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Defects Reduction in Casting Process by Applying Six Sigma Principles and DMAIC Problem Solving Methodology (A Case Study)

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Abstract

DMAIC one of the Six Sigma methodologies used to improve quality by reducing defects through its several techniques. In this paper Six Sigma and DMAIC used as a defect reduction technique to reduce defects happening during the casting process. For this different type defects are identified, root causes are found and provide a way for minimizing the defects according to the DMAIC phases. Through DMAIC phases from many defects surface roughness is found as main defect and its root causes are found as pouring temperature too high and too coarse the molding sand grain size. For improving the condition, combination of design of experiments (DOE), and two way analysis of variance (ANOVA) are accomplished by Vassar Stats online two way ANOVA solver to find the significance of pouring temperature and grain size on surface roughness. With the help of IBM SPSS Software, boxplot is performed and through trial and error process an optimum solution is gained. At about 50% surface roughness defects are concentrated after performing DMAIC methodology which helped to reduce its defects per million opportunities (DPMO) from 609,302 to 304,651 and improve its Sigma level from 1.2 to 2.

Keywords: Six sigma, DMAIC, Casting process, Defects reduction, ANOVA

"1. Introduction"

In today's world Competition has become much harder. TO be profitable and survive, well performance is required for every industries and organizations. As well as for different shapes and sizes products, making through the casting process, has to uphold the class of the products so that customers get delighted and excellently compete in market place. In general, one of the most vital concerns of the production which is based on casting process is the reduction of common quality defects such as surface roughness, gas porosity, shrinkage defects etc. in casting. From this theme, an organization not only wastes its means and times to rework the products, but also customer's gratification and dependence is also reduced. This paper investigates quality issues of casting and provides a solution so that the common defects can be diminished. In order to complete it, most effective quality management and improvement methodology, Six Sigma used in this paper. In precise, the DMAIC (Define-Measure-Analyze-Improve-Control) problem-solving and improvement model of Six Sigma is followed. With the help of this model, several statistical and quality improvement tools such as fishbone diagram, Pareto chart, Design of Experiments (DOE) and two-way analysis of variance (ANOVA) have been used. As an early step, some of the relevant theories are briefly reviewed about Six Sigma and DMAIC, giving precise attention to the supports and the positive impact on performance that these approaches bring to organizations, and the manufacturing process studied.

"2. Literature Review on Six Sigma"

Six sigma was proposed by Motorola, in the mid-1980s, as an approach to improve production, productivity and quality, as well as reducing operational costs [1]. The Sigma's name originates from the Greek alphabet and in quality control terms, Sigma (σ) has been traditionally used to measure the variation in a process or its output [2]. In the Six Sigma's terminology, the "Sigma level" is denoted as a company's performance [3]. Particularly, a Six Sigma level refers to 3.4 defects per million opportunities (DPMO) [4], or in other words, to have a process which only produces 3.4 defects per every one million products produced. Besides being a measure of variability and organization's quality performance, Brue and Howes [5] mention that Six Sigma is also a management philosophy and strategy as well as a problem-solving and improvement methodology that can be applied to every type of process to eliminate the root cause of defects. In particular, some authors argue that the main benefits that an organization can gain from applying Six Sigma are: cost reduction, cycle time improvements, defects elimination, an increase in customer satisfaction and a significant raise in profits [3, 4, 6, and 7]. Markarian [8] suggests that not only can the process improvement generated by Six Sigma be used in manufacturing operations, as it is the case for the project presented in this paper, but it can also be expanded to improve business sectors such as logistics, purchasing, legal and human resources. In addition, Kumar et al. [9] state that although Six Sigma is normally used in defects reduction (industrial applications), it can also be applied in business processes and to develop new business models. Banuelas et al. [10] claim that other benefits such as (1) an increase in process knowledge, (2) participation of employees in Six Sigma projects and (3) problem solving by using the concept of statistical thinking can also be gained from the application of Six Sigma. To illustrate this point, during the utilization of Six Sigma in this research project, several tools and techniques were employed. One of the Six Sigma's distinctive approaches to process and quality improvement is DMAIC [11]. The DMAIC model refers to five interconnected stages (i.e. define, measure, analyze, improve and control) that systematically help organizations to solve problems and improve their processes. Dale et al. [6] briefly defines the DMAIC phases as follows:

• **Define** – this stage within the DMAIC process involves defining the team's role, project scope and boundary, customer requirements and expectations and the goals of selected projects [12].

