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# Enhancement in production efficiency using DMAIC methodology of six sigma

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**The business concern is primarily interested in the industrial system's production efficiency from an economic standpoint. The primary sources of inefficiency and challenges stem from the decisions made about production operations, particularly in cases where machinery plays a significant role in manufacturing. The manufacturing industry is experiencing increased worldwide rivalry, which has led to a constant increase in customer demand for high-quality and varied products. As a result, improving performance and productivity is now required to strengthen the process's quality. This manuscript uses the Define, Measure, Analyse, Improve, and Control (DMAIC) technique to reduce crankshaft defects and increase quality in the manufacturing business. Quality practices from the Six Sigma DMAIC methodology can be effectively applied to produce high production rates, lower losses, and less waste. Highway Industries Limited has a forging shop that fabricates a variety of crankshaft types, including P-19, KZNA, and M2W. Crankshafts have intricate forms, and a variety of forging flaws, including pitting, unfilling, undersizing, bending, and flash defects, can occur throughout the manufacturing process. The results show that the overall rejection rate of the M2W crankshaft dramatically drops to 1.88% with the deployment of the Six Sigma technique, as opposed to 3.04% before implementation. This study aims to evaluate the effectiveness of the Six Sigma methodology by using the DMAIC cycle methodically. Therefore, the recommended approach saves money, which in turn helps to increase the industry's total economics.**

**Keywords** Improvement, Production efficiency, Six sigma, Rejection rate, DMAIC, Forging

Six Sigma is a disciplined and data-driven methodology designed to help organisations deliver high-quality products and services with minimal defects. By systematically reducing variability and eliminating waste, it improves overall process efficiency and performance[1,2]. The term "sigma" refers to the statistical measure of standard deviation, which indicates how much a process varies from the mean. In this context, Six Sigma evaluates how close a process is to achieving perfection, with a higher sigma level signifying greater process capability and fewer errors[3]. The Six Sigma estimates that there are 3.4 flaws per million[4]. One of the most effective ways to improve organisational performance is by integrating Six Sigma with Business Process Management (BPM) techniques[5]. This combination not only enhances efficiency but also increases profitability by reducing defects and waste. The term "Six Sigma" refers to a statistical measure indicating that process variation remains within six standard deviations from the mean. Key benefits of Six Sigma include improved process flow, reduced defect rates, increased productivity, minimised waste, and sustained quality. The DMAIC (Define, Measure, Analyze, Improve, Control) methodology is a data-driven approach within the Six Sigma framework, primarily used for improving existing processes by identifying and eliminating sources of variation and defects. In contrast, new product or process designs are developed using the Design for Six Sigma (DFSS) methodology, such as DMADV (Define, Measure, Analyze, Design, Verify). The DMAIC methodology (shown in Fig. 1) is used to design new products or processes[6], to boost efficiency, decrease fluorescent powder waste, and save money on the expense of

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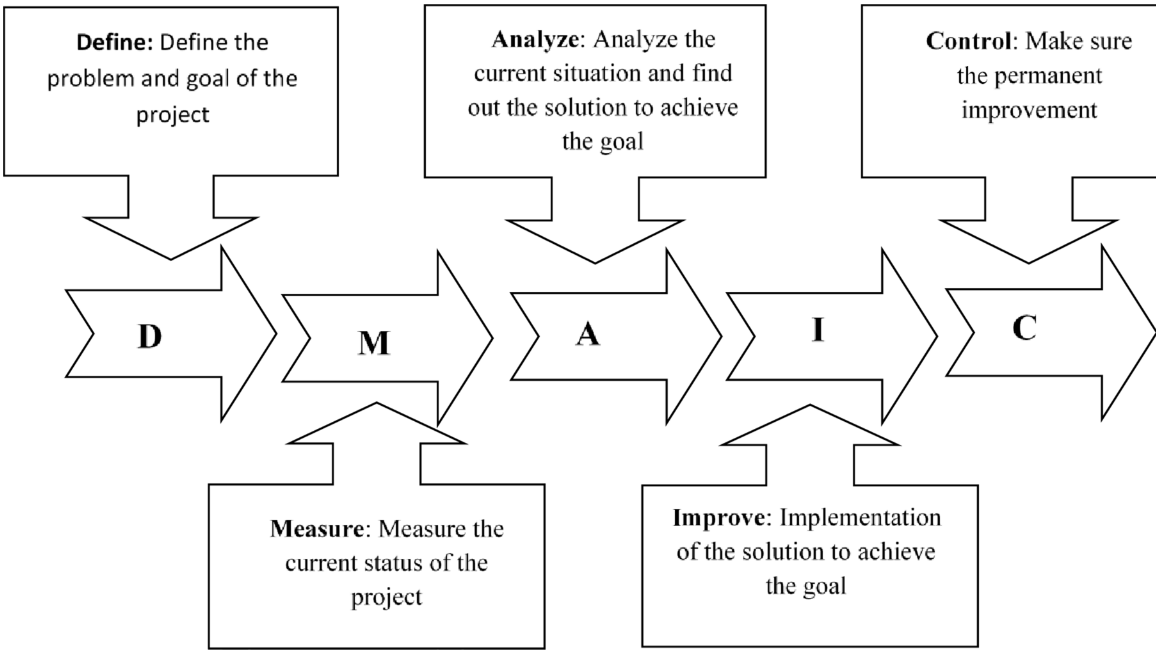


**Fig. 1**. DMAIC flow chart.

wasting more powder in a way that will produce performance that is more predictable, mature, and error-free, by fusing an in-depth comprehension of six sigma statistical principles with a thorough investigation of the service quality model, offered a novel perspective on the application of six sigma to services through total redesign of the product to achieve the intended improvement[7]. A study's recommendation to revamp the curricula of Six Sigma black belt training programmes through waste elimination by using the Lean Six Sigma strategy to achieve the greatest quality, minimise scrap and defects, and the lowest cost with the shortest lead time[8]. The distillation unit of a naphtha reforming plant uses the five-phase DMAIC methodology to increase energy efficiency[9,10].

