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ORIGINAL RESEARCH

Process capability improvement through DMAIC for aluminum alloy wheel machining

G. V. S. S. Sharma[1] · P. Srinivasa Rao[2] · B. Surendra Babu[3]

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Abstract This paper first enlists the generic problems of alloy wheel machining and subsequently details on the process improvement of the identified critical-to-quality machining characteristic of A356 aluminum alloy wheel machining process. The causal factors are traced using the Ishikawa diagram and prioritization of corrective actions is done through process failure modes and effects analysis. Process monitoring charts are employed for improving the process capability index of the process, at the industrial benchmark of four sigma level, which is equal to the value of 1.33. The procedure adopted for improving the process capability levels is the define-measure-analyze-improve-control (DMAIC) approach. By following the DMAIC approach, the C_p, C_{pk} and C_{pm} showed signs of improvement from an initial value of 0.66, −0.24 and 0.27, to a final value of 4.19, 3.24 and 1.41, respectively.

Keywords Alloy wheel · CTQ (critical-to-quality) characteristic · DMAIC (define-measure-analyze-improve-control) · Ishikawa diagram · PFMEA (process failure modes and effects analysis) · Control charts

✉ G. V. S. S. Sharma
sarma.gvss@gmail.com

[1] Department of Mechanical Engineering, GMR Institute of Technology, Rajam, A.P. 532127, India

[2] Department of Mechanical Engineering, Centurion University, Parlakhemundi, Odisha 761211, India

[3] Department of Industrial Engineering, GITAM University, Visakhapatnam, A.P. 530045, India

Introduction

The past two decades have seen the realization of the manufacturing firms towards quality consciousness. In pursuit of quality, the main concerns for alloy wheel machining process areas follows: alloy wheel unclean, surface finish deterioration, non-conformance to geometric and dimensional specification, over hump diameter over size or undersize. The spoke profile and rim profile not as per the requirement lead to non-optimal weight and premature wheel failure in the radial fatigue test. Over used machining inserts result in surface finish deterioration and a patchy surface in the paint line. The prime concern in machining is the problem of unclean leading to rework. Hence, aluminum alloy wheel machining constitutes an important area of study for improvement of process capability. In this process more prominence is laid on prevention of defects rather than simply detecting and rejecting the defect in the usual traditional end inspection quality check.

In order to obtain an improved end product quality, process control plays an important role instead of end quality inspection. The modern work on process control was pioneered by Schilling (1994) and was succeeded by employing process control charts by John (1994). Process capability indices, process failure modes and effects analysis (PFMEA), Taguchi's orthogonal array, control charts and process capability monitoring figure comprise the various tools for achieving the sustained process improvements (Lin 2004; Rupinder Singh 2011; Lin et al. 2013; Kumaravadivel and Natarajan 2013; Mariajayaprakash et al. 2013; Chen et al. 2013; Lal et al. 2013; Burlikowska 2005; Yu et al. 2007).

The define-measure-analyze-improve-control (DMAIC) constitutes a systematic procedure for achieving sustained

Table 1 Project Charter of the DMAIC project pertaining to the machining of alloy wheel manufacturing

Objectives

To recognize alloy wheel center hole boring operation as a process capable operation
To relieve the centre hole boring operation from being as a bottle-neck and with a smooth work-in-flow without any staggered inventory

Deliverables and success metrics

To achieve the process potential capability index and process performance capability index i.e., C_p and C_{pk} values for the centre hole boring operation of the alloy wheel, to be greater than 1.33, i.e., more than 4 sigma levels
The C_p and C_{pk} values to be achieved consistently greater than 1.33 for over a persistent period of three months

Team

Team members scope: plant leader, module leader, cell leader, supervisors and operators involved in machining of alloy wheel

Time-line in months → / Stages ↓	1	2	3	4	5	6	7	8	9	10	11	12
Defining the scope of the project, formulating project charter, identifying CTQ characteristic												
Taking measurements of the CTQ characteristic under consideration												
Perform Analysis of the measurements utilizing different quality tools like cause-and-effect diagram, FMEA, PM analysis, and ANOVA												
Improve, control and sustain the improvements achieved over a continuous period of six months by implementing the process monitoring charts and control charts												

Business impact

Raise the process capability levels and awareness of the importance of process monitoring charts in daily production.
Reduce the component rejection and rework by 99% in the first six months after sustenance

S. No.	Components of the project area	Value
1	Plant turnover of alloy wheels per month	=8000
2	Total no. of rejects and reworks per production shifts of 8 h each	=10 wheels
3	Time taken for segregation and rework of components	=2 h per day
4	Production loss due to rejection and rework per month	=30 × 2 = 60 h
5	Monetary loss of 2 h delay in the CNC machining cell	=$5000
6	Total monetary loss per month with 25 working days per month	=25 × $5000 = $125000
7	By avoiding 99% of rejections & rework, the economical savings per month is	=0.99 × $125000 = $123750

The values projected above are on the basis for target turnover of about 8000 components per month

