REDUCTION OF DIE CASTING DEFECTS IN ADC12 STEERING RACK HOUSING USING PARETO, P-CHART AND ROOT CAUSE ANALYSIS

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Abstract—

Automotive housing production continues to be rejected due to porosity and other hidden defects for high pressure die casting (HPDC). The study of this problem on the ADC12 aluminium Steering Rack Housing made at Tyche Cast Tech Pvt. Ltd., Mambattu, Andhra Pradesh. Collecting 12 weeks of baseline inspection data from 24,000 components and then categorizing it by defect type. Surface defects were detected visually and internal defects by means of X-ray radiography. Pareto analysis results were obtained, where the highest number of defective components were found to be porosity with 37.33% of the total 450 defective components. A P-chart in Minitab indicated a process to be in statistical control with an average of 1.88% defective but a regression on week number indicated a significant drift upward that had not been detected by the control limits. Brainstormed possible causes using an Ishikawa diagram, pursued those causes using 5Why analysis and assessed them against 5 evidence criteria before accepting them. Then put nine corrective actions in place. They had to grapple with degassing, melt and die temperature, venting, parameter settings, monitoring and operator training. Over the next twelve weeks (24,200 components) the defective rate dropped to 0.83%, a reduction of 55.85%, and porosity fell from 168 to 65 cases, a reduction of 61.31% ($p < 0.001$). Records of shot setting, temperatures and degassing were not available, so causes rest on observed practice, published evidence, and do not depend on plant measurements, as stated in the paper.

Keywords—Die Casting, ADC12 Alloy, Porosity, Pareto Analysis, P-Chart, Root Cause Analysis, X-Ray Inspection, Statistical Process Control.

I. INTRODUCTION

Aluminium die castings are used in many parts of a modern car, and steering components are among the most demanding of them. A steering rack housing has to hold the rack in alignment under load, so a void hidden inside its wall can affect how the part performs. In high pressure die casting, molten metal is forced into a steel die at high speed and pressure and freezes within seconds. This speed makes the process repeatable, but it also traps air in the cavity, and the last metal to solidify may not get enough feed [1], [2].

Parts of this kind are typically produced in an Al–Si–Cu alloy such as ADC12 which fills thin section well. Despite all this, porosity, blow holes, cold shut, shrinkage, misrun and flash are all defects in its castings. The surface defects can be seen by an inspector but internal defects cannot, so plants used for automotive customers also perform X-ray radiography.

While most plants maintain defect records, few follow the records to create a structured effort for improvement. The standard procedure is to look hard, shave off the kinks and proceed. This paper is different, and has been taken on a running production line. Firstly, started with the defect data and then used a Pareto chart to determine a focus area. A P-chart indicated stability of the process and an Ishikawa diagram recorded potential causes of the issue. Then subjectively tested each possible cause against evidence, and evaluated its effect against a baseline period that matched in length to the period under the test.

The work was carried out in the ADC12 Steering Rack Housing of Tyche Cast Tech Pvt. Ltd, Mambattu, AP. It's certified to IATF 16949, and provides automotive manufacturers with almost one million rack housings per year.

II. LITERATURE REVIEW

Quite a few studies on ADC12 have looked at how porosity forms. Kang et al. [3] studied plunger velocity and the fast-shot set point in an ADC12 plate casting. The best result came at 1.0 m/s with the set point at the 25% position. Hamasaki and Miyahara [4] looked at how porosity is distributed and how feeding affects it. Porosity in their die-casting tests came to 3.1–4.6% by volume, and more than 98% of it came from solidification shrinkage, not gas. A second paper from them tied pores larger than 200 µm to local solidification conditions [5]. The practical point is that the dominant mechanism has to be identified for the casting in question and cannot be assumed.

Process settings matter as well. Matejka et al. [6] varied the maximum piston velocity for AlSi9Cu3(Fe), an alloy close to ADC12, and macro porosity fell as the velocity rose from 2 to 3 m/s before levelling off. A study of ADC12 using X-ray computed tomography found that higher intensification pressure reduced both the fraction and the number of pores, although it had no effect in 2 mm walls [7]. Foundry practice notes describe gas porosity as round and smooth, and shrinkage porosity as irregular and jagged. The first is linked to degassing, venting and shot profile, the second to die temperature and feeding [8], [9].