Six sigma study in the industrial manufacture of electronic sets improves the sigma level from 4.91 Sigma to 5.02 sigma by reducing the defects per million (DPMO) level from 200 units to 180 units. This was achieved through the Enhanced Rolled Throughput Yield (ERTY) technique by reducing the curing period from five to four hours, along with increasing its temperature to 350 °C suggested through Design of Experiments (DOE)[11].

The six-sigma approach was applied in a hydrogen power plant to raise public awareness of the hydrogen economy's infrastructure's advanced efficiency through analysing the financial data of 200 six sigma adopting enterprises and using several matching processes that use varying combinations of pre-adoption return on assets (ROA), industry, and size as matching criteria. Adoptions of Six Sigma methodology have been shown to improve ROA[12,13]. By examining the performance of 84 six sigma companies over ten years, it was found that the effects of six sigma adoption on corporate performance, and discovered that six sigma never hurts corporate performance[14]. In the context of improvement teams, the roles of individual experience, team leader experience, organisational experience, and teamwork experience (team familiarity). The study found a significant correlation between the project's improvement and the team leader's experience[15].

The DMAIC problem-solving methodology from Six Sigma improved quality in a rubber glove manufacturing company by lowering product defects. The study's findings demonstrated a 50% decrease in the quantity of leaky gloves, which greatly aided the organisation in lowering its defects per million opportunities (DPMO) from 195,095 to 83,750 and raised its sigma level from 2.4 to 2.9[16]. Six sigma techniques were applied in the automotive industry to lower quality costs[17], in Lean logistics for essential cutting down on non-value-added operations and enhancing intrinsic processes[18], and in the healthcare industry to reduce information variance[19].

Many researchers developed a correlation between an academic model (CLTE) for cross-collaborative engineering on variation and tolerances and an industrial scenario on improvements[20]. In a Portuguese telecommunications company, a Lean Six Sigma (LSS) project management improvement model, a set of statistical tools supported by the DMAIC cycle was developed[21]. Optimising maintenance for industrial systems through the application of lean Six Sigma was developed[22]. Based on a combination of ANP and DEMATEL techniques, a unique method to assist container terminals in identifying crucial Six Sigma transportation plans was created[23,24].

DMAIC analysis of a crankshaft produced in Jamshedpur by TATA Motors showed the rejection rate dropped from 7.53% to 2.8%, saving an estimated Rs. 5.5 lakh annually in costs, with a few corrective actions and recommendations made for the forging shop's crankshaft manufacturing line[25]. A DMAIC tool is utilised to generate high-quality goods at the lowest feasible cost, which resulted in a reduction in the current rejection rate from 2.43% to 0.21%[26]. In order to lower the paste rejection production defect, M/s Amara Raja Batteries, Tirupati, conducted a DMAIC study from 3.09% to 2.26% with the installation of sensors such as paste sensors, jam-detecting sensors, and door sensors[27]. The transformer's oil leakage in the transformer manufacturing

Industry resulted in a 50% reduction in defects and an annual savings of Rs. 0.01929 million by employing appropriate sealing in the bushing[28]. A significant proportion of aluminium businesses dealing with issues like coil slippage in the hot mill utilized in the forging process to lessen forging flaws such as lapping, mismatch, scales, quench fractures, under filling, resulting in a 70% reduction in heat losses[29]. DMAIC research in casting industries showed that flaws can be minimised by using anti-scale coatings, lubricants, and dies that are properly designed by polishing, grinding, and using simulation programmes to track the movement of material inside the dies, resulting in the rejection rate dropping from 6.53% to 2.5%[30]. Similar casting industries apply DMAIC studies to identify flaws in the casting process, such as blow holes, miss runs, slag inclusion, and rough surfaces. Sand's moisture content can be altered to lessen these flaws[31]. In the hydraulic jack manufacturing industry, Six-Sigma implementation at SSI results in an annual cost savings of Rs. 0.01929 million and an improvement in Z-bench Sigma from 2.21 to 5.64[32]. The axle system manufacturing study the lubricating dies and billets during the process in order to reduce the unfilling fault. By keeping the die at a constant temperature, the lap defect is decreased, resulting in a decrease in the percentage of rejections from 3.04% to 1.21%[33]. In metallurgical operations product quality control process is to enhance product quality by minimising or eliminating the incidence of defects that lead to subpar product quality. The outcome demonstrates a 50% reduction in the number of failed deliveries and a drop in the defects per million opportunities indicator value from 81,038 (2.9 sigma) to 39,636 DPMO (3.3 sigma) with six sigma's use of the DMAIC methodology[34]. A multinational health-care company utilised the Lean Six Sigma (LSS) tool for improving the supplier selection process of outsourced logistics services. Lack of information visibility, top-down changes and unclear communication lines were identified and removed through LSS to improve logistical activities[35]. Taiwan's National Health Insurance (NHI) system adopted the Lean Six Sigma technique to avoid incorrect deductions due to delays in medical expense claims. By removing wasteful and non-value-added steps in the process through Robotic Process Automation (RPA) tools, the process time is reduced by 380 min and enhances Process Cycle Efficiency (PCE) from 69.07 to 95.54%[36]. Thailand-based electric vehicle parts manufacturing identifies inefficiencies, improvements, and establishes control mechanisms to improve and streamline the procurement process to optimize and reduce the costs for 3PL services employed[37].