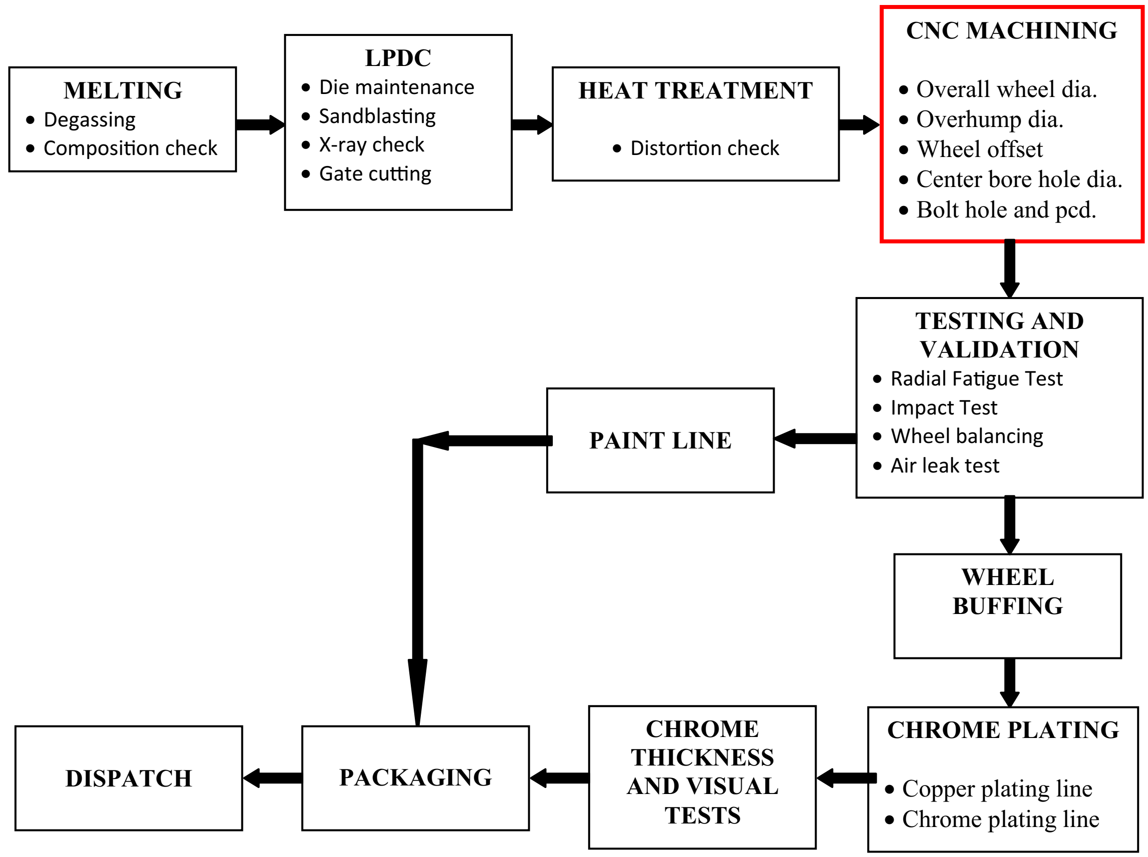

Fig. 1 Process flow chart of A356 aluminum alloy wheel manufacturing process

improvements in the manufacturing process and ultimately in the end product. The DMAIC approach was employed for the quality improvement of the printed circuit boards, integrated circuit (IC) delamination, manufacturing and mechanical execution systems (Tong et al. 2004; Su et al. 2005; Hwang 2006; Gentili et al. 2006). The DMAIC approach was used for standardizing the process parameters involved in the manufacture of optical lens with good surface contour precision in the injection-molding process by Lo et al. (2009). DMAIC approach is followed in varied platforms such as for improving the process parameters and capability of solder printing process, to analyze the manufacturing lines of a brake lever at an automotive components manufacturing company, to improve the fracture resistance of TFT-LCDs and improve the process capability levels of connecting rod and crankshaft manufacturing cells and minimizing variations in food processing industry (Li et al. 2008; Chen et al. 2009; Sahay et al. 2011; Su et al. 2012; Sharma and Rao 2013, 2014; Desai et al. 2015).

Thus, the literature survey indicates that the firms worldwide are adopting the DMAIC procedure for improving the manufacturing process and curtailing down the process rejections. The various firms worldwide are employing the quality control tools for minimizing the deviations and subsequently the number of rejects of the manufactured parts. The present work exemplifies the improvement of machining process capability levels of A356 aluminum alloy wheel.

The structure of the paper is elaborated as follows. This paper starts with introduction and literature survey on DMAIC procedure in "Introduction" section and followed by mapping of manufacturing process flow of alloy wheels in "Alloy wheel manufacturing process flow study" section. Then, the critical-to-quality (CTQ) characteristic of prime importance is identified and the project charter is charted in the Define phase in "Definition phase" section. This is followed by the measurement phase where the dimensional values of the CTQ characteristic are measured and plotted on the process monitoring charts in four successive iterations in "Measurement phase" section. The analysis phase comprises tracing out the causes and prioritizing the corrective actions through the ishikawa diagram and PFMEA in "Analysis phase" section. "Improvement phase" and "Control phase" sections comprise improvement and control phases, respectively, where the process improvement is witnessed in the process monitoring charts. Comparison of the capability

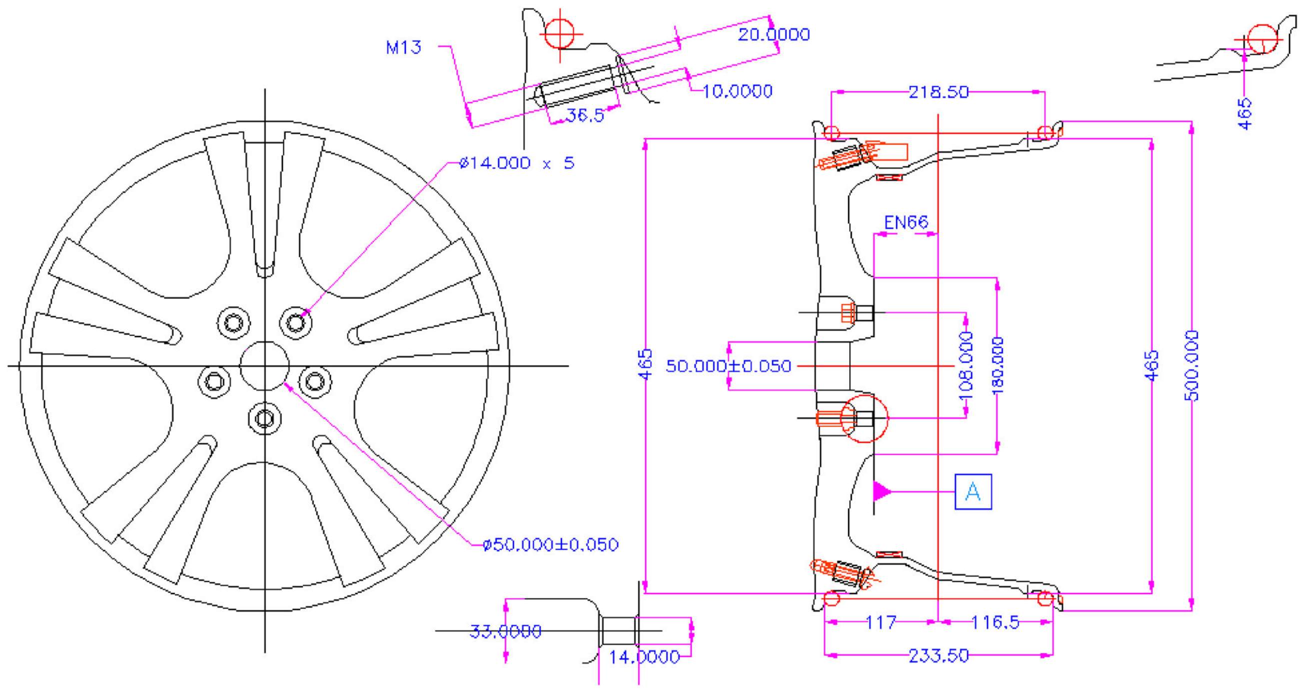

Fig. 2 Alloy wheel machining drawing with center hole diameter of ø50.000$^{(\pm 0.050)}$

