Implementation of the PDCA continuous improvement cycle (Plan-D0-Check-Act) as a tool for improving the quality of the cast AA5083 alloy produced in the foundry laboratory

Abdelaisalam Ali Al-Bakoosh¹, Zamani Ahmad² and Jamaliah Idris³
³School of Mechanical Engineering, Faculty of Engineering, UniversitiTeknologi Malaysia, Skudai 81310, Johor Bahru, Malaysia

Email: ¹phd_bakoosh@yahoo.com, ²drmohdzamani@gmail.com, ³jamaliah@fkm.utm.my

Abstract. Production of the high-quality alloy sample using the casting process it is not an easy and simple matter, it is one of the critical difficulties faced by the foundry technologist and researchers. Since the PDCA continuous improvement cycle is a key tool to achieve quality improvement of the product. Therefore, it was applied as an attempt to produce a high-quality cast AA5083 alloy. The main purpose of this paper is to avoid the defects that occur during the production of cast AA5083 alloy using the casting technique, which leads to minimizing product quality. The defects that may take place during the casting process of aluminium alloys have been identified through the literature reviews and taken into consideration to avoid them. The cause-effect diagram (Fishbone-Diagram) was constructed to show the root cause of the defects to avoid them, as well as the PDCA cycle was used to minimize the defects effectively. The results obtained showed that by applying the PDCA continuous improvement cycle and using the quality control tools, the quality of the cast AA5083 alloy can be improved.

Keywords: AA5083 alloy, Quality Control, PDCA cycle, Cause-and effect diagram, Casting

1. Introduction
The PDCA cycle (plan-Do-Check-Act) is a high-level method to achieve continuous improvement. Thus it was a basic element of the total quality management ( TQM) movement [1]. It is also known as Deming cycle or Shewhart cycle, and it is a continuous loop of planning, doing, checking and acting, that provides a simple and effective approach for solving problems and managing change[1]. In addition, it can be described as an important methodology to implement new ideas under control, to ensure that you are successful every time an improvement is proposed. Figure.1 display the PDCA cycle[2].
Figure 1. The PDCA continuous improvement cycle (Plan-Do-Check-Act)

The flow chart of the PDCA cycle can be presented as shown in figure 2. It is consisting of four main phases, which can be described as follows[2, 3]:

- The first phase (Plan): Identify the problem causes clearly to be solved, then set measurable and achievable goals.
- The second phase (Do): this phase aims to implement the action plan after an experiment design. Furthermore, unexpected events learned lessons and the acquired knowledge must be considered.
- The third phase (Check): In this phase, the results of the actions implemented in the second phase are analyzed and evaluated to check whether there have been improvements or not.
- The fourth phase (Act): This phase consists of developing methods aimed to standardize the improvements (in the case objectives have been achieved). In addition, look for other improvement opportunities.
Figure 2. The flow chart of the PDCA cycle - Overview

The PDCA cycle can be described as an important methodology to implement new ideas under control, to make sure that you get it right every time an improvement is proposed [4]. The Casting defects can be attributed to the 4M (Material – Method - Machine-Manpower) as follows[4, 5]:

- Material. The materials used (raw material and mould) were unsuitable (low quality).
- Method. The method used for the casting process was not adequate.
- Machine. The machines (furnace, thermocouple.) used was not proper.
- Manpower. The technician or engineer of the casting has not enough experience and skills.

In term of production of high-quality cast product for Al-alloys casting, there are three main features that can play a critical role in the quality of the metal: Reduction of dissolving gas, Control of trace elements and eliminate of non-metallic inclusion[6, 7]. Therefore, these features must be taken into consideration during casting of AA5083 alloy.

2. Case Study Method
This study was as an attempt to produce a high-quality cast AA5083 alloy through the application of the PDCA continuous improvement cycle (Plan-Do-Check-Act). The Steps of study involved the following:

2.1. Plan-I
The plan was designed after collecting information on the aluminium alloys' casting defects from the previous literature reviews and suggesting process through the Cause-effect diagram for defects to be skipped. The plan was remodified three times to obtain the optimal result

2.2. Do-II
The production of the cast AA5083 alloy product has been improved after four continues different attempts of casting methods. In every attempt, there is modifying to obtain a better product. The four attempts of the casting process were as follows:
(i) The first attempt was Conventional casting, the second attempt was (ii) In-situ casting without degassing, (iii) then the third attempt was(In-situ casting with degassing, by pump the argon gas vertically to the surface), and then the fourth attempt was (iv) In-situ casting with degassing, by pump the argon gas horizontally to the surface, respectively.