The main goal of this paper was to describe the application of Six Sigma using the DMAIC methodology at Highways Industries Limited in Ludhiana, Punjab, India, and to reduce the forging process's rejection rate in the production of crankshafts, which will save money. The plant's manufacturing efficiency is impacted by eliminating several forging flaws through the present study.

## Research methodology

The main objective of this study is to apply the Six Sigma DMAIC methodology to reduce forging defects in M2W crankshaft production at Highway Industries Limited, Ludhiana, India. The research addresses the question: 'How can the structured application of DMAIC improve production efficiency and reduce rejection rates in forging operations?' The study aims to contribute practical insights into the implementation of DMAIC for defect reduction and process optimization in the forging industry. The rejection rate in the manufacturing of Crank Shafts at Highways Industries Limited, Ludhiana, Punjab, India, is proposed to be reduced using DMAIC Methodology of Six Sigma by following the underlying five steps, which are depicted in Fig. 2 as given below:

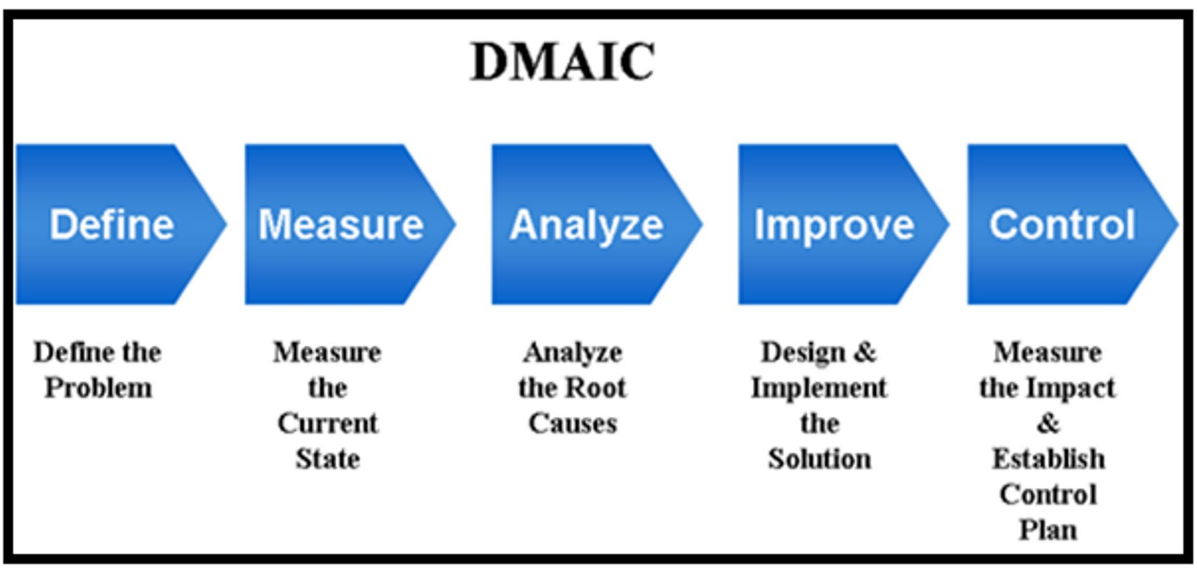


**Fig. 2**. Phases of DMAIC Methodology.

## Define phase

The DMAIC research begins with the define phase. It's represented by the capital letter D. The manufacturing process is briefly explained in the definition step. This stage of the process is devoted to identifying manufacturing process flaws and rejection rates. The problem identification, scope, and specific goals are now explicitly linked to the production data of three crankshaft types (P-19, KZNA, and M2W), with justification for selecting M2W as the focus due to its higher rejection rate.

- Material used: In the said industry S48C grade carbon steel is used for manufacturing crankshafts (M2W, P-19 and KZNA) in forging shop.

(a) Billet cutting: S48C grade carbon steel rod is cut by a double-column band saw machine in the shape of a billet. This billet is used for making the Crankshaft. The length of the billet is 85.05 mm, as shown in Fig. 3.

(b) Induction heating: After cutting the billet, it is heated at 1210–1250 °C in an induction heating machine by passing the material through an induction coil with the help of a conveyor. The heating is carried out to increase the hardness of the billet.
(c) Forging press: In a forging press, the operations are performed in two stages. In the first stage, a hot billet is placed on the bottom blocker and consequently struck by the top blocker, which gives the rough shape of the crank. In the second stage, the rough crank is placed on the bottom finisher, and after being struck by the top finisher, it is converted into the final forged crank.
(d) Trimming press: The unwanted material of the forged crank is removed by the trimming process. This process is carried out by placing the hot forged crank on the die, followed by punching along guiding plates on the forged crank, which ultimately removes the unwanted material from the crank.
(e) Products: Various types of Crankshafts, viz., P-19, KZNA, and M2W, are manufactured in the forging shop as shown in Fig. 4.

(f) Define products: The information was gathered over the course of five weeks in August for three distinct types of crankshafts: P-19, KZNA, and M2W. Table 1 shows the total production in five weeks as well as the total number of rejections.