The quality tools themselves are standard textbook material: control charts for attribute data, Pareto analysis, cause-and-effect diagrams and 5-Why analysis [10], [11], [12]. Experimental and simulation studies explain the physics well, but they seldom describe a production-based sequence that starts from inspection records, picks the defect to attack, shows how each suspected cause was confirmed and measures the result statistically. Causes are often brainstormed and listed without any account of how they were confirmed. And added an explicit verification step to address this.

OBJECTIVES

The aim is to reduce die casting defects in ADC12 Steering Rack Housing. Specific objectives are:

I. To gather and categorize defect information with visual and X-ray inspection.
II. To Use Pareto analysis to identify the major defect and to perform process stability check using a P-chart.
III. To Identify likely causes using Ishikawa and 5-Why analysis and evaluate using evidence criteria.
IV. To take corrective action to the accepted causes.
V. To compare the post-improvement data to the baseline, using the same inspection methods and a statistical test.

III. METHODOLOGY

A. Component and Process

The component is an ADC12 casting created on a cold chamber HPDC machine. The process is performed from raw material to the melt, degassing, dosing, injection, intensification, solidification, ejection, trimming and machining up to the final inspection (Fig. 1). Prior to the study, the control was largely through the practice of the operators and on a periodic basis. We didn't check degassing, die temperature and venting on any defined basis, and that's where started the investigation.

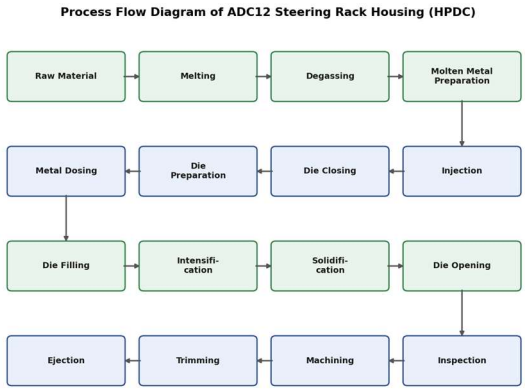

Fig. 1. Process Flow of the ADC12 Steering Rack Housing

B. Defect Data Collection

Inspection records were taken from the past 12 weeks of production. The quantity of inspections has varied according to the production schedule. All the faulty parts were recorded and identified according to their type. Visual inspection revealed that the product had cold shut, crack, misrun, flash and other surface defects. The porosity, blow hole and shrinkage which are below the surface were confirmed by the plant's inspection system (X-ray radiography), (Fig. 2). Plant weekly inspection report and defect classification report were used to provide the counts. That classification report did not have a type recorded for 30 out of 450 defective components. We did not have any components without a record being made where kept them as a separate category until the very end.

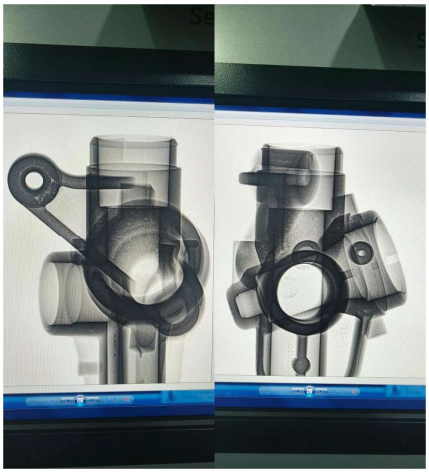

Fig. 2. Sample X-ray Radiographic Images of the Steering Rack Housing Used to Identify Internal Defects

C. Pareto Analysis

Listed the defects in order of occurrence and calculated the percentage of the total number occurring. The defect with the highest percentage advanced to further investigation. As 30 of the components were not reported with a type, and also examined how the ranking might change with alternative assumptions about these components.

D. P-Chart

The data was of the attribute type with the sample size changing weekly for defective and non-defective. For this case a P-chart with variable control limits is therefore appropriate [10]. The proportion defective for week i is, the centre line is and the control limits are

$$p_i = d_i / n_i \quad (1)$$

$$\bar{p} = \Sigma d_i / \Sigma n_i \quad (2)$$

$$\text{UCL, LCL} = \bar{p} \pm 3\sqrt{[\,\bar{p}(1-\bar{p}) / n_i\,]} \quad (3)$$

n = the number inspected and d = the number of defectives in week i. If the lower limit is less than zero then it is set to zero. The charts were created using the program Minitab [13].

E. Ishikawa and 5-Why Analysis.

Arranged the potential causes of porosity on an Ishikawa diagram under six headings: Man, Machine, Method, Material, Measurement and Environment [11]. The causes most associated with the porosity were then pulled up with a 5-Why chain to a systemic cause.