• **Measure** – this stage includes selecting the measurement factors to be improved [2] and providing a structure to evaluate current performance as well as assessing, comparing and monitoring subsequent improvements and their capability [4].

• **Analyze** – this stage centres in determining the root cause of problems (defects) [2], understanding why defects have taken place as well as comparing and prioritizing opportunities for advance betterment.

• **Improve** – this step focuses on the use of experimentation and statistical techniques to generate possible improvements to reduce the amount of quality problems and/or defects [2].

• **Control** – finally, this last stage within the DMAIC process ensures that the improvements are sustained [2] and that ongoing performance is monitored. Process improvements are also documented and institutionalized [4].

DMAIC resembles the Deming's continuous learning and process improvement model PDCA (plan-do-check-act) [14]. Within the Six Sigma's approach, DMAIC assures the correct and effective execution of the project by providing a structured method for solving business problems [15]. Pyzdek [16] considers DMAIC as a learning model that although focused on "doing" (i.e. executing improvement activities), also emphasizes the collection and analysis of data, previously to the execution of any improvement initiative. This provides the DMAIC's users with a platform to take decisions and courses of action based on real and scientific facts rather than on experience and knowledge, as it is the case in many organizations, especially small and medium side enterprises (SMEs) [11].

"3. Casting process"

Casting process which is studied and investigated in this paper, are generally comprised of six main steps, namely: (1) mold-making, (2) clamping, (3) pouring, (4) cooling, (5) removal, and (6) trimming.

The process cycle for casting consists of six main stages, which are explained below.

"3.1 Mold-making"

The first step in the sand casting process is to create the mold for the casting. In an expendable mold process, this step must be performed for each casting. A sand mold is formed by packing sand into each half of the mold. The mold-making time includes positioning the pattern, packing the sand, and removing the pattern.

"3.2 Clamping"

Once the mold has been made, it must be prepared for the molten metal to be poured. The surface of the mold cavity is first lubricated to facilitate the removal of the casting. Then, the cores are positioned and the mold halves are closed and securely clamped together. It is essential that the mold halves remain securely closed to prevent the loss of any material.

"3.3 Pouring"

The molten metal is maintained at a set temperature in a furnace. After the mold has been clamped, the molten metal can be ladled from its holding container in the furnace and poured into the mold. Enough molten metal must be poured to fill the entire cavity and all channels in the mold. The filling time is very short in order to prevent early solidification of any one part of the metal.

"3.4 Cooling"

The molten metal that is poured into the mold will begin to cool and solidify once it enters the cavity. When the entire cavity is filled and the molten metal solidifies, the final shape of the casting is formed. The desired cooling time can be estimated based upon the wall thickness of the casting and the temperature of the metal. Most of the possible defects that can occur are a result of the solidification process.

“3.5 Removal”

After the predetermined solidification time has passed, the sand mold can simply be broken, and the casting removed. This step, sometimes called shakeout, is typically performed by a vibrating machine that shakes the sand and casting out of the flask.

“3.6 Trimming”

During cooling, the material from the channels in the mold solidifies attached to the part. This excess material must be trimmed from the casting either manually via cutting or sawing, or using a trimming press.

“4. Six Sigma and DMAIC Application”

“4.1 Define”

Casting is one of the most versatile forms of mechanical process for producing components because there is no limit to the size, shape and intricacy of the articles that can be produced by casting. But during casting process different types of defects are happened. Those defects are responsible for high machining cost, low product quality. So, identifying the most happening defects and reduce as many defects as possible will be the goal of these project. Numbers of casting defects were identified. The casting defects are as below. Among these the most happening casting defects were surface roughness, gas porosity and shrinkage defect.

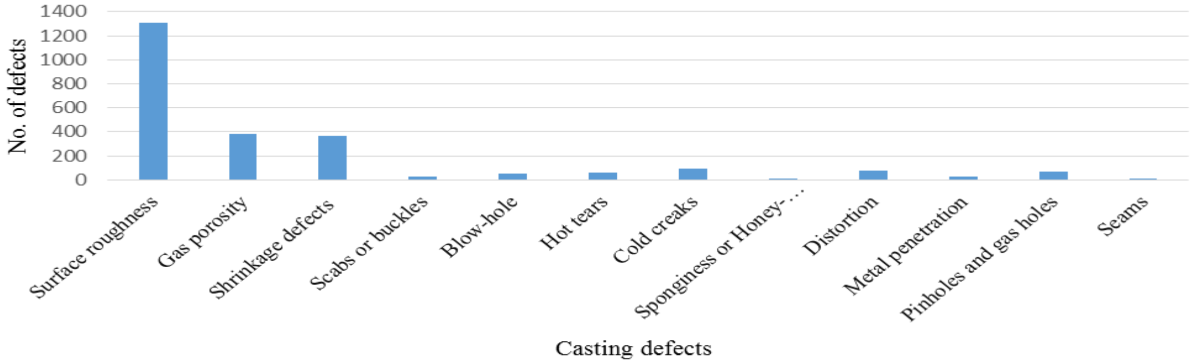

Fig. 1. Defects of casting

“4.2 Measure”