Because of its greater rejection rate, the M2W crankshaft was selected for this case study. Defects like pitting, unfilling, total length undersize, flash, and dent marks are what lead to rejection.

## Measure phase

The DMAIC study's second phase is measurement. All production and rejection data were recorded daily by the Quality Assurance (QA) team at Highway Industries Limited and verified by the Production Department. Measurements were cross-validated using inspection reports and rejection logs maintained for each shift. This ensured data reliability and consistency across the five-week intervals before and after the improvement activities. The data was collected in terms of the number of pieces concerning the manufacturing of M2W crankshaft product from 1st August, 2013 to 4th September, 2013 (Five Weeks) as shown in Table 2. Detailed quantitative data covering five weeks of production have been included (Table 2), with a defect-wise breakdown and percentage analysis to provide a clear baseline for performance assessment.

**Fig. 3**. Billet.

**Fig. 4**. Forged crankshaft.

| S.No. | Products (type of crankshaft) | Production (no. of pieces) | Rejection (no. of pieces) | Rejection (in %) |
|---|---|---|---|---|
| 1 | P-19 | 248,045 | 5128 | 2.06% |
| 2 | KZNA | 210,024 | 4876 | 2.32% |
| 3 | M2W | 230,564 | 7032 | 3.04% |

**Table 1**. Total production and rejection in five weeks.

| Weeks | Production | Rejection | Pitting defect | Total length undersize defect | Un-filling defect | Flash defect | Bend defect |
|---|---|---|---|---|---|---|---|
| 1 | 45,633 | 1406 | 461 | 410 | 432 | 65 | 38 |
| 2 | 46,018 | 1389 | 422 | 435 | 407 | 58 | 67 |
| 3 | 46,326 | 1379 | 447 | 411 | 436 | 48 | 37 |
| 4 | 46,494 | 1435 | 475 | 462 | 442 | 34 | 22 |
| 5 | 46,123 | 1423 | 446 | 427 | 410 | 78 | 62 |
| Total | 230,564 | 7032 | 2251 | 2145 | 2127 | 283 | 226 |

**Table 2**. Data on M2W crankshaft production and rejection (five weeks).

Overall Percentage of Pieces of M2W Crankshaft Rejected in Five Weeks = 7032/230,564 = 0.0304*100 = 3.04%.

## Analyze phase

The third stage of the DMAIC study is the analyze phase. This stage is devoted to identifying the underlying causes of various manufacturing flaws in M2W crankshafts. The root causes of each major defect type (pitting, undersize, unfilling, flash, and bend) have been analyzed using process observation, defect classification, and root-cause analysis techniques (Figs. 4, 5, 6, 7 and 8). These analyses clearly demonstrate how process parameters and operational practices contributed to defects. The details of this phase in the context of our study are given as follows:

(a) Pitting defect: Small cracks in the corners of the forged part are known as pitting defects, and they are mostly caused by extremely tight fillet radii, which prevent the material from flowing smoothly towards the die's corner. Figure 5 shows the pitting defect for this study. Pitting Defect is primarily caused by improper lubrication of the top and bottom die, reusing of billet, and overheating of the die and billet in the forging process.

(b) Total length undersize defect: When a product is smaller than its usual size, it is referred to as a Total Length Undersize Defect. This defect is shown in Fig. 6. The use of more packing plates causes Total Length Undersize Defect, the ejector system not working properly, and less billet weight in the forging process.


**Fig. 5**. Pitting defect.

**Fig. 6**. Total length undersize defect.

(c) Unfilling defect: An unfilling defect occurs when part of the die chamber is not filled to the top by the flowing metal. Unfilling Defect is caused by improper die setting, low air pressure, and an undersized billet in the forging process. Figure 7 shows the unfilled defect of this research work.

(d) Flash defect: The excess metal, which squirts out of the cavity as a thick ribbon, is known as a flash defect. Flash defect is caused by untimely change of die blocker, material overlap, and die shortage in the forging process. A flash defect of this research work is shown in Fig. 8.

(e) Bend defect: Any structural element that experiences an external load applied perpendicularly to its longitudinal axis will exhibit bend, sometimes referred to as flexure. Bend Defect is caused by a non-standardised Die punch and die loss during the production process in forging process. This defect is shown in Fig. 9.

## Improve phase

It is denoted as I. The improvement phase is the fourth process in the DMAIC study. This phase mainly focuses on improving the process and consequently helps in reducing the defects. Table 3 shows the methods used to improve the process. Process control during the forging and inspection stages was monitored using internal

**Fig. 7**. Un-filling defect.

**Fig. 8**. Flash defect.

rejection trend charts maintained by the Quality Assurance (QA) team. The forging shop followed established SOPs for die lubrication, billet weight verification, and preventive maintenance schedules. These standard procedures ensured consistency in process parameters and operator practices during both pre- and post-improvement phases. A comprehensive improvement plan (Table 3) has been added, showing the corrective methods applied to each identified cause, including training interventions, process standardization, and preventive maintenance actions.

## Control phase

The Control phase is denoted as C. It is the last phase of the DMAIC study. The total production is 231,134 pieces (Five weeks), and the total rejection is 4351 pieces (five weeks). After activity changes in the improvement phase, the overall rejection is 1.88%. The data about various types of defects is collected in five weeks (16th September, 2013 to 20th October, 2013) of the M2W crankshaft product as shown in Table 4. The sustainability of improvements is now verified through post-intervention data (Table 4), showing a reduction in the rejection rate from 3.04% to 1.88%. Control measures such as preventive schedules, die standardization, and operator training have been institutionalized to ensure long-term quality consistency.

