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Experimental Investigation of Low Alloy Cast Aluminum Surface Defects (Case at Akaki Basic Metals industry)

Chandrashekar K

Associate Professor Department of Mechanical Engineering

SJB Institute of Technology,Bengaluru, Karnataka 560060

Karthik Raj K V

Assistant Professor Department of Mechanical Engineering

SJB Institute of Technology,Bengaluru, Karnataka 560060

Abstract:

Aluminum is one of the engineering materials used for various purposes,which haveexcellent mechanical properties when alloyed with several metals such as magnesium, silicon, zinc, copper and other metals. Low alloy aluminum is the most common one which can be cast using sand casting method. Surface defects including porosity, sand sintering, inclusions etc. affect the surface quality of this alloy casts and leads to the economic crisis of the company and the country as well. The defect must be minimized and thus the objective of this article was to experimentally investigate surface defects of aluminum silicon alloy casts, which are commonly cast in the case factory. Experimental research methodology with quantitative and qualitative approaches was used and the research was conducted at Akaki basic metals industry. Samples of various shapes and sizes were selected randomly and about 21 samples were investigated forsurface defects. All sand-casting procedureswere used to conduct the research. The research method included physical observation, photographic analysis and measurementof cast dimensions, and Ishikawadiagram. From photographic analysis it was under stood that defects including slag inclusion,pin holes,porosity, lap, shrinkage cavity, and deposits of dirt wear observed from casts of flat,rectangular, cylindrical and square cross section castings.From the Ishekawa diagramit was understood that defects were occurred due to improperpouring process, materials property, lack of skilled man power and solidification process. From the interview it was also understood that about 20000 .00USD lose is occurring everyyear.

Key words: Aluminum siliconalloy, surface defect, shrinkage cavity,mechanical property

1. INTRODUCTION

Aluminum is[1] one of the most economical ,versatile, and smart metallic materials for a wide range of uses from soft, extremely ductile wrapping foil to the most demanding engineering applications. Aluminum alloys are next only to steels in use among engineeringmetals. Same author expressed thataluminum alloys are excellent in their high strength to weight ratio and therefore these alloys are considered as good option materials for automotive and air craft applications, , home goods etc. Researcher [2] underlined that casting is the oldest manufacturing method and familiar metallurgical process. Very simple and high-end intricate shapes and designs can be made from any metal that can be melted. Even though high-quality aspects are measured by casting, defects are extremely much inherent in casting process. The same author presented that sand casting, is a metal casting process processed by using sand as the mold material. Sand casting as discussed are produced in foundry. As [1, 2], over 80 -90% of all metal castings are produced via sand casting process. Using of sand-casting different sizes and complicated shapes can be made. Dimensional precision and surface finish of the castings made by sand casting processes are drawbacksofsand casting. These limitations can occur due to different reasons and cause economic crises of the industry and the nation as a whole. Author[3] explained about defects of castings including porosity, puncture, shrinkage and shrinkage cavity, sand sintering which are affecting the surface quality of the cast and reduce productivity. The service usefulness of the casts is also affected by surface defects and also sand properties and molten metal pouring temperature. As mentioned in [4] aluminum is very rare in native form, and the process to refine it from ores is complex. From history of metallurgy[4] it is understood that discovery of this metal wasannouncedin1825,whoseworkwasextendedbyAuthors[5]

The mass production of aluminum led to wide use of the light, corrosion-resistant metal in industry and everyday life of human being. In view of [5] aluminum began to be used in engineering and construction widelyduring World Wars I and II and that time aluminum was a crucial strategic resource for aviation and automobile. World production sustained to rise, getting 58,500,000 metric tons in 2015. Accordingly, aluminum production exceedsto the sum of all other non-ferrous metalcasts.

In view of [6] aluminum alloys are used in various areasthat needlow weight, high strength, ease of processing, low-temperature resistance, low maintenance conditions, in machinery manufacturing, shipbuilding and chemical industries .Today aluminum and aluminum alloys are widely used in civil works (construction works).

As stated in [7] among different aluminum alloy systems, the mainly used type alloy to date is the Aluminum- Silicon (Al-Si) group with Si concentrations in the range of 5 to 23 wt.%. This alloy system has a eutectic point at 12.6 wt. % Si at 577 °C .From the related literature it has been understood that Si increases the fluidity of the molten metal, therefore improving the cast ability. Increased tensile strength, good corrosion resistance as well as machine ability are also results of alloying aluminum with Si. Depending on the Si content [7], different structures will form; hypoeutectic, eutectic or hypereutectic phases. The resulting microstructure is a result of the solidification path, hypoeutectic alloys are characterized by α-Al dendrites that solidify first, surrounded by Al-Si eutectic. Hypereutectic alloys have primary Si particles forming first followed by the Al-Si eutectic.The principal alloy elements in aluminum base casting alloys are copper, silicon, magnesium, chromium, tin, titanium etc. The alloy behavior of magnesium in aluminum is similar to that of copper. Copper content of 2 to 5 % provides optimum ductility where as high percentage of copper add hardness and strength. Zinc makes it possible to obtain a maximum of mechanical properties in the castcondition.