The “measure” phase of the DMAIC problem solving methodology consists of establishing reliable metrics to help monitoring progress towards the goals, which in this research consisted of reducing the number of defects in the casting process. Particularly, in this project the “measure” phase meant the definition and selection of effective metrics in order to clarify the major defects which needed to be reduced [2]. Also, a collection plan was adopted for the data to be gathered efficiently. One of the metrics defined was simply number of defects per type. In addition, two other metrics were used to compare the “before and after” states of the casting process when conducting the Six Sigma’s project. These factors were quality level, which was measured through DPMO, and the Sigma level of the process. After defining the total number of defects, the DPMO and Sigma level of the casting process were calculated.

Table 1. Defect summary before the improvement

Types of defects	Number of defects	Percentage of defects
Surface roughness	1310	60.93
Gas porosity	385	17.90
Shrinkage defect	365	16.98
Others	90	4.19
Total	2150	100

As a next step, a Pareto analysis was carried out to identify the utmost occurring defects and priorities the most critical problem which was required to be tackled. The collected data was generated in the form of a Pareto chart, which is illustrated in Figure 2. The Pareto chart shown in Figure 2 indicated that the highest rate of defects was caused by Surface roughness. In particular, this type of defect contributed to over 60 percent of the overall amount of defects. Therefore, the improvement team and organization decided to initially focus on the reduction of the Surface roughness. The Surface roughness rate was then translated into the quality and Sigma levels as “Quality level 609302 DPMO” and “Sigma level 1.2 Sigma”. The calculation of the DPMO and Sigma metrics allowed the improvement team and organization to have a more detail and operational definition of the current state of the casting process as well as the Six Sigma’s goal in terms of the casting process improvement. These are shown in Table 2. The next stage in the Six Sigma project, and following the DMAIC methodology, consisted in analyzing the root causes of this particular problem, as well as identifying an appropriate solution.

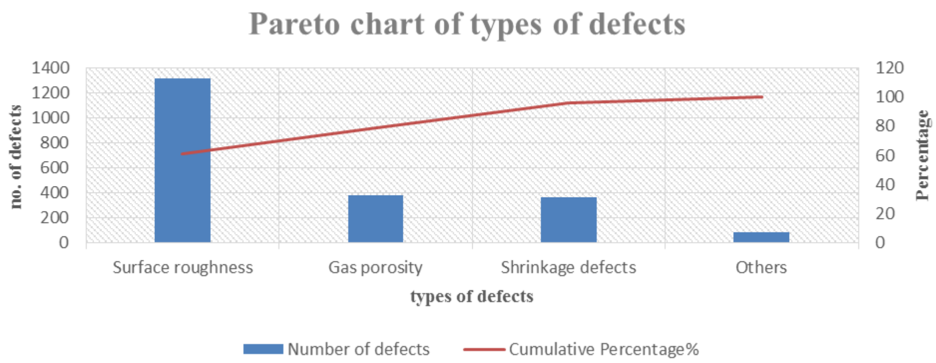

Fig. 2. Casting defects Pareto chart

Table 2. Casting process current and expected states

Major type of defects	Number of the major defect (units)		Quality levels (DPMO)		Sigma levels	
	C*	E*	C*	E*	C*	E*
Surface roughness	1310	655	6,09302	3,04651	1.2	2

C*= Current process performance;

E*= Expected process performance after the completion of the Six Sigma project

"4.3 Analyze"

This phase in the DMAIC improvement methodology involves the analysis of the system, in this case the casting process that produces product, in order to identify ways to reduce the gap between the current performance and the desired goals [11]. To do this, an analysis of the data is performed in this phase, followed by an investigation to determine and understand the root cause of the problem [7]. In order to gain an enhanced comprehension and understanding of the casting process an analysis was done through the whole process. Once that the inputs, outputs and sequence of the process were understood with the help of the flow chart, an analysis was carried out to identify the root cause of the Surface roughness. Several brainstorming sessions were conducted to identify based on the improvement team member's experience, possible causes as to why the Surface roughness problem in casting occurred. In order to illustrate and categorized the possible causes of the problem, a cause-and-effect diagram was constructed. The possible root causes brainstormed are illustrated in the cause and effect diagram shown in Figure 3.