**Fig. 9**. Bend defect.

| Defect | Identified the root cause problem | Method |
|---|---|---|
| Pitting | The top and bottom die is not properly lubricated during working time | By training the oilman to lubricate the die after 3–4 pieces of manufacturing |
| | Die and billet are overheated during working time. | By maintaining a proper temperature range, depending on the product size |
| | Reusing of used billet | Do not use more than two times a billet |
| Total length undersize | Use of more packing plate | Do not reuse more than three packing plates |
| | Less billet weight | Proper billet cutting by the cutting machine and weighing machines provided for efficient control |
| | Not the proper function of the ejector system | By proper lubrication in the ejector system and by using a new ejector pin in the ejector system. Ejector pin is standardised depending upon the length of the product or by changing the ejector pin as per the preventive schedule |
| Un-filling defect | Die setting not proper | Use of a bolt and a clamp |
| | Low air pressure | By providing a pressure gauge in the machine |
| | Undersize billet | Proper billet cutting by band saw machine and weighing machines to be provide better control. |
| Flash defect | Untimely change of die blocker | By changing the top blocker and bottom blocker after 6500–8500 pieces of manufacturing |
| | Material overlaps | By maintaining proper clearance between the top and bottom blocker dies and maintaining proper temperature |
| | Die shortage | Maintain the single minute exchange die properly. |
| Bend defect | Unstandardised die punch | By using a new die or fewer than three packing plates |
| | Die loss during production | Die change by a preventive schedule. Top and bottom die change in 6500–8500 pieces of manufacturing |

**Table 3**. Use of new method to improve the process.

| Weeks | Production pieces | Rejection pieces | Pitting defect | Total length undersize defect | Un-filling defect | Flash defect | Bend defect |
|---|---|---|---|---|---|---|---|
| 1 | 45,747 | 874 | 284 | 275 | 267 | 35 | 13 |
| 2 | 46,129 | 876 | 278 | 283 | 274 | 32 | 9 |
| 3 | 46,432 | 867 | 265 | 274 | 282 | 25 | 21 |
| 4 | 46,599 | 868 | 279 | 273 | 271 | 34 | 11 |
| 5 | 46,227 | 866 | 288 | 272 | 264 | 27 | 15 |
| Total | 231,134 | 4351 | 1394 | 1377 | 1358 | 153 | 69 |

**Table 4**. Total production and rejection data after five weeks.

The structured documentation of process parameters, SOPs, and data validation steps ensures that the study can be replicated in similar forging and manufacturing environments with comparable equipment and operational setups.

## Results and discussion

One of the six-sigma tools is the DMAIC. Six sigma projects are guided by the DMAIC cycle of process improvement. It can be applied to other enhancement applications in the framework. DMAIC is a well-known approach for tackling problems that makes use of many statistics and quality techniques to enhance basic processes. The following improvements in the areas of pitting defect, total length undersize defect, unfilling defect, flash defect, and bend defect were made possible by the application of the DMAIC study.

(a) Proper lubrication in the die and ejector system.
(b) Correct product shape and decrease in internal cracks.
(c) Billet crack is less owing to controlled heating.
(d) Product shape is better.
(e) Product is of standard size.
(f) The length of the product is not undersized.
(g) Die position stability during working time.
(h) Maintaining of proper stable pressure in the machine.
(i) No delay in the production line.

The purpose of this study was to demonstrate how the DMAIC methodology of Six Sigma can be applied in a forging industry to reduce defect rates, improve quality, and enhance economic efficiency. The following section presents the results in a structured manner, aligned with the five DMAIC phases: Define, Measure, Analyze, Improve, and Control, followed by a broader discussion on the implications of the findings. The Define phase set the foundation of the project by identifying the central problem and scope. Among the three crankshaft types manufactured at Highways Industries Limited (P-19, KZNA, and M2W), the M2W crankshaft was found to have the highest rejection rate at 3.04%. While the other product lines (P-19: 2.06% and KZNA: 2.32%) also faced quality issues, the relatively higher rejection in M2W crankshafts represented a critical challenge because of its larger production volume and greater financial impact on the organization. The project objective was therefore defined as reducing the rejection rate of M2W crankshafts through a structured application of the DMAIC cycle. Specific attention was placed on recurring defects such as pitting, total length undersize, unfilling, flash, and bend, which collectively accounted for most of the observed rejections. In line with Six Sigma principles, the overall aim was to minimize process variability, improve yield, and translate these improvements into tangible financial and operational gains for the company. By clearly articulating the scope and setting measurable goals, the Define phase established a strong baseline for subsequent analysis and interventions.

The Measure phase quantified the problem and provided baseline data for performance evaluation. Over five weeks (August–September 2013), production and rejection figures were collected for M2W crankshafts. A total of 230,564 units were produced during this period, of which 7,032 were rejected, yielding a rejection rate of 3.04%.

A detailed defect-wise breakdown revealed the following distribution of rejections:

Pitting defect: 2,251 pieces (32.0% of total rejections).

Total length undersize defect: 2,145 pieces (30.5%).

Unfilling defect: 2,127 pieces (30.2%).

Flash defect: 283 pieces (4.0%).

Bend defect: 226 pieces (3.2%).