2.3. Check-III
To conduct the assessment process for quality of the cast AA5083 alloy for each case, three types of NDT (VT, LT, UT) was conducted as follows:
Where the Visual Inspection (V.T) was conducted according to ISO 10049, Liquid Penetrant Testing (L.T) was performed according to ISO 9916, and Ultrasonic Test (U.T) was carried out according to ASTM B548-76 specification.

2.4. Action-IV
The casting process has been modified three times. In each case, the re-plan was performed to obtain a better product. Where the cast AA5083 alloy product is checked through three NDT techniques (VT, LT, UT) for each process to assess its quality.

3. Case Study Results and Discussions
The PDCA cycle has been applied for producing a high-quality cast AA5083 alloy, the PDCA cycle comprises of four phases for continuous improvement: (1) Plan, (2) Do, (3) Check, and (4) Act. Table.1 describes how each PDCA phase was applied and its result in this study.

3.1. Phase -I: (Plan)
The plan of the casting process was designed after collecting information on the aluminium alloys' casting defects from previous literature reviews. Table .2 shows the summary of common defects that may occur during the casting of aluminium alloys. Base on this information collected, the Cause-effect diagram for casting defects to be skipped was designed. Figure .3 shows in detail the Cause-effect diagram for casting defects to be skipped at the foundry laboratory.

3.2. Phase -II: (Do)
Once the cause of casting defects is fully understood from the previous literature reviews and the experience of the casting technicians. The improvement plan has been established, and the "Do" phase is implemented. After each proposed casting method for AA5083 alloy, the cast product was evaluated by the NDT techniques (VT, Lt, and UT). Based on the results obtained from the NDT tests (see Table.6), a new method is proposed to eliminate the detected defects. The decided solutions are implemented one by one until the optimal process is obtained. The suggested plans for casting process was as follows:
The first attempt of casting of AA5083 alloy was (i) Conventional casting, the second attempt was (ii) In-situ casting without degassing, (iii) then the third attempt was(In-situ casting with degassing, by pump the argon gas vertically to the surface), and then the fourth attempt was (iv) In-situ casting with degassing, by pump the argon gas horizontally to the surface, respectively.

3.3. Phase -III: (Check)
Three NDT methods were performed in this study to assess the quality of the product. The visual inspection (V.T) to detect surface defects such as porosity, Cracks, etc. while the liquid penetrant testing (L.T) to detect the defects that are hard to detect by (V.T) whereas the ultrasonic testing (U.T) for detecting the internal defects. The NDT results obtained for the different casting methods are shown in the table.1
The first attempt was the conventional casting method. The product was inspected through the (V.T), where intensive porosities were clearly observed. Therefore, this method was rejected, and another method was suggested (In-situ casting without degassing). The product produced by this method was inspected by (V.T), non-intensive porosities were observed. While when LT testing was performed, intensive porosities were detected. But in general, this method has efficiency for an improvement in porosities reduction compared to the first method. In addition, this method not adopted, and another method was suggested. (In-situ casting with degassing, by pump the argon gas vertically to the surface). the product of this method was inspected by VT testing and a hole and cluster porosities around it were observed therefore this method was rejected and suggested another method (In-situ casting with degassing, by pump the argon gas horizontally to the surface). the product was inspected by VT, LT, Ut and the results obtained did not detect any defect. Therefore, selected as an optimal method for production cast AA5083 alloy.

3.4. Phase -IV: (Act)
The actions were taken based on the check results obtained (NDT results) and it was as follows: the check results obtained (NDT results) of cast AA5083 alloy produced according to the (plan-I) was significantly below the optimization objective and, therefore, had to be modified to become (Plan-II) where it was applied and showed improvement, but even less than the optimization objective. Therefore, it was modified to become (Plan-III), where it was implemented and showed improvement, but this improvement is not yet satisfactory. Therefore, it was modified to become (Plan-IV) where it was implemented, and the results were satisfactory. Once the improvement cycle had reached this step, this plan (plan-IV) was adopted as a method for producing the synthetic AA5083 alloys. Figure .3 shows the actions that have been taken and the reason for its action (applying the PDCA cycle).