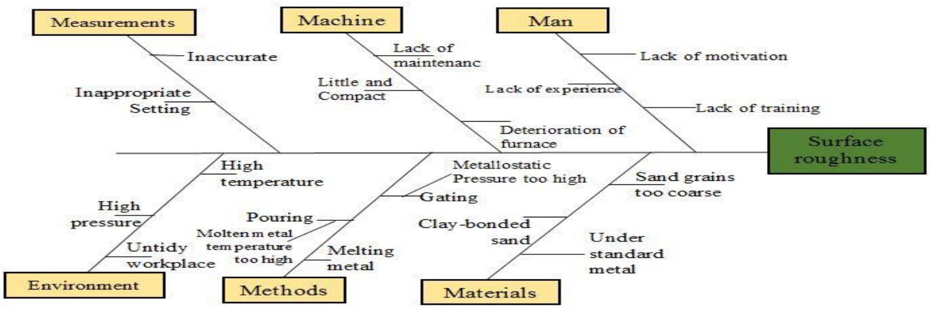

Fig. 3. Cause and effect diagram related to the surface roughness problem

In particular, it was determined that two process factors (i.e. pouring temperature and grain size of molding sand) had a direct effect on the number of Surface roughness. Therefore, the pouring temperature of molten metal and grain size of molding sand and their impact on the number of surface roughness produced was inspected in the following DMAIC's "improve" phase.

"4.4 Improve"

After the root cause(s) has/have been determined, the DMAIC's "improve" phase aims at identifying solutions to reduce and tackle them [2]. Stamatis [4] suggests the use of design of experiments (DOE), which is defined as a statistical technique to investigate effects of multiple factors, in the "improve" phase. According to Montgomery [17], benefits of DOE can be seen as enhancing process yields, decreasing variability and lowering the overall expenses. The DOE technique was used to investigate whether the assumed problem was statistically significant. In particular, an experiment was designed to investigate whether the parameters of both high temperature and too coarse grain size had a negative effect on the process, causing surface roughness. To do this and in order to analyze the experiment's results, two-way analysis of variance (ANOVA) was used. ANOVA is a statistical model for comparing differences among means of more than two populations [18]. However, if there are two sources of data (like in this case) that need to be investigated, two way ANOVA, which is a statistical methodology for analyzing the effect of two factors, is required [18]. The two factors which were mentioned earlier (i.e. pouring temperature and molding sand grain size) were investigated with four different ranges of temperatures; 700°c, 725°c, 750°c and 775°c respectively based on aluminum melting temperature which is 660°c and three distinct grain size; .030in, .015in and .0075in respectively. These parameters were defined based on the process knowledge. From this point, the experiment was conducted with two parameters (i.e. pouring temperature and grain size) at four levels. Pyzdek and Keller [3] suggest the two-way ANOVA with replication as the most effective tool to be used for this type of analysis. As the statistical test aimed at investigating whether the two factors (i.e. pouring temperature and grain size) resulted in surface roughness, a hypothesis that indicated that a variation in the number of defects would occur if the pouring temperature and grain size of molding sand were varied was formulated. The two way ANOVA with replication are shown in table-3.

Table 3. Two way ANOVA with replication

ANOVA Summary					
Source	SS	df	MS	F	P
grain size	1040.22	2	520.11	456.74	<.0001
temperature	12404.31	3	4134.77	3630.97	<.0001
grain size x temperature	2.45	6	0.41	0.36	0.8969
Error	27.33	24	1.14		
Total	13474.31	35			

The results presented in ANOVA summary table indicated that the molding sand grain size and pouring temperature both has the effect significantly, based on its significance level which is above 0.05. Therefore, the analysis helped to statistically conclude that both pouring temperature and grain size influenced for the amount of surface roughness. The next step was to determine the finest grain size based on temperature that would result in the lowest amount of defects. The numbers of defects from the experiment replications are summarized in the form of column chart in figure-4 and boxplots in figure-5. These figures denoted that 700°C temperature and grain size of .0075in provided the lowest amount of surface roughness. After the optimum parameters were defined, a trial was performed in order to test whether the optimum parameters (i.e. 700°C and .0075in) defined by the experiment were the best options to provide an improvement for the casting process and reduce defects.