F. Accepting a Cause as an Actual Cause

An Ishikawa diagram can identify what might have caused a defect but is unable to reveal what actually did. A sound-sounding cause, or a course of experience that supports it, can be error-prone, and for this reason, each candidate was submitted to five tests. T1: is there an established physical mechanism? T2: Is the x-ray profile of the defect consistent with the cause? T3: Did the cause exist in the process at the baseline? T4: Are the defect data as predicted by the cause?

 ISSN: 3107-6513

R5: Do you believe if the cause were controlled, the defect would go away?

Each test was scored either Met, Partial (consistent with the cause, but not identifying it) or No record (no plant record available). A cause was considered Verified if 4 or more Tests were Met. If three were Met or two were Met and two were Partial, it was considered Supported. If it weren't, it was Provisional. And also reported on "Supported" and "Provisional" causes, as the actions are inexpensive and adhere to good practice, but are not proven.

G. Evaluation of the Improvement

With the actions implemented, the same inspection procedures were used for the next 12 weeks. Reductions were determined by:

$$\text{Reduction (\%)} = [(B - A) / B] \times 100 \quad (4)$$

Where B and A are the value before and after. A two-proportion z-test was performed to test the significance of difference between the two periods.

$$z = (p_1 - p_2) / \sqrt{[\,\hat{p}(1-\hat{p})(1/n_1 + 1/n_2)\,]} \quad (5)$$

where p1 and p2 are the proportions in the two periods, n1 and n2 the numbers inspected in the two periods and $\hat{p}$ the pooled proportion. Weekly values were also compared with a Mann–Whitney test, which makes no assumption of normality.

IV. Results and Discussion

A. Baseline Data

The baseline inspection revealed that there were 24,000 components and 450 were found to be faulty. In the baseline, 450 out of the 24,000 components were found to be defective. The average proportion defective was 450/24,000 = 0.01875, or 1.88%. Weekly values ranged from 1.52% to 2.15% (Table 1).

Table 1. Weekly Inspection Data Before and After Improvement

Week	Before: inspected	Before: defective	Before: %	After: inspected	After: defective	After: %
1	1,800	28	1.56	1,900	20	1.05
2	2,000	31	1.55	2,000	18	0.90
3	1,900	35	1.84	2,100	19	0.90
4	2,100	32	1.52	2,000	17	0.85
5	2,000	40	2.00	2,050	18	0.88
6	1,950	36	1.85	1,950	16	0.82
7	2,050	39	1.90	2,100	17	0.81
8	2,100	42	2.00	2,000	15	0.75
9	2,000	38	1.90	2,050	16	0.78
10	2,050	44	2.15	2,000	14	0.70
11	2,000	43	2.15	2,050	15	0.73
12	2,050	42	2.05	2,000	15	0.75
Total	**24,000**	**450**	**1.88**	**24,200**	**200**	**0.83**

B. Defect Classification and Pareto Analysis

Porosity was the biggest single category, with 168 components or 37.33% of all defective components (Table 2, Fig. 3). Blow hole came next at 18.67%, then cold shut at 11.11% and shrinkage at 9.33%. The top five defect types combined exceeded the 80% mark at 82.89%. We thus chose to take porosity as the critical defect.

Table 2. Baseline Defect Classification and Pareto Data

Defect	Method	Qty.	%	Cum. %
Porosity	X-ray	168	37.33	37.33
Blow hole	X-ray	84	18.67	56.00
Cold shut	Visual	50	11.11	67.11
Shrinkage	X-ray	42	9.33	76.44
Crack	Visual	29	6.44	82.89
Misrun	Visual	21	4.67	87.56
Flash	Visual	15	3.33	90.89
Other defects	Visual	11	2.44	93.33
Type not recorded	—	30	6.67	100.00
Total		**450**	**100.00**	

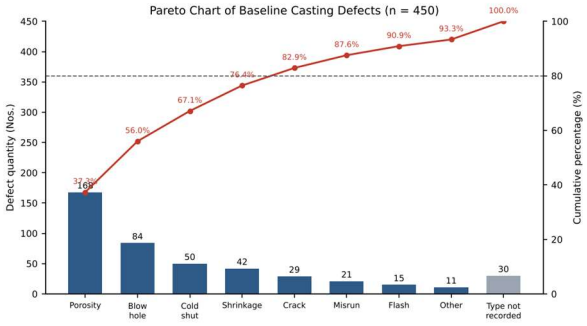

Fig. 3. Pareto Chart of Baseline Casting Defects

This is not affected by the 30 unrecorded components. If none of them were porosity, then its percentage would be 37.33%. If all of them are, it would be 44.00%. Blow holes (114) would still be well below porosity (168) if all 30 were blow holes. The Wilson 95% confidence interval for the share of porosity is 32.99% to 41.89%, which is completely higher than the confidence interval for the blow hole share, (15.34% to 22.53 %). There are 252 parts, of which 168 have a defect, namely porosity, and a binomial exact test with the hypothesis of a split indicates that $p < 0.001$. It is obvious that this is not just a matter of chance; porosity wins by a long shot.