Fig. 3 Alloy wheel in assembly, $X =$ center hole diameter of ø50.000$^{(\pm 0.050)}$

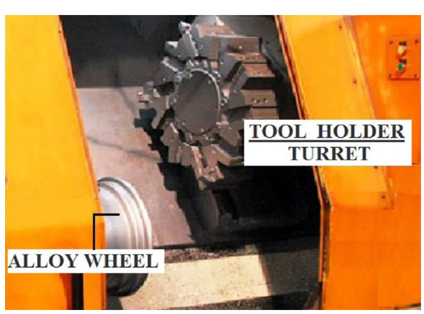

Fig. 4 Set up for center bore diameter machining operation

indices and tolerance zones, using a tolerance capability expert software, is done in "Comparison with a tolerance capability expert software" section. The paper is concluded in "Conclusion" section and followed by references and appendices.

Alloy wheel manufacturing process flow study

Alloy wheels constitute a very prominent aspect of an automobile. This is because it forms an integral part of overall visual esthetic appeal of the automobile. The A356 aluminum alloy with 7% silicon as its prime alloying element forms the popular material for the manufacture of automotive alloy wheel castings. The alloy wheel manufacturing process starts with ingots which form the input into the furnace of the melting section. After ladle preheating, the liquid metal treatment (degassing) is performed in the melting section. The die in the die maintenance area is preheated and sandblasted in order to clean the die surface, increase the surface finish and relieve the external surface stresses. Then, the prepared die is preserved in the Die preservation yard. As per the production schedule the required die is retrieved from the die preservation yard and then fitted onto the low-pressure die cast (LPDC) machine unit.

The LPDC machine unit employed here is a vertical cold chamber die casting unit. The wheel casting coming out of the LPDC unit is quenched in water and is sent for checking internal casting defects in the non-destructive x-ray checking machine. After non-destructive x-ray

Table 2 List of machining operations and corresponding CTQ characteristics

Machining operation No.	Machining operation	CTQ characteristic confirming to the machining operation
10	Back face profile machining	Spoke profile
20	Rim machining	Overall wheel dia-back face
		Overall wheel dia-street face
		Over hump dia-street face
		Over hump dia- back face
30	Wheel center hub machining	ET-wheel offset
		Center bore hole dia
		Bolt hole dia
		Bolt hole pitch circle dia (pcd)
40	Function hole drilling	Tire Pressure sensor bore hole dia drilling
		Air chuck gage hole dia
50	Wheel deburring	Manual deburring
60	Final inspection of CNC machining quality check	

Table 3 Dimensional measurement readings of CTQ characteristic pertaining to the intial Iteration 1

S. No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
I1	50.09	50.04	50.08	50.09	50.04	50.08	50.06	50.03	50.06	50.07	50.06	50.07	50.05	50.08	50.03
S. No	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
I1	50.09	50.02	50.02	50.00	50.08	50.05	50.04	50.05	50.03	50.08	50.05	50.03	50.05	50.04	50.04

check, the alloy wheel casting then follows the gate-cutting process, heat treatment, shot-blasting, CNC machining and air-leak testing. After air-leak test depending on the product requirement the alloy wheel is either sent to the paint line or sent to the Chrome Plating Plant. The paint line mainly consists of degreasing the machined alloy wheel, deoxidizing, conversion coating, pre-heating in dry-off oven, color coating and packing and dispatch. On the other hand, the machined wheels entering the Chrome Plating Plant are subjected to rigorous surface finish improvement by buffing operation. After this it enters the chrome plating process which consists of the copper plating line followed by chrome plating line.

Thus, the manufacturing process of alloy wheel is a complete wholesome process encompassing all the fields of manufacturing ranging from melting in furnace, post-melting treatment, die preparation, sand blasting of die, casting, x-ray inspection of wheel castings, heat treatment, CNC machining, deburring, wheel shot blasting, paint-line process, chrome plating, fatigue test, impact test, CASS (cupric acid salt spray test) and chrome thickness test. The complete manufacturing process of the alloy wheel is charted in Fig. 1.

Definition phase

The present study focuses on the process improvement of CNC machining where the cast wheels are machined to accurate dimensions and tolerances as per the machining drawing specifications. CNC machining is of prime importance in the process of alloy wheel manufacturing, because it is at this place where the shaping of critical dimensions takes place. From functional view point, the wheel gets ready here, for further functional tests. The machining drawing of the alloy wheel is shown in Fig. 2. The photograph of the alloy wheel in assembly is shown in Fig. 3. Figure 4 depicts the machine set-up where the center bore hole boring operation is performed. Also in this "Define Phase" the Project Charter of the DMAIC project pertaining to the machining of Alloy Wheel is defined and is shown in Table 1. The machining operations of the alloy wheel machining and the corresponding CTQ characteristic pertaining to the machining operation are shown in Table 2. After identifying the multiple CTQ characteristics of machining process it is deduced that the CTQ characteristic of prime importance is the Center Bore hole diameter of ø**50.000** $^{(\pm 0.050)}$, as this CTQ dimension forms