4. Conclusion
- The quality control process (QC) must be applied to all casting sub-process (melting, handling, solidification) to achieve a high-quality product.
- The application of the PDCA cycle has played a critical role in the continuous improvement of the quality of the AA5083 alloy casting, where the casting process (in-situ-casting with degassing by injection of argon gas horizontally to the molten surface) achieved the best result among the other methods applied.
- The application of the PDCA cycle to improve the quality of (Casted AA5083 alloy) product, it requires integrity between the theoretical background of total quality management (TQM) and technical principles of the casting methods as well as the physical metallurgy of the casting process.

Acknowledgement
The Staff Members in the Department of Materials, Manufacturing and Industrial Engineering, School of Mechanical Engineering, Faculty of Engineering, UniversitiTeknologi Malaysia are sincerely appreciated for their financial and technical support during and after this work. This work was partially supported by the Ministry of Higher Education of Malaysia (MOHE), Research Management Centre, UniversitiTeknologi Malaysia, through GUP no: 20H28, 4F577 and TDR 10.3.
| Category of defect | Defect Code | Type of defect | Cause of defect |
|--------------------|-------------|----------------|-----------------|
| **Internal defects (A)** | A1.1 | Macro-shrinkage | Formed inside a hot spot and due to the volume contraction during solidification and depend on mould-filling conditions [6, 8] |
| | A1.2 | Interdendritic shrinkage | Wide solidification range and low temperature gradient [9, 10] |
| | A1.3 | Layer porosity | forms when the solidification fronts converge towards two surfaces and the last solidifying liquid metal con not flow within the dendrites of the mushy zone [11, 12] |
| | A2.1 | Air entrapment porosity | Due to air bubbles trapped inside the liquid metal[13, 14] |
| | A2.2 | Hydrogen porosity | Due to the presence of hydrogen in the melt [15, 16] |
| | A2.3 | Vapour entrapment porosity | Due to residual humidity of the die Ref:[17, 18] |
| | A2.4 | Lubricant entrapment porosity | The gases resulting from the decomposition of the lubricant [19, 20] |
| | A3.1 | Joint | Cold liquid metal flow at least partially solidified and sometimes covered by oxide film. Meets another warmer metal that can flow around it.[21, 22] |
| | A3.2 | Lamination | Metal foil contact with surface of the die and cool down with rate higher than surrounding region. [23, 24] |
| | A3.3 | Cold shot | Turbulent flows of alloy melt with a front characterized by a considerable presence of drops ( spray effect ) [25, 26]. |
| | A4.1 | Inclusion | In case of aluminum alloys most of inclusion is Al-oxide,( Liquid metal comes into contact with air ) or other non-metallic phases [27, 28]. |
| | A5.1 | Crack | Due to localized stress, or thermal concentration [29, 30]. |
| | A5.2 | Hot tear | Due to stress concentration and wide solidification temperature range and in hot spot areas at stresses far below the tensile stress at the temperature [12, 31]. |
| **Surface defects (B)** | B1.1 | Sink | During solidification, a hot spot localizes close to the metal/die interface [6, 25]. |
| | B2.1 | Blister | When the internal pressure of sub-surface gas-related porosity is high enough to plastically deform the thin metallic layer that cover it [27, 32]. |
| | B3.1 | Joint and Vortex | Due to relatively cold metal flow, at least partially solidified and in some cases covered by an oxide film-meet another warmer metal vein that can flow around it [25, 33]. |
| | B3.2 | Lamination | Due to deformation of the die or when a relatively warm vein flows between the steel-die and another cooler at low viscosity [25]. |
| | B4.1 | Surface deposit | Due to a lubricant excess, which can transfer from the die to the casting[8, 34]. |
| | B4.2 | Contamination or inclusion | Due to the interaction between metal and substances locally came into contact with it[17, 35]. |
| **Geometrical Defects (C)** | C1.1 | Incomplete casting | Due to the metal flow stopped, before the die cavity has been completely filled.[36, 37]. |
Figure 3: Cause-effect diagram for casting defects to be skipped for cast AA5083 alloy at foundry laboratory.