The results highlighted that three defect categories, pitting, undersize, and unfilling, accounted for nearly 85% of the total rejections. These findings underscored the need for targeted improvement measures, focusing on a few high-impact areas rather than dispersing efforts across all possible defects. The baseline measurement phase also provided a quantitative foundation for evaluating the impact of interventions in subsequent stages. The Analyze phase identified the root causes behind the high rejection rates, using both defect observations and process diagnostics.

Pitting defects are small cracks in forged parts were traced to improper lubrication of dies, overheating of billets, and occasional reuse of billets. Inadequate lubrication caused uneven material flow, while excessive temperatures increased the likelihood of surface cracks. Total length undersize defects occurred when crankshafts were shorter than the required specification. Contributing factors included excessive use of packing plates, malfunctioning ejector systems, and inaccurate billet cutting that reduced billet weight. Unfilled defects arose when die cavities were not filled during forging. Root causes included incorrect die settings, insufficient air pressure, and undersized billets. Flash defects are excess metal formation around the crankshaft was linked to untimely die blocker changes, poor clearance settings, and lack of die maintenance. Bend Defects are bending or warping of crankshafts was traced to non-standardized die punches and wear-and-tear of dies during production. The analysis confirmed that the rejections were not random but systemic, resulting from preventable process deviations and lack of standardization. Importantly, many causes were related to operational practices (e.g., lubrication intervals, preventive maintenance), suggesting that improvements could be achieved through relatively simple, low-cost interventions rather than expensive capital investments.

The control phase ensured that the improvements achieved were sustained over time. Data was collected over the next five weeks (September–October 2013) to evaluate the impact of the interventions. Based on Figs. 9, 10, 11, 12 and 13, all observations have been made, that is discussed below.

Total production: 231,134 pieces.

Total rejections: 4,351 pieces.

New rejection rate: 1.88%.

This represented a 38% reduction in the rejection rate compared to the baseline (3.04%). The defect-wise reductions were as follows:

Pitting: reduced by 38.07%.

Total length undersize: reduced by 35.80%.

Unfilling: reduced by 36.15%.

Flash: reduced by 45.93%.