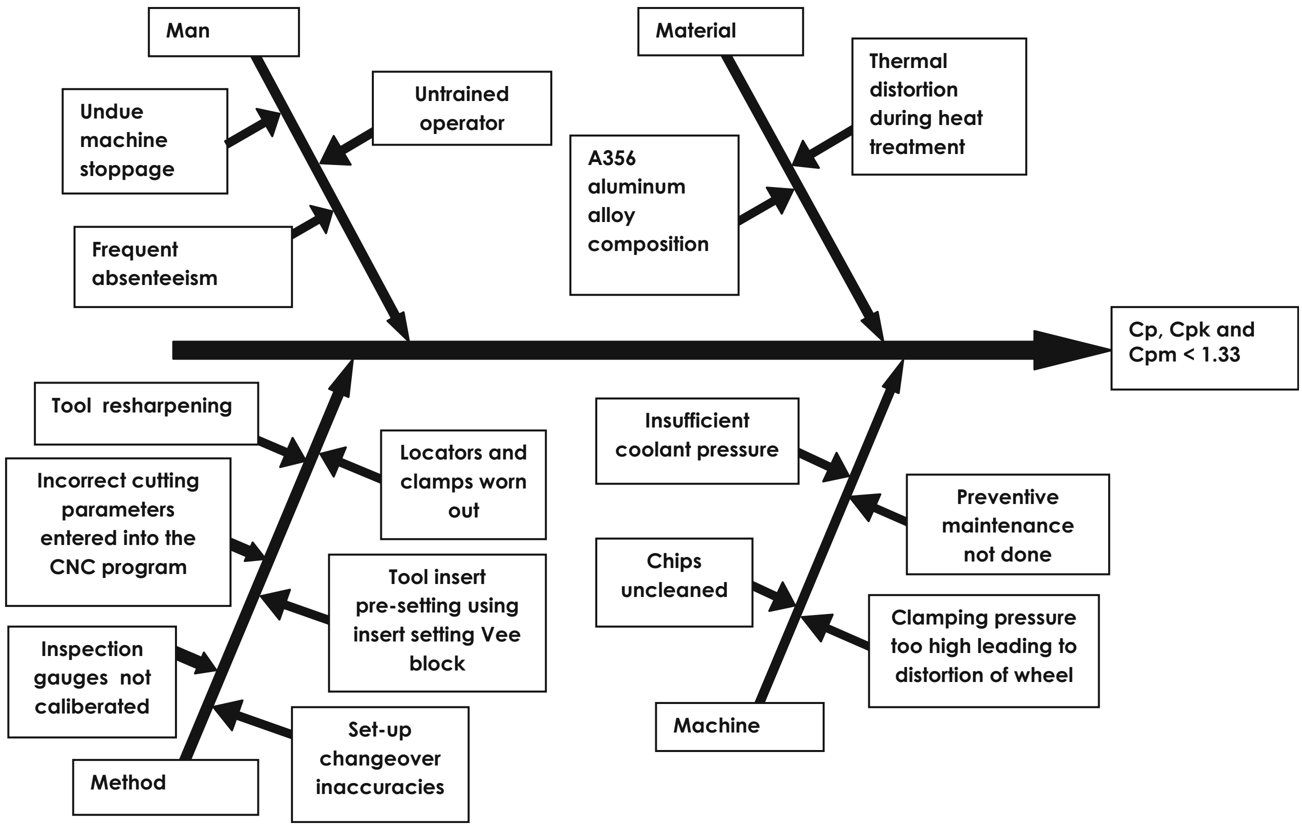

Fig. 5 Cause and Effect Ishikawa diagram

the basic locating dimension for further machining operations, mainly the drilling of pitch circle diameter holes and any deviations of it leads to bottleneck.

Measurement phase

In measurement phase, first the initial data about the CTQ characteristic is collected. This machining data reflect the initial uncorrected state of the process for which the analysis needs to be carried out for obtaining sustained improvements. Based on the six sigma sample size formula the samples are collected:

$$n = \left(\frac{1.96}{\Delta}\right)^2 P(1 - P), \tag{1}$$

where P is the proportion defective that we are estimating (expressed in %) and Δ is the precision or the level of uncertainty in the estimate that we are willing to accept (expressed in %).

With an estimated proportion defective of 10% (i.e., $P = 0.1$) and target Δ of 2.5% ($\Delta = 0.025$) we estimate the sample size of $n = 553$.

Samples of about 800 components are collected. The best fit of 30 consecutive components out of the 800 measured values in each iteration is projected while carrying out the Statistical Process Control during this DMAIC project. This initial data set is termed as Iteration 1 (I1) which is depicted in Table 3. An iteration means a stage depicting the state-of-affairs which reflects the existing condition of the machining process in context of the CTQ characteristic.

The process capability indices C_{p}, C_{pk} and C_{pm} for a target value of 50.010 mm are obtained as 0.66, −0.04 and 0.27, which reflects a large scope of improvement in the process in context of the selected CTQ characteristic.

Analysis phase

After Measurement Phase the analysis phase succeeds, comprising tracing out the causes for poor process performance through the Ishikawa diagram shown in Fig. 5. The potential failure modes of the boring process are estimated through process failure modes and effects analysis (PFMEA) depicted in Table 4. The PFMEA is

Table 4 PFMEA sheet

Process name	Potential failure	Potential effect	Severity	Potential cause	Occurrence	Current controls	Detection	RPN
Center hole diameter boring operation ø50.000(+0.050/−0.050)	Bore hole diameter oversize	Wheel wobbling in assembly	9	Incorrect TOOL insert pre-setting using insert setting Vee block	9	Tool insert setting mandrel calibration	8	648
		Loose fitment of wheel in assembly	9	Tool resharpening not proper	8	Tool resharpening control chart	7	504
				Unclean chips obstruction	3	Chip cleaning made compulsory in the operator instruction sheet	7	189
				Incorrect cutting parameters entered into the CNC program	7	CNC program lock with password protect	8	504
	Bore hole diameter undersize	Incorrect wheel fitment in assembly	5	Incorrect Tool insert pre-setting using insert setting Vee block	9	Tool insert setting mandrel calibration	2	90
		Incorrect location for bolt hole drilling	7	Tool insert not indexed	7	Tool insert to be indexed as per the instructions in process sheet	3	147
				Set-up changeover inaccuracies	5	Set-up changeover instruction to be followed in process sheet	2	70
	Incorrect geometrical tolerance	Eccentricity of PCD leading to incorrect wheel fitment in assembly	7	Unclean chips obstruction in wheel location	5	Chip cleaning made compulsory in the operator instruction sheet	2	70
				High clamping pressure leading to wheel distortion	4	Clamping pressure specified in process sheet	2	56

an analysis tool for identifying the effects of the failure modes, causal factors for the process deviations. PFMEA helps the process personnel to prioritize the corrective actions and confirms which causal factor needs to be addressed first. Rankings for Severity of the effects, causal occurrence frequency and detection control ability are allotted from 1 to 10 point scale (Lange et al. 2001). The product of severity, occurrence and detection rankings is the risk priority number (RPN). Suitable corrective actions for the corresponding failure modes are suggested based on the RPN. The RPNs greater than 100 are given top priority.