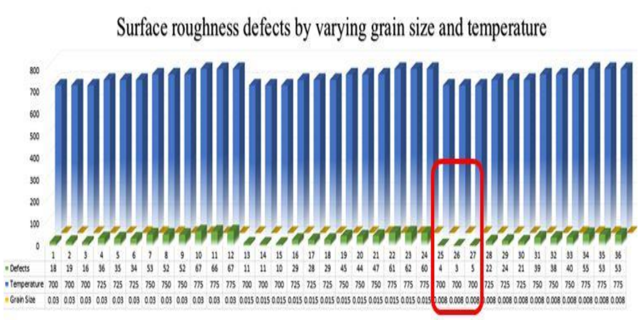

Fig. 4. Surface roughness defects by varying grain size and temperature

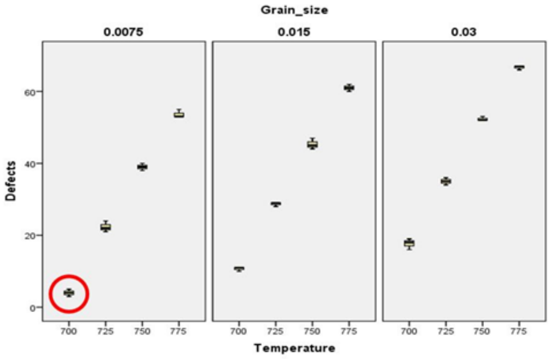

Fig. 5. Box plot of Surface roughness

Table-4 presents the results of the trial and a comparison between the "before and after" setting the new parameters. The results indicate that the optimum parameters identified in the experiment improved the casting process by reducing the amount of surface roughness by about 50%. This resulted in a reduction of DPMO from 609,302 to 304,651 and a Sigma level improvement from 1.2 to 2. Consequently, the initial targets set for DPMO and Sigma level, see Table3, were fulfilled.

Table 4. Percentage of defects between before and after the improvement

Types of defects	% of defects before the improvement	% of defects after the improvement
Surface roughness	60.93	29.465
Gas porosity	17.90	10.57
Shrinkage defect	16.98	9.75
Others	4.19	3.4
Total	100	53.185

It can be concluded that, by setting up the pouring temperate at 700°c and grain size at .0075in., not only reduced the amount of surface roughness defect but also reduced the other types of defects. The improvement also demonstrated that the utilization of Six Sigma and DMAIC problem solving methodology was effective and efficient to minimize the number of defects. A comparison between the "before and after" the Six Sigma improvement project presented in this paper is illustrated in Figure 6.

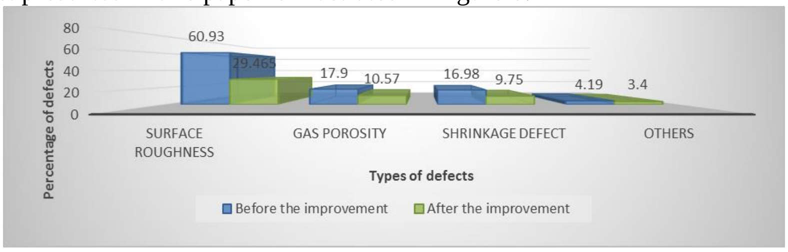

Fig. 6. "Before and after" states of conducting the Six Sigma project in the casting process

"4.5 Control"

The aim of the "control" phase is to sustain the gains from processes which have been improved by the six sigma process and controlling ongoing operations. So to keep going with this improved process the organization should concern about their pouring temperature of the molten metal so that it will not become too high and also about the grain size of molding sand that it will not become too coarse. By controlling these two things it can keep going through better surface finish.

"5. Results, Discussion and Conclusions"

This paper presented a successful study of defects reduction in casting process by applying Six Sigma principles and the DMAIC problem solving methodology. Therefore, the paper can be used as a reference for Manufacturing Industrialists to guide specific process improvement projects, in their organizations, similar to the one presented in this paper. After the analyses carried out in the "analyze" and "improve" phases of DMAIC, the improvement project presented in this paper found that the pouring temperature and grain size of molding sand had a statistically significant impact on the surface roughness defect. By considering this, a reduction in the amount of defects was obtained by determining the optimum pouring temperature and grain size, which were defined as 700°c and .0075in. respectively. This demonstrates that as long as the organization continues embracing Six Sigma within its continuous improvement culture and applies its concepts and principles to systematically solve quality problems, it is believed that benefits such as cost savings, increase in products' quality and customer satisfactions will be enhanced. The suggested methodology can be used for any type of selection problem involving any number of selection criteria. Application of this method in a wider range of selection problems in real-time manufacturing environment remains as a future research scope of this paper.

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