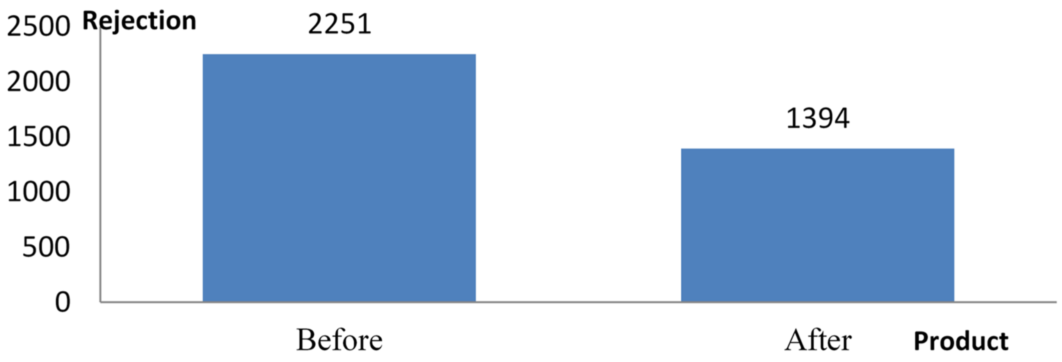


**Fig. 10**. Rejection of M2W crankshafts due to pitting defect in five weeks.

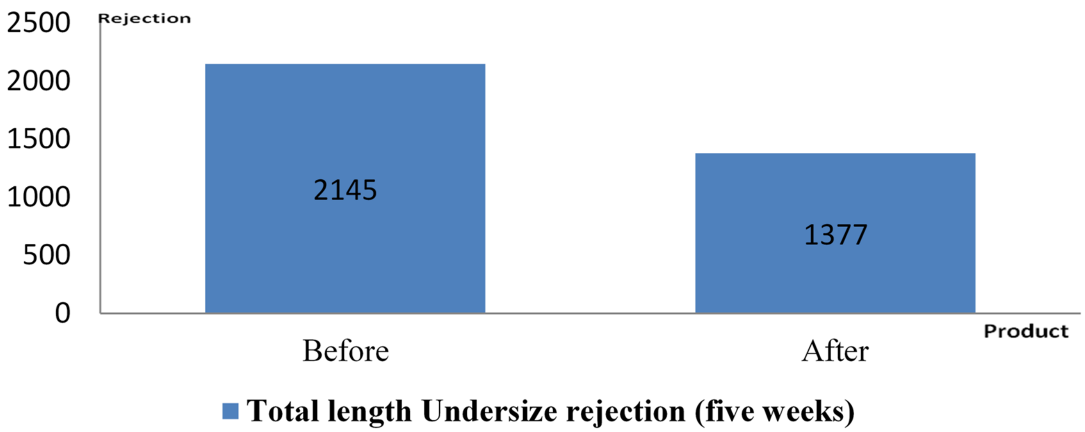


**Fig. 11**. Rejection of M2W crankshafts due to total length undersize defect in five weeks.

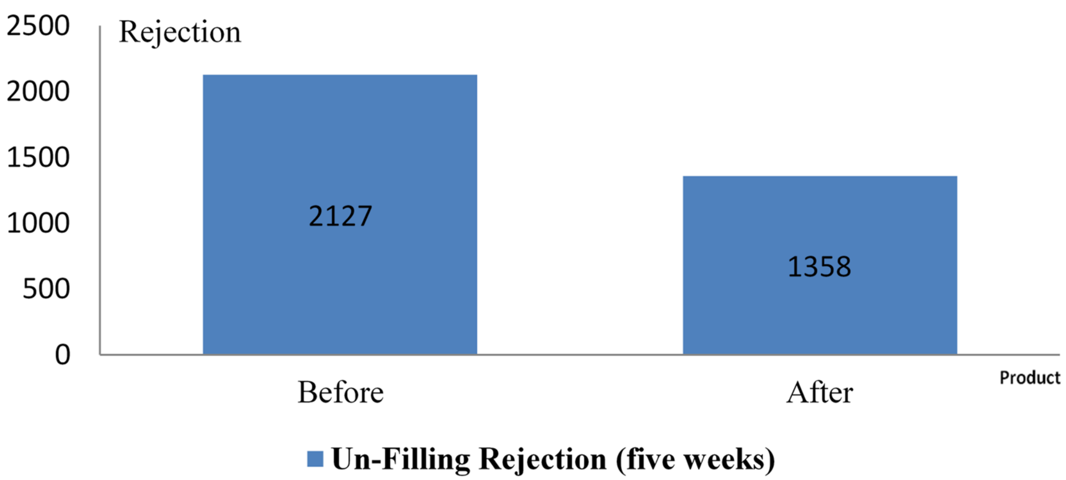


**Fig. 12**. Rejection of M2W crankshafts due to un-filling defect in five weeks.

Bend: reduced by 69.46%.
The improvements translated into significant financial gains:
Approximate daily savings: 75 crankshaft units.
Approximate monthly savings: 2,250 crankshaft units.
Approximate annual savings: 27,000 crankshaft units.
Annual cost savings: Rs. 29.7 lakh.

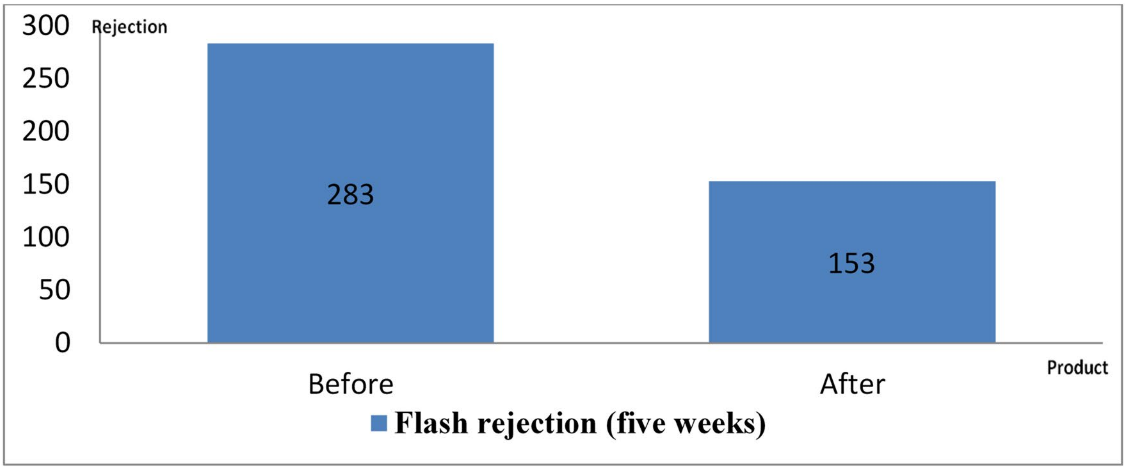


**Fig. 13**. Rejection of M2W crankshafts due to flash defect in five weeks.

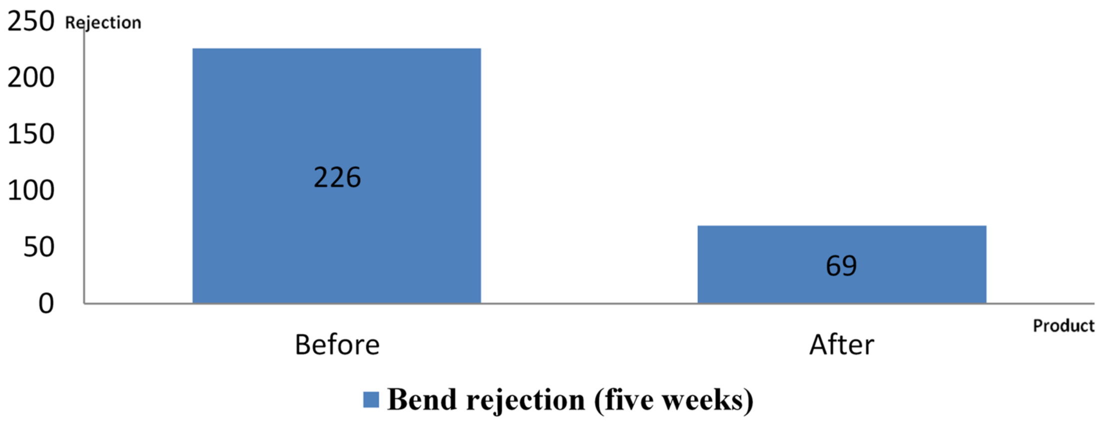


**Fig. 14**. Rejection of M2W crankshafts due to bend defect in five weeks.

In addition to defect reduction, the company reported improvements in process stability, reduced production delays, and greater worker confidence in the manufacturing system. Preventive schedules, training programs, and monitoring mechanisms were institutionalized to maintain these gains. The structured application of the DMAIC cycle successfully reduced rejection rates, improved production efficiency, and delivered significant economic benefits. To further validate the observed improvements statistically, a chi-square test for proportions was conducted to compare the pre- and post-intervention rejection rates of the M2W crankshaft. The test yielded a statistically significant difference ($\chi^2$ = 25.76, $p < 0.001$), confirming that the reduction from 3.04% to 1.88% was not due to random variation but a genuine improvement following DMAIC implementation. Additionally, a p-control chart was developed to visualise weekly defect variation before and after process changes. The control chart indicates that all post-improvement data points remained within control limits and clustered closer to the process mean, signifying enhanced process stability and reduced variability. The results confirm the potential of Six Sigma methodologies for systematic quality improvement in forging industries. However, their broader applicability requires further validation through longitudinal studies and cross-industry comparisons.