Improvement phase

In the Improvement Phase, the causal matrix is formulated for detailing down the causes responsible for the poor performance among the Iterations. This causal matrix is charted in Table 5. From the ANOVA technique (discussed in detail in the Appendix 2) it is deduced that 73% of variability is due to the improper tool insert setting v-block, inaccuracies in setup changeover and undue machine stoppage. After taking the corrective actions in the successive iterations (dimensional measurements of the CTQ characteristic in the 2nd, 3rd and 4th iterations are

Table 5 The causal matrix

Cause. No.	Category	Colour code	Cause	Iteration 1	Iteration 2	Iteration 3	Iteration 4
01	Material		Thermal distortion	✓			
02			Alloy composition	✓			
03	Man		Untrained operator	✓			
04			Undue machine stoppage			✓	
05			Frequent absenteeism		✓		
06	Method		Tool resharpening		✓		
07			Incorrect cutting parameters entered into the CNC program	✓			
08			Inspection gauges not calibrated	✓			
09			Set-up changeover inaccuracies		✓	✓	
10			Tool insert pre-setting using insert setting Vee block			✓	
11			Locators and clamps worn out	✓			
12			Chips uncleaned		✓		
13	Machine		Insufficient coolant pressure				
14			Machine Preventive maintenance	✓			
15			Clamping pressure too high leading to distortion of wheel	✓			
16			Frequent changes in ECN				✓

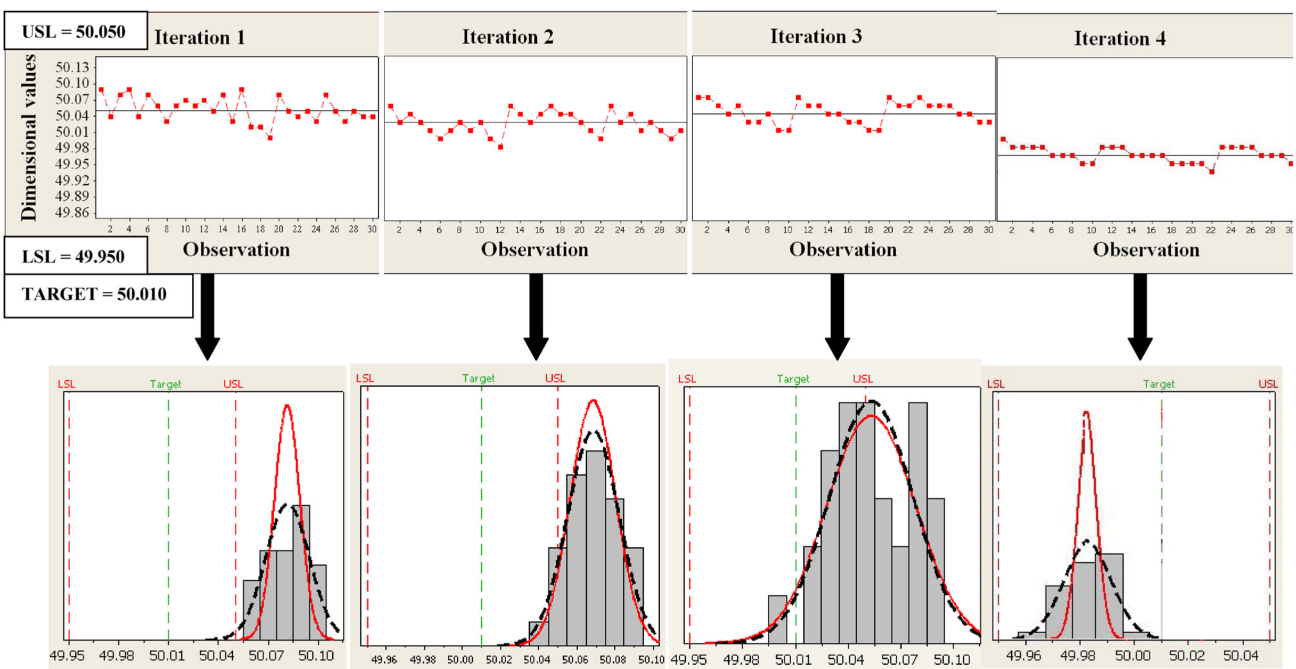

Fig. 6 Process capability analysis depicting run charts and histograms of Iterations 1, 2, 3 and 4

projected in a tabular form in the Appendix 2) and corresponding process capability indices are computed. This datum pertaining to the CTQ characteristic is plotted on the process monitoring charts for performing the process capability analysis and this is shown in Fig. 6.

On analyzing the process monitoring charts it can be deduced that Iteration 1 does not show any significant pattern but in Iteration 2 indicates a cyclic pattern (Du et al. 2013). Upon testing for the causal factors, this cyclic pattern in the observations emerges strongly in Iterations 3 and 4. The reason for this cyclic pattern is elaborated as follows: In order to eliminate the inaccuracies in the boring bar insert setting, after every ten components being machined, the boring bar insert is raised to compensate for constant progressive wear-out of the boring bar insert on continued boring operation. The insert is elevated by about 0.060 mm, over the diametric dimension. This exercise is performed with the help of a test mandrel and a boring bar tool insert setting V-block22, shown in the Fig. 7. Due to progress in machining the cutting tool insert gets worn out which is reflected in the dimension of the CTQ characteristic. In order to compensate the wear in the insert, it is elevated by 0.060 mm over the diametric dimension every time the wear exceeds 0.060 mm over the diametric dimension. This results in a cyclic wear pattern on the dimensions as captured in iteration 4 of Fig. 6 of the process monitoring charts. The contact surfaces of the Vee-Block are case hardened to achieve hardness up to 55 HRc. The case depth of hardness is of about 0.5–0.8 mm in order to sustain wear and tear. Table 6 summarizes the values of process capability indices derived from each improvement Iteration.

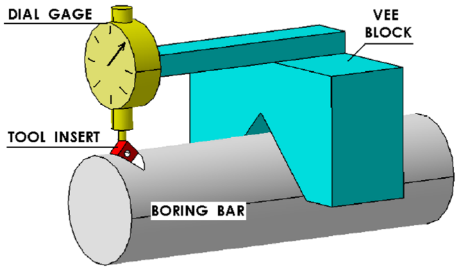

Fig. 7 Schematic diagram of tool insert setting Vee-Block

Control phase

After recording the improvements, the real challenge for a process engineering personnel lies in control and sustenance of recording improvements in the C_p, C_{pk} and C_{pm} values. In this perspective, the X bar and R control charts are employed as a measure for sustaining improvements.