C. Process Stability

The variable limits of Eq. (3) gave the centre line of 0.01875. For week 1, with n = 1,800, the upper limit was 0.0283 and the lower limit 0.0092. The weekly proportions were within the established limits and no run tests occurred during the 12 weeks, indicating that the baseline process was statistically stable (Fig. 4). But Stable was not necessarily good. The average number of defective wasd 1.88%, which still has ample scope for improvement.

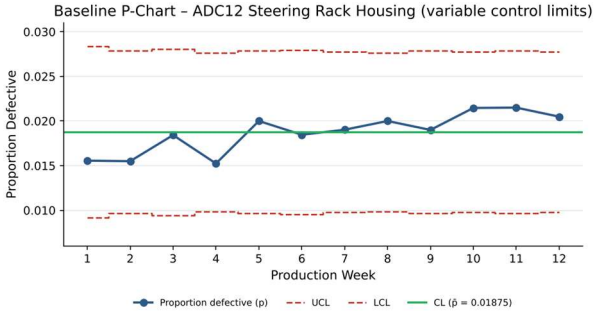

Fig. 4. Baseline P-Chart with Variable Control Limits

The weekly values convey more information than the limits. When the weekly percentage was regressed on week number a positive slope of +0.052 percentage points per week ($r = 0.84$, $t = 4.97$, $p < 0.001$) was obtained. The 6 consecutive weeks (weeks 7 to 12) were above the centre line. Regrettably, the regression didn't satisfy the nine-point run rule, which would have left a run-rule test silent, and therefore the nine-point run rule would not have been applied. It was rising within the boundaries and no one objected.

D. Root Causes of Porosity

The potential causes listed under each heading are given in table 3. The highest priority was given after screening to the following factors: condition of the molten metal, effectiveness of degassing, die temperature, condition of the vent and level of filling or pressure.

Table 3. POTENTIAL CAUSES OF POROSITY (ISHIKAWA ANALYSIS)

Category	Potential causes
Man	Variation in operating practice; process sequence not followed; limited awareness of critical parameters
Machine	Die temperature variation; pressure parameter variation; venting deterioration; machine setting variation
Method	Degassing not standardised; parameter monitoring weak; inconsistent die preparation
Material	Variation in molten-metal condition; possible moisture or contamination; return material reused without control
Measurement	Temperature measurement variation; verification too infrequent; records not detailed enough
Environment	Moisture near material and process area; shop-floor variation; consumables stored badly

The 5-Why chain was as follows. Gas or air trapped in casting during solidification. Was not taken out regularly during the cycle. The degassing and venting were not controlled. Critical parameters and condition checks were not standardised, nor checked periodically. There was no systematic monitoring of the parameters related to porosity. The systemic problem was therefore weak standardisation and verification of conditions under which gas removal, venting and casting is carried out. These were the six root causes that went forward: C1 inconsistent degassing control, C2 variation in molten-metal condition, C3 die temperature variation, C4 venting condition not consistently verified, C5 critical parameters not systematically monitored and C6 verification frequency not sufficiently defined.

E. Evidence for the Causes

The first was whether it was gas related, as the causes are different, or shrinkage related. The gas cavity (blow holes) accounted for 18.67% of the baseline defects, and shrinkage accounted for 9.33% of the baseline defects. The type of porosity may be either. Gas-type defects were thus a fraction of the total number of baseline defects, ranging somewhere between 18.67% and 56.00%. We did not assume a gas explanation because of the fact that in one ADC12 casting, shrinkage was found to be the primary cause of porosity, by Hamasaki and Miyahara [4]. The baseline X-ray images could not be counted versus the morphology criteria in the foundry notes [8] and [9] and therefore the signature test T2 is found to be Partial for all causes. Both mechanisms are included in the 6 causes. The main mechanism of action of degassing, melt condition, venting and shot parameters is on the basis of gas entrapment. Mainly filling and solidification is the effect of die temperature and intensification pressure.