The new method used in the process results in drastically reduces the various types of defects in the manufactured M2W crankshaft, consequently resulting in significant savings as shown in Figs. 10, 11, 12, 13 and 14.

### Overall rejection and cost savings

The Overall rejection of the M2W crankshaft product is reduced to 1.885% as compared to 3.04% in five weeks.

(a) Cost of one piece is Rs. 110/-.
(b) Saving pieces per day (approximate) = 200 – 125 = 75 pieces.
(c) Monthly saving pieces (approximate) = 75*30 = 2250 pieces.
(d) Annually saving pieces (approximate) = 2250*12 = 27,000 pieces.
(e) Annual Cost Saving (approximate) = 2700*110 = Rs. 29,70,000/-.

## Conclusions

This study investigated the application of the Six Sigma DMAIC methodology to reduce forging defects in the manufacturing of M2W crankshafts at Highways Industries Limited, Ludhiana, India. The research aimed to evaluate how systematically implementing the Define, Measure, Analyze, Improve, and Control phases could improve production efficiency, reduce rejections, and deliver measurable economic benefits. The findings confirm that DMAIC is an effective structured approach for diagnosing problems, implementing corrective measures, and sustaining improvements in a highly competitive industrial context.

The implementation of DMAIC resulted in a substantial reduction of the rejection rate, from 3.04% to 1.88% within ten weeks. Specific improvements were observed across all defect categories: pitting reduced by 38.07%, total length undersize by 35.80%, unfilling by 36.15%, flash by 45.93%, and bend defects by 69.46%. These reductions not only enhanced product quality but also led to significant financial savings, with annualized benefits estimated at approximately Rs. 29.7 lakh. More importantly, the interventions, such as improved lubrication protocols, standardization of die changes, precise billet cutting, and preventive maintenance schedules, strengthened process stability and reduced downtime, thereby increasing overall production efficiency. Beyond the immediate results, the study demonstrates broader managerial and operational implications. First, it illustrates how data-driven root cause analysis can help industries move beyond ad hoc problem-solving toward systematic improvement. Second, it highlights the importance of workforce training and standard operating procedures in sustaining quality gains. For instance, training oilmen to lubricate dies at regular intervals proved as critical as technical process changes. Third, the findings underscore the economic value of preventive actions, where relatively small adjustments (such as ejector pin replacement schedules) generated substantial long-term savings. These insights may be applied not only in forging industries but also in other discrete manufacturing sectors seeking to optimize efficiency and reduce losses. The study acknowledges certain limitations. The analysis was restricted to a single organization and focused on one product category (M2W crankshaft). While the outcomes were positive, they may not be directly generalizable to other products, industries, or geographical contexts without further validation. Additionally, the data collection period covered only ten weeks, limiting the ability to assess the long-term sustainability of improvements. External factors, such as raw material variability, supply chain disruptions, or workforce fluctuations, were beyond the scope of the present analysis but could influence outcomes in real-world applications. Recognizing these constraints, the conclusions are framed cautiously, emphasizing that while the study demonstrates the potential of DMAIC, its wider applicability must be tested through further empirical studies.The study demonstrates a statistically significant defect reduction using DMAIC tools. However, uncertainty analysis remains limited; future work should include confidence intervals and advanced modeling to enhance robustness and address process variability.

The study also links directly back to the research objective. DMAIC contributes to both theory and practice: it validates Six Sigma's utility in forging industries while offering actionable recommendations for practitioners. Future research should expand the scope by applying DMAIC to multiple product lines or across diverse industries, thereby enhancing generalizability. Incorporating advanced statistical methods, such as Design of Experiments (DOE), regression modeling, or simulation techniques, could also deepen the analysis of defect causality. Integrating Lean tools and emerging digital technologies (e.g., IoT-based monitoring, machine learning for predictive defect detection) with DMAIC offers promising avenues for achieving more sustainable and scalable improvements. This study provides evidence that DMAIC is a powerful methodology for improving production efficiency in forging industries. It reduces defects, improves quality, and delivers tangible economic savings. However, given the study's exploratory nature and its context-specific scope, the findings should be interpreted with caution. With further application and validation, DMAIC has the potential to be a cornerstone of continuous improvement in modern manufacturing. It is acknowledged that the present study primarily relied on descriptive and proportion-based analyses to evaluate improvement outcomes. While the applied chi-square test confirmed the statistical significance of defect reduction, future studies could benefit from incorporating broader inferential tools, such as confidence intervals, regression modelling, or control limit analysis, to quantify measurement uncertainty and strengthen causal inferences. Including such statistical rigour would further enhance the reliability and generalizability of Six Sigma applications across diverse industrial contexts.

## Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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## Declarations

### Competing interests
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