Table 6 Process capability indices

S. No.	Capability index	Iteration 1 (initial stage)	Iteration 2 (1st optimization step)	Iteration 3 (2nd optimization step)	Iteration 4 (3rd optimization step)
1	C_p	0.66	1.40	2.18	4.19
2	C_{pk}	−0.04	−0.52	−1.38	3.24
3	C_{pm}	0.27	0.22	0.18	1.41

S.No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
X1	50.04	50.00	50.00	50.03	50.01	50.01	50.03	50.00	50.02	50.00	50.02	50.02	50.03	50.01	50.02	50.01	50.00	50.02
X2	50.02	50.01	49.99	50.04	50.00	50.02	50.03	50.00	50.02	50.00	50.02	50.01	50.02	50.01	50.02	50.01	49.99	50.01
X3	50.03	50.02	50.04	50.03	50.04	50.01	50.02	50.01	50.02	49.99	50.03	50.01	50.02	50.01	50.02	50.00	50.02	50.01
X4	50.02	50.01	50.03	50.03	50.02	50.00	50.01	49.99	50.01	49.99	50.02	50.00	50.02	50.00	50.01	50.00	50.02	50.01
X5	50.01	50.02	50.02	50.02	50.03	50.01	50.02	49.99	50.01	50.03	50.02	50.00	50.02	50.00	50.01	50.00	50.02	50.00

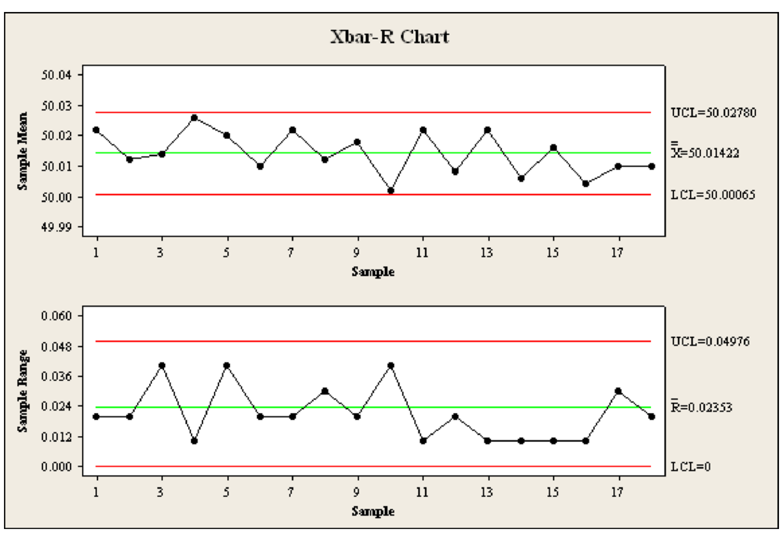

Fig. 8 $\overline{X}$ and R control chart

Table 7 Comparison of process performance with Tolerance Capability Expert software

Characteristic	Graphical Plot 1 with predicted C_{pk} for predetermined tolerance
Center hole diameter after precision boring operation with process dimension as ø50.000 mm	Please refer Fig. 9
Characteristic	Graphical Plot 2 with predicted tolerance for predetermined C_{pk}
Center hole diameter after precision boring operation with process dimension as ø50.000 mm	Please refer Fig. 10

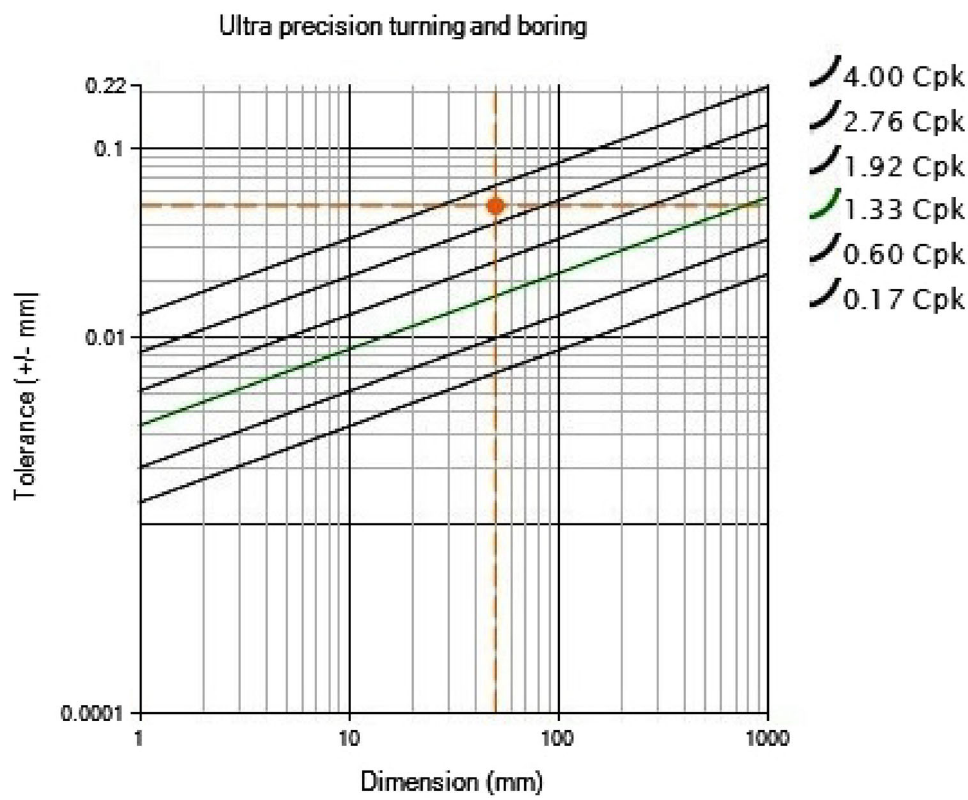

Fig. 9 Graphical plot for center hole diameter precision boring with predicted C_{pk} of 3.27 for predetermined tolerance of ±0.050 mm

Figure 8 depicts the X bar and R control charts for monitoring the machining process under consideration. The observations from this control phase are from Iteration 3.

Since there are no outliers and no out-of-control subgroups and the values are consistently within the control limits, the CNC alloy wheel machining is declared to be process capable with respect to the CTQ characteristic of center bore hole diameter.

Comparison with a tolerance capability expert software

The improved Process performance capability index for the center hole diameter of ø50.000 $^{(\pm 0.050)}$ obtained through boring operation is compared with a tolerance capability expert software (https://tce.tolcap.com/login, 2016) as observed by Sharma et al.(2016). The graphical outputs are tabulated in Table 7.

It is observed from the graphical plots of Tolerance Capability Expert software that for center hole diameter precision boring with predetermined tolerance of ±0.050 mm, the predicted C_{pk} is 3.27 which is almost equal to the obtained final value of 3.24 through this process improvement work. This is depicted in Fig. 9. Also it is observed that for center hole diameter precision boring with predetermined C_{pk} of 2.000 catering to 6σ levels, the predicted tolerance ±0.027 mm leads to a generous improvement in curtailing down the existing tolerance levels from the existing ±0.050 to ±0.027 mm, i.e., almost by 50%. This is reflected in Fig. 10.