Table 4. EVIDENCE MATRIX FOR THE SIX ROOT CAUSES

Cause	T1	T2	T3	T4	T5	Status
C1 Degassing	Met	Partial	Met	No record	Met	Supported
C2 Melt condition	Met	Partial	No record	No record	Met	Provisional
C3 Die temperature	Met	Partial	Met	Partial	Met	Supported
C4 Venting	Met	Partial	Met	Partial	Met	Supported
C5 Parameters	Met	Partial	Met	No record	Met	Supported
C6 Verification frequency	Met	n/a	Met	Met	Met	Verified

n/a: test not applicable to a systemic cause.

The status in Table 4 is obtained by applying the rule of Section III-F. C6 is Verified. The proportion increased weekly for twelve weeks, no reaction was recorded, and the weeks after the improvement decreased after a frequency of verification was recorded. C1, C3, C4 and C5 are Supported by a known mechanism, observed practice and response to action. C2 is Provisional since there is no evidence of variation in the melt at a practice level. These parameters are provided in the literature, for instance, 710 ± 10 °C for the melt temperature and 195 ± 5 °C for the die temperature in a similar alloy [6]. These indicate where a parameter should be found and they are not measurements taken on this plant.

F. Corrective Actions

Came up with 9 actions that we introduced at the same time (Table 5) and that were each associated with one or more cause. The goal was to prevent porosity rather than only detect it after it happens through x-ray and visual inspection.

Table 5. CORRECTIVE ACTIONS IMPLEMENTED

No.	Area	Action
1	Degassing	Standard procedure with defined sequence and verification
2	Melt temperature	Defined and monitored temperature range
3	Die temperature	Verification before production
4	Venting	Periodic vent cleaning and condition check
5	Process parameters	Documented settings displayed at the machine
6	Monitoring	Parameter monitoring and recording sheet
7	Verification	Defined periodic verification frequency
8	Work instruction	Standard work instruction including first-piece inspection
9	Operator awareness	Training on degassing, monitoring, die and vent inspection, defect verification

G. Post-Improvement Results

As a result of implementation, 24200 components were inspected and 200 found to be defective, giving a rate of 0.00826 or 0.83% (Table 1). By Eq. (4), the overall defect percentage fell by 55.85%, and porosity cases fell from 168 to 65, a reduction of 61.31% (Fig. 5). The percentages 1.88 and 0.83 rounded to the nearest percent add up to 55.85%. The two are in agreement since the exact proportions are 55.9%.

 ISSN: 3107-6513

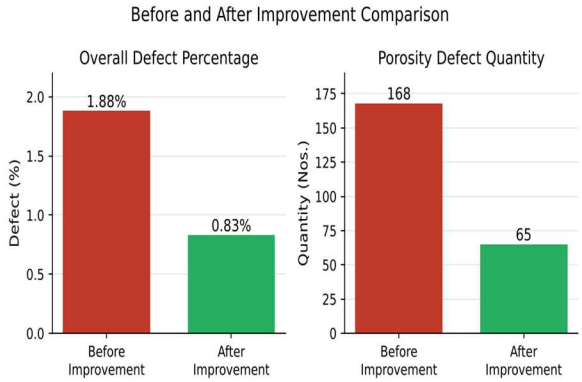

Fig. 5. Overall Defect Percentage and Porosity Quantity Before and After Improvement

All defect type decreased (Table 6). Porosity decreased most and the gas-type defects (porosity plus blow hole) decreased by 57.54%. The defects that are not directly related to gas, such as flash, decreased the least. Cold shut, shrinkage and crack also decreased by 44-48%. This implies better control of the die temperature and better filling and process stability as a whole.

Table 6. DEFECT-WISE RESPONSE TO THE IMPROVEMENT

Defect	Before	After	Reduction (%)
Porosity	168	65	61.31
Blow hole	84	42	50.00
Cold shut	50	28	44.00
Shrinkage	42	23	45.24
Crack	29	15	48.28
Misrun	21	10	52.38
Flash	15	9	40.00
Other defects	11	8	27.27
Type not recorded	30	0	—
Total	**450**	**200**	**55.56**

Quantities are raw counts; inspected quantity was 24,000 before and 24,200 after.

Two-proportion tests (Table 7) show that the overall fall from 1.875% to 0.826% is significant ($z = 9.98$, $p < 0.001$). So is the porosity fall from 0.700% to 0.269% ($z = 6.83$, $p < 0.001$). Both still hold after a Bonferroni correction for four comparisons. The shrinkage difference ($p = 0.017$) does not, so we treat it as indicative only.

