are to be studied and further tightened to avoid these types of non-conformances observed post machining. The possibility of making these components by forge route instead of castings, 3D printing or following a refined casting method like investment casting also can be explored. Improved fixturing during heat treatment is to be employed to prevent undue distortion.

6.5 Other factors

The NCs due to deviation from fabrication process, visual non-conformances during fabrication and surface treatment related non-conformances are 6% each of the total non-conformances. Non-conformances like deviation in drill depth, bell mouth of drilled holes, etc. can be avoided by strictly adhering to the approved process for fabrication. Handling and transportation proceduresare to be reviewed, updated and implemented to avoid visual non-conformances. All assemblies for match machining, pre assembly and proof pressure testing are to be done in a clean room only. Scratch marks and peel off are mostly seen in aluminium components anodized by chromic acid process which can be replaced with thin layer sulphuric acid process having higher anodisation thickness and hardness. Most of the visual NCs are coming on the gasket seating area which occurred during the removal of gasket from the groove after proof pressure test or pre assembly. The possibility of making a special fixture for removing the gasket can be explored. Black patches are noticed after anodisation in some of the aluminium components. This effect is to be studied in detail and preventive measures are to be evolved. Weld related NCs like lack of fusion and pores are noticed particularly in aluminium alloy components like the propellant injector and POGO correctors. Fully machinedversion of POGO corrector and propellant injector can be used to avoid these non-conformances. Maintenance of cleanliness in the weld shop and cleaning of hardware just before welding is of utmost importance in reducing the pores in the final weld.

7. Conclusion

An average of forty two hardware non-conformances is reported during the fabrication of earth storable rocket engine. As a requirement of continuous improvement the number of non-conformances are to be reduced to improve the reliability of the engine. The non-conformances reported from industrial consortium during fabrication of 20 rocket engines are classified under 11 heads and Pareto analysis was carried out. Around 74% of the total non-conformances are due to 36% causes (4 nos.).

After in-depth study of the existing processes and non-conformances observed, a total of twenty one numbers of improvements are suggested in sections 6.1 through 6.5 towards control of raw material, fixtures, welding, inspection, etc aimed at reducing the non-conformances, thereby improving the hardware quality. With these measures, number of NCs per engine can be brought down to less than 10 numbers.

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