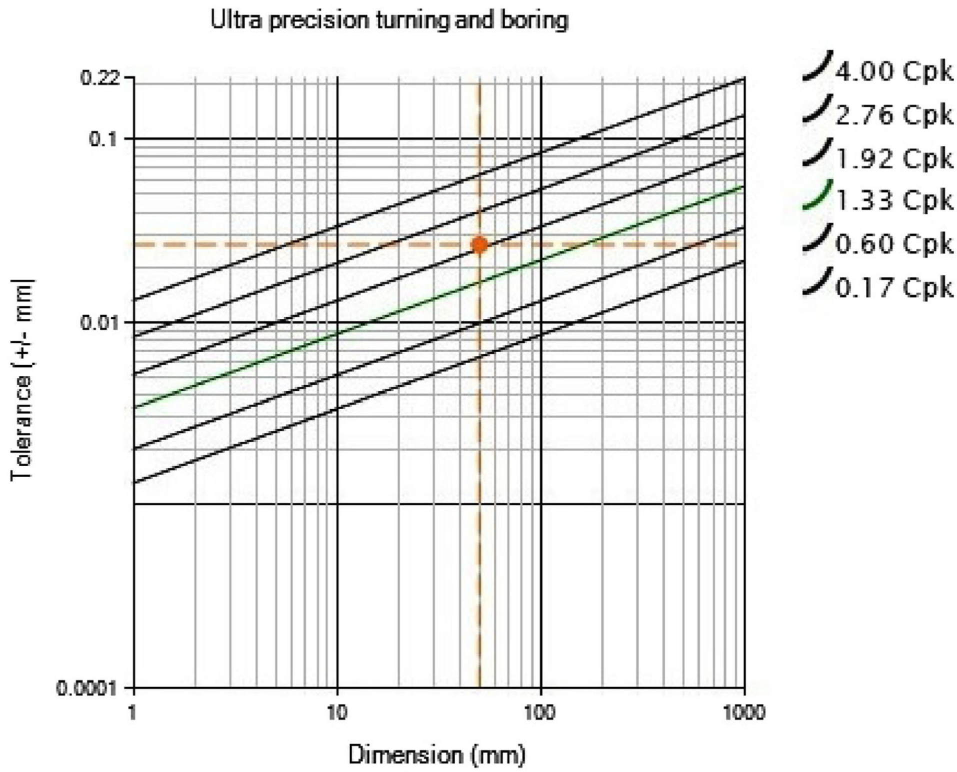

Fig. 10 Graphical Plot for center hole diameter precision boring with predicted tolerance ±0.027 mm for predetermined C_{pk} of 2.000 of 6σ levels

Conclusion

In this paper, by following the DMAIC approach the CNC machining cell is declared to be a process capable cell, with respect to the identified CTQ characteristic of center hole diameter of ø50.000$^{(\pm 0.050)}$. The CFT (cross-functional team), apart from increasing the process capability levels of the CNC machining process, also developed a better control over the process by employing the *X*-bar and *R* control charts at the work shop-floor site. As a result of the process improvement the C_p, C_{pk} and C_{pm} improved from an initial value of 0.66, −0.24, 0.27, to a final value of, 4.19, 3.24 and 1.41, respectively, thereby making the process a statistically capable process. The comparison with tolerance capability expert software strengthens the observation that the process improvement of C_{pk} equal to 3.24 is achievable and for achieving six sigma levels of C_{pk} of 2.000 the tolerances can be narrowed down to 0.027 mm, i.e., by about 50%. It can be concluded that the present DMAIC methodology can be readily horizontally deployed as a disciplined problem solving approach for the process engineers to solve the process-related problems in the other manufacturing cells of the A356 aluminum alloy wheel manufacturing process.

Appendix 1

Nomenclature

μ	Process mean
μ_i	*i*th value of μ
σ	Standard deviation
σ^2	Variance
USL	Upper specification limit
LSL	Lower specification limit
C_P	Process potential capability index
C_{PK}	Process performance capability index
H_0	Null hypothesis
H_1	Alternative Hypothesis
x_{ij}	Data from the *i*th level and *j*th observation
N	The total sample size
K	Number of levels
SST_T	Sum of squared deviations about the grand mean across all N observations
SST_L	The sum of squared deviations for each level mean about the grand mean
SST_E	The sum of squared deviations for all observations within each level from that level mean

MST_L Mean of squared deviations between levels
MST_E Mean of squared deviations within levels
HSD Honestly significant difference
Q Studentized range statistic
η^2 Eta square, a measure of proportion of the between factor variability to the total variability
ω^2 Omega square
$_T$ (Subscript) Total
$_E$ (Subscript) Error
$_L$ (subscript) Level
Df Degrees of freedom for ANOVA test

Appendix 2

Analysis of variance (ANOVA)

ANOVA starts with checking for the assumption about the normality of the data and then formulation of the hypothesis to be tested. A post hoc analysis becomes mandatory if $F_{STATISTIC}$ is found to be greater than $F_{CRITICAL}$.

Testing the assumptions for normality of data and Formulating the Hypothesis

The pre-requisites for performing one-way ANOVA test is to find departure from normality among the sets of the data. The normal probability plot is seen linear with equispaced values. The P value is less than the α value of 0.05 thereby indicating that a linear relationship exists with normality retained. The results are further strengthened by the fact that there are no unusual data points.

The null hypothesis (H_0)and the alternate hypothesis (H_1) can be formulated in the present context as:

H_0: $\mu_i = \mu$ all $i = 1, 2, 3, 4$
H_1: $\mu_i \neq \mu$ for some $i = 1, 2, 3, 4$ where,
μ_i is the population mean for level i, and
μ is the overall grand mean of all levels.

In the present study there are 4 levels (i.e., 4 iterations) with each level consisting of 30 measurement readings of center bore hole diameter of alloy wheel. The box plot and the normal probability plot are captured in Fig. 11.