Table 2. Summary of NDT results to assess the quality of different casting methods for cast AA5083 alloy

| Casting process method | NDT | Assessment result |
|------------------------|-----|--------------------|
|                        | Method | Inspection % | A / R | Discontinuities |
| 1st Method             | Conventional casting | V.T | 100% | R | Intensive porosities |
|                        | In-situ casting method without degassing | L.T | N/A * | - |
|                        | in inadequate Crucible/Molding materials | U.T | N/A * | - |
|                        | Improper calibration | V.T | 100% | R | Intensive porosity |
|                        | Poor quality management | L.T | 100% | R | Cluster porosities and hole |
|                        | Improper保温 Degassing process | U.T | N/A * | - |
|                        | Inadequate solidification technique | V.T | 100% | R | Intensive porosity |
|                        | Improper Type of furnace | L.T | N/A * | - |
|                        | Poor maintenance | U.T | N/A * | - |
|                        | Out of specification Material grade | V.T | 100% | R | Cluster porosities and hole |
|                        | Out of specification Additives grade | L.T | N/A * | - |
|                        | Improper/insufficient Degassing process | U.T | N/A * | - |

N/A * : Not applicable; V.T = Visual inspection; Liquid penetrant testing L.T; Ultrasonic Testing = U.T; Rejected=R; Accepted=A
Table 3. describes how each PDCA phase was applied and its result in this study

| Plan – I | Conventional casting | Implementation of the casting process according to the plan | The check process was achieved through NDT techniques (VT, LT, UT) to verify whether the desired objective was achieved or not. If yes, go to the act, otherwise modify the plan. |
| Plan – II | In-situ casting without degassing | Implementation of the process according to the plan | Based on NDT results the porosities were detected. (see figure. 4.4) |
| Plan – III | In-situ casting with degassing, by injection of argon gas vertically to the molten surface | Implementation of the process according to the plan | Based on NDT results the porosities were detected. (see figure. 4.4) |
| Plan – IV | In-situ casting with degassing, by injection of argon gas horizontally to the molten surface | Implementation of the process according to the plan | Based on NDT results no defects were detected. (see figure. 4.4) |

Take action on the plan applied. If the results obtained (NDT results) were satisfactory, then the plan will be adopted, otherwise, go to another plan (return to the plan and develop more ideas to solve and reduce defects) and then repeat the cycle.

Next plan was set, for solving existing of porosities

Next plan was set, for solving existing of porosities

Next plan was set, for solving existing of porosities

This plan (Plan-IV) was accepted and adopted to produce cast AA5083 alloys.
Figure 4. Quality improvement of the casting product of AA5083 modified alloys as a function in the fabrication method.
References

[1] Lodgaard, E. and K.E. Aasland. An examination of the application of plan-do-check-act cycle in product development.

[2] Du, Q.-L., et al. Application of PDCA cycle in the performance management system.

[3] Realyvásquez-Vargas, A., et al., Applying the Plan-Do-Check-Act (PDCA) Cycle to Reduce the Defects in the Manufacturing Industry. A Case Study. Applied Sciences, 2018. 8(11): p. 2181.

[4] Bhosale, S.D., S. Shilwant, and S. Patil, Quality improvement in manufacturing processes using SQC tools. International Journal Engineering Research and Application, 2013. 3: p. 832-837.

[5] Patel, P.J., S.C. Shah, and S. Makwana, Application of Quality Control Tools in Taper Shank Drills Manufacturing Industry: A Case Study. International Journal of Engineering Research and Applications, 2014. 4(2): p. 129-134.

[6] Cocks, D. A proposed simple qualitative classification for die-casting defects. in Proc. Die-casting Conference, Montreux. 1996.

[7] Davis, J.R., Aluminum and aluminum alloys. 1993: ASM international.

[8] Timelli, G. and F. Bonollo. Microstructure. Defects and Properties in Aluminum Alloys Castings: A Review. in Proc. Int. Conf. Aluminium Two Thousand, Firenze. 2007.

[9] Shih, T.-S., L.-W. Huang, and Y.-J. Chen, Relative porosity in aluminium and in aluminium alloys. International Journal of Cast Metals Research, 2005. 18(5): p. 301-308.

[10] Nicoletto, G., R. Konečná, and S. Fintova, Characterization of microshrinkage casting defects of Al–Si alloys by X-ray computed tomography and metallography. International journal of fatigue, 2012. 41: p. 39-46.

[11] Lee, P., A. Chirazi, and D. See, Modeling microporosity in aluminium–silicon alloys: a review. Journal of light metals, 2001. 1(1): p. 15-30.