Table 7. TWO-PROPORTION TESTS OF THE BEFORE–AFTER DIFFERENCE

Measure	Before (%)	After (%)	z	p
Overall defective	1.875	0.826	9.98	< 0.001
Porosity	0.700	0.269	6.83	< 0.001
Blow hole	0.350	0.174	3.79	< 0.001
Shrinkage	0.175	0.095	2.39	0.017

Two-proportion tests (Table 7) show that the overall fall from 1.875% to 0.826% is significant ($z = 9.98$, $p < 0.001$). So is the porosity fall from 0.700% to 0.269% ($z = 6.83$, $p < 0.001$). These remain following a Bonferroni correction for four comparisons. The difference in shrinkage ($p = 0.017$) is not considered significant so we use it only for indication.

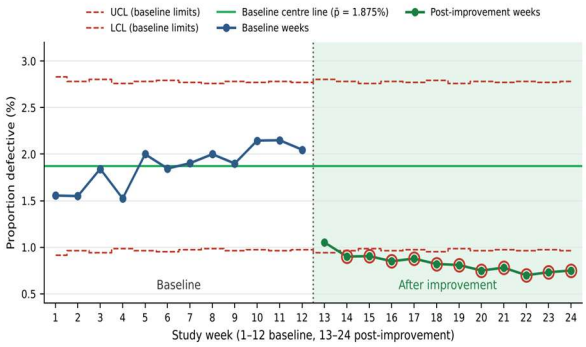

Fig. 6. Post-Improvement Proportion Defective Against Baseline Control Limits

A second check is provided by the control chart. All twelve weeks after the improvement were below the baseline centre line and eleven of them (weeks 2 to 12) were below the lower control limit (Fig. 6). That's an indicator of a real change in the process. This did not begin one lucky week and it went on for the entire twelve weeks.

H. Discussion and Limits

There are three restrictions to bear in mind. First, the absolute decrease in porosity exceeded that of most of the other defect types, but there was no significant difference in the proportion of all defects that were porosity (37.33% to 32.50%, $z = 1.19$, $p = 0.236$). The actions enhanced the process overall and the data do not focus on porosity alone. Second, there were 9 actions taken, and the improvement was not caused by any single action, so the improvement can't be attributed to any single cause. Also, a before – after comparison is not a randomised experiment. A lot change in raw materials or differences in die maintenance or inspection during period could have contributed. Third, there were no records of shot, temperature, degassing and vent for either period. Causes C1 to C5 are consequently based on observed practice, published evidence, the pattern in the defect data and the effect of action. Those records enabled tests T3 and T4 to be finished and some causes could shift from Supported to Verified.

Inspection consistency was also checked. Two inspectors take a week at a time in the baseline and report 1.90% and 1.85% defective ($p = 0.80$) and so the baseline is not thought to be caused by one inspector grading more strictly. This does not indicate that both inspectors made the right classifications for the components. This would require both of them to examine the same components.

V. CONCLUSIONS

This work reduced the die casting defects in an ADC12 Steering Rack Housing by taking the data from inspection to improvement. A Pareto analysis of 450 defective components from 24,000 components tested showed that the defect of concern was porosity (37.33%). The baseline P-chart was stable at 1.88% defective but a regression indicated there was a definite upward trend that was not detected by the control limits. Ishikawa and 5-Why analysis resulted in 6 causes. Tested against five evidence criteria, one is Verified, four are Supported and one is Provisional.

The overall defect percentage reduced from 1.88% to 0.83% (55.85%) after taking nine corrective actions and the

ISSN: **3107-6513**

porosity also reduced from 168 to 65 cases (61.31%) after X-ray inspection. Both of these changes were statistically significant ($p<0.001$). Each post-improvement week was lower than each of the baseline weeks and the process became more consistent and lower. This result pertains to this component, plant and period, and the improvement can't be credited to any individual action.

Future work should focus on measuring shot parameters, melt and die temperature, degassing and vent during production, so as to be measured by future shooting to confirm the causes. It should also present actions one at a time or in an experiment or as a design, and should have a cost–benefit analysis. The most direct method to hold the gain is to keep the P-chart running and have a clear frequency of verification.

ACKNOWLEDGEMENT

The authors thank the Quality Assurance and Production teams of Tyche Cast Tech Pvt. Ltd., Mambattu, for permission to carry out this study and for access to the production and inspection records.

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