The dimensional measurement readings of the CTQ characteristic spanning over the four successive Iterations is shown in Table 8

Finding the $F_{STATISTIC}$

The ANOVA Table obtained from Minitab software is captured in Table 9. Here it is seen that:

$$F_{STATISTIC} = 110.61 \quad (2)$$

An α value of 0.05 is typically considered, corresponding to 95% confidence levels. If α is defined to be equal to 0.05, then, the critical value for rejection region is $F_{CRITICAL\ (\alpha,\ K-1,\ N\text{-}K)}$. and is obtained to be 2.68. Thus,

$$F_{CRITICAL} = 2.68 \quad (3)$$

Hence, it is seen that:

$$F_{STATISTIC} > F_{CRITICAL} \quad (4)$$

Therefore, the decision will be to reject the null hypothesis. This indicates that there is at least one of the means (μ_i) is different from the remaining other means. In order to figure out where this difference lies, a post hoc test is required.

Post-hoc test

Since here the sample sizes are same, we go for the Tukey's test for conducting the Post-hoc ANOVA test. In Tukey's test, the honestly significant difference (HSD) is calculated as:

$$HSD = q\sqrt{\frac{MST_E}{n}} = 3.92\sqrt{\frac{25.3 \times 10^{-5}}{30}} = 0.0113 \quad (5)$$

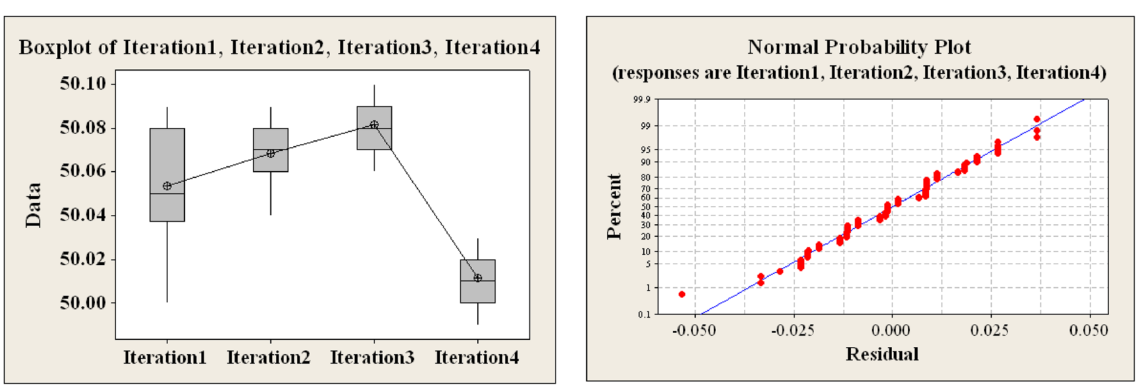

Fig. 11 The box plot and normal probability plot for center bore hole dimensional observations

Table 8 Dimensional measurement readings of CTQ characteristic

S. No.	Iteration 2	Iteration 3	Iteration 4
1	50.09	50.10	50.03
2	50.07	50.10	50.02
3	50.08	50.09	50.02
4	50.07	50.08	50.02
5	50.06	50.09	50.02
6	50.05	50.07	50.01
7	50.06	50.07	50.01
8	50.07	50.08	50.01
9	50.06	50.06	50.00
10	50.07	50.06	50.00
11	50.05	50.10	50.02
12	50.04	50.09	50.02
13	50.09	50.09	50.02
14	50.08	50.08	50.01
15	50.07	50.08	50.01
16	50.08	50.07	50.01
17	50.09	50.07	50.01
18	50.08	50.06	50.00
19	50.08	50.06	50.00
20	50.07	50.10	50.00
21	50.06	50.09	50.00
22	50.05	50.09	49.99
23	50.09	50.10	50.02
24	50.07	50.09	50.02
25	50.08	50.09	50.02
26	50.06	50.09	50.02
27	50.07	50.08	50.01
28	50.06	50.08	50.01
29	50.05	50.07	50.01
30	50.06	50.07	50.00

where q is the studentized range statistic which is equal to a value of 3.92, for a degree of freedom of 116 and $k = 4$, i.e., number of levels as 4.

If "C1" denotes for "Iteration 1" and "C2" denotes for "Iteration 2" and "C3" denotes for

"Iteration 3", and "C4" denotes for Iteration 4, then from Minitab software, the following Grouping Information using Tukey method is shown in Table 8:

From Table 10, it is inferred that Means that do not share a letter are significantly different, i.e., all the Iterations are significantly different from each other.

The pairwise comparison using Minitab is depicted in Table 11.

In the Table 11, it is seen that all the pairwise comparison between the Iterations are greater than that of the HSD in Eq. (5), with the difference between C3 and C4 is 0.07033, being the largest. So, it is deduced that the differences are

Table 9 The ANOVA Table

One-way ANOVA: Iteration 1, Iteration 2, Iteration 3, Iteration 4					
Source	DF	SS	MS	*F*	*P*
Factor	3	0.084036	0.028012	110.61	0.000
Error	116	0.029377	0.000253		
Total	119	0.113412			

Table 10 Grouping information using Tukey method

Iteration Column 'C'	*N*	Mean	Grouping
C1	30	50.08167	A
C2	30	50.06867	B
C3	30	50.05333	C
C4	30	50.01133	D

Table 11 Pairwise comparisons of Iterations

S. No.	Pairwise comparison	Value
1	C1 subtracted from: C2	0.01533
2	C1 subtracted from: C3	0.02833
3	C1 subtracted from: C4	0.04200
4	C2 subtracted from: C3	0.01300
5	C2 subtracted from: C4	0.05733
6	C3 subtracted from: C4	0.07033

statistically significant. Hence, it is concluded that among all the different causes enumerated in the causal matrix, the most influencing causes are those in Iteration 3, namely, the improper tool insert setting v-block, inaccuracies in setup changeover and undue machine stoppage. The extent of influence is given by eta-square (η^2). It measures the proportion of "the between factor variability" to "the total variability" and is given by:

$$\eta^2 = \frac{\text{sum of square between the levels}}{\text{sum of squares across all the 96 observations}} \quad \Rightarrow \eta^2 = \frac{0.084036}{0.113412} = 0.7409 = 74.09\% = 74\% \tag{6}$$

Eta-square is just a ratio of treatment effect variability to total variability. One drawback with eta-square is that it is a biased estimate and tends to overestimate the effect. A more accurate measure of the effect is the omega-square (ω^2) given by:

$$\omega^2 = \frac{SST_G - (k-1)MST_E}{SST_T + MST_E} \quad \Rightarrow \omega^2 = \frac{0.083277}{0.113665} = 0.73265 = 73.265\% = 73\% \tag{7}$$

Hence, from above Eq. (6) it is deduced that 73% of variability is due to the causes addressed in Iteration 3, i.e., improper tool insert setting v-block, inaccuracies in setup changeover and undue machine stoppage.

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