[12] Dahle, A. and D. StJohn, Rheological behaviour of the mushy zone and its effect on the formation of casting defects during solidification. Acta materialia, 1998. 47(1): p. 31-41.

[13] Timelli, G., F. Bonollo, and G. Cupito, The impact of defects on the quality of aluminium alloy die castings. 2009.

[14] Homayonifar, P., et al., Numerical modeling of splashing and air entrapment in high-pressure die casting. The International Journal of Advanced Manufacturing Technology, 2008. 39(3-4): p. 219-228.

[15] Do Lee, C., Variability in the impact properties of A356 aluminum alloy on microporosity variation. Materials Science and Engineering: A, 2013. 565: p. 187-195.

[16] Tian, C., et al., Effect of melt cleanliness on the formation of porosity defects in automotive aluminium high pressure die castings. Journal of materials processing technology, 2002. 122(1): p. 82-93.

[17] Campbell, J., Complete casting handbook: metal casting processes, metallurgy, techniques and design. 2015: Butterworth-Heinemann.

[18] Albonetti, R., Porosity and intermetallic formation in lost foam casting of 356 alloy. 2000: Faculty of Graduate Studies, University of Western Ontario.

[19] Wang, L., P. Turnley, and G. Savage, Gas content in high pressure die castings. Journal of Materials Processing Technology, 2011. 211(9): p. 1510-1515.

[20] Zhou, B., et al., R-HPDC process with forced convection mixing device for automotive part of A380 aluminum alloy. Materials, 2014. 7(4): p. 3084-3105.

[21] Faura, F., J. López, and J. Hernández, On the optimum plunger acceleration law in the slow shot phase of pressure die casting machines. International Journal of Machine Tools and Manufacture, 2001. 41(2): p. 173-191.
[22] Hajjari, E., et al., Microstructure characteristics and mechanical properties of Al 413/Mg joint in compound casting process. Metallurgical and Materials Transactions A, 2012. 43(12): p. 4667-4677.

[23] Campbell, J., An overview of the effects of bifilms on the structure and properties of cast alloys. Metallurgical and Materials Transactions B, 2006. 37(6): p. 857-863.

[24] Brennan, J.B., Method of continuous casting. 1954, Google Patents.

[25] Fiorese, E., et al., New classification of defects and imperfections for aluminum alloy castings. International Journal of Metalcasting, 2015. 9(1): p. 55-66.

[26] Gariboldi, E., F. Bonollo, and M. Rosso, Proposal of a classification of defects of high-pressure diecast products. Metallurgia Italiana, 2007. 99(6): p. 39.

[27] Zhang, B., et al., Casting defects in low-pressure die-cast aluminum alloy wheels. JOM, 2005. 57(11): p. 36-43.

[28] Seniw, M.E., J.G. Conley, and M.E. Fine, The effect of microscopic inclusion locations and silicon segregation on fatigue lifetimes of aluminum alloy A356 castings. Materials Science and Engineering: A, 2000. 285(1-2): p. 43-48.

[29] Arami, H., et al., Microporosity control and thermal-fatigue resistance of A319 aluminum foundry alloy. Materials Science and Engineering: A, 2008. 472(1-2): p. 107-114.

[30] Francis, J.A. and G.D. Cantin, The role of defects in the fracture of an Al–Si–Mg cast alloy. Materials Science and Engineering: A, 2005. 407(1-2): p. 322-329.

[31] Farup, I., J.-M. Drezet, and M. Rappaz, In situ observation of hot tearing formation in succinonitrile-acetone. Acta materialia, 2001. 49(7): p. 1261-1269.

[32] BONOLLO, F., et al., DELIVERABLE D2, 2013.

[33] Campbell, J., Castings. 2003: Elsevier.

[34] Timelli, G. and F. Bonollo, Quality mapping of aluminium alloy diecastings. CORRELATION BETWEEN PROCESSING AND QUALITY OF ALUMINIUM ALLOY CASTINGS, 2008: p. 107.

[35] Marder, J. and C. Kortovich, Characterization of casting defects in typical castings of a directionally solidified superalloy. 1979, TRW INC CLEVELAND OH.

[36] Hamilton, R., et al., Multiscale modeling for the prediction of casting defects in investment cast aluminum alloys. Materials Science and Engineering: A, 2003. 343(1-2): p. 290-300.

[37] Alagarsamy, A. Casting defect analysis procedure and a case history. in Keith Mills Symposium on Ductile Cast Iron. 2003.