According to many authors [5, 6, 7) in aluminum silicon alloy, increasing silicon content is to increase the strength, and lowering ductility. In the work of [8] it was explained that in aluminum-silicon alloys, other alloying elements need to be added beside silicon are: Mg, Cu, Fe, Ni, Sr. These help to modify the properties. The mechanical properties in aluminum-silicon alloys depend on the microstructure, chemical composition, and amount of defects made on the cast. Author [9] explained that various types of aluminum silicon alloys such as high strength, high alloy, high strength low alloy, and medium strength classes are used for different purposes like air craft engines, automobile bodies, and ingots reprocessed for different purposes. The most important cast aluminum alloy system is Al–Si, where the high levels of silicon (4.0–13%) contribute to give good casting properties [10, 14]. Using these alloys at temperatures above200

°C will start coarsening of silicon phases that have a negative impact on the mechanical properties.

As literature [10] underlined aluminum sand casting has various surface defects such as, gas porosity, shrinkage, hard spot etc. Several parts and devices made by casting, including pistons, engine blocksand turbine blades may be defective. Defects occurdue to various reasons. Gas porosity as one serious surface defectthat inaccordance with root causes can be sub-divided into

three: Gas held in solution in the molten metal that can be precipitated as the metal solidifies, as an outcome of the reduced solubility on freezing, if the mold is filled below very poor conditions, air can be entrained in the metal stream and then trapped as the metal solidifies and the sand binders used to build the molds and cores often break down when in contact with the molten metal and the gaseous decomposition products can force their system into the solidifying metal, leading to defects which are usually known as blowsholes.

Author [11] discussed that hard spots are one of the major machining defects in cast Al alloys. According to same author there are four types of "hard spots" in Al-Si-0.4Mg cast alloys:, inter metallic, oxides, refractory particles and cold shots. The oxides in Al-Si-0.4Mg cast alloys include Al_2MgO_4, Al_2O_3 and MgO. SiO_2 inclusions are entrained sand or refractory material. Some inter metallic or non-metallic compounds originate from the use of grain refiners in the charges. Cold shots are the small droplets of cast alloy themselves formed during excessively violent mold filling. The machining damage is often exacerbated by these hard spots and associated oxides. Various remedial actions may be considered in preventing the aluminum alloy cast from theses defects. However most gas related defects are difficult to avoid.

At Akaki Basic metals industry aluminum casting alloy is one of the products which face problems of surface defects. Due to this the factory loses large amount of money and consequently minimizing these defects to increase the cast quality and to save financial lose is important task. Thus investigation of the surface defects to minimize the loss is the main issue of this research.

Various products including spares of different kind, ingots, strips, bars and sheets are produced using basically sand casting. On the process of casting aluminum alloys various defectshave been observed on the surface.Such defects were shrinkage cavities, pin holes, gas porosities, laminations, contaminations and cold lap, etc.

These defects affect the surface quality of the cast and reduce the productivity, requests high production cost. Most defects are associated with the inappropriate casting process including mold making, sand preparation, core making, melting and pouring conditions. Other parameters like pouring time and speed, design of gating systems, charge cleaning, molding materials, poor worker skill etc. cause the factory to lose 150000.00 to 20000.00 USD or approximately ETB750000.00 to1000,000 .00per year.

2. MATERIALS ANDMETHODOLOGY

2.1. Materials

Aluminum and its alloys have broad applications in industry and mechanical works like in automobile, air craft and furniture areas. Most aluminum alloysproduced at Akaki basic metal industry are low alloy types mostly aluminum silicon types. The materials composition usually used in the industry is displayed in table 1.

Table1.Materials compositions usually used to cast at Akaki basic metals industry (Spectroscopic result of thefactory)

$AlSi_3$	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
	3.0	0.45	0.03	0.25	0.4	0.04	0.03	Balance
$AlSi_4Mg$	5.58	0.28	0.04	0.4	0.5	0.5	0.07	Balance

As is known in practicewhen the content of alloying particles in some alloy is less than 5% the alloy is said to be low. Thus, the specific materials groups that will be used for this research are aluminum silicon alloys with low amounts of alloying elements (Table2).

Table2. Chemical composition in (%) of Al Si alloys selected for the investigation

Si,%	Fe	Cu	Mn	Mg,	Zn	Ni	Cr	Pb	Sn	Ti	Ag
9.43	1.44	1.59	0.213	0.458	0.53	0.372	0.047	0.044	0.046	0.054	0.002
B	Be	Bi	Ca	Cd	St	Li	Zr	Co	V	Ga	Al
<0.001	0.000	<0.006	0.001	<0.005	<0.005	,0.0070	0.006	,0.002	0.005	0.011	85.8

2.2. Methodology

To conduct the investigation experimental methodology was used. This type of methodology is effective to control variables & parameters existing while casting the selected alloy aluminum. Parameters considered were melting temperature, speed of flow, design of gating system characteristics of melt and others. Quantitative and qualitative approaches were also considered for analysis.

To cast different components in the factory from the alloy the usual casting procedures were carried out.

Shaped castings including plates, bars of various shapes, ingots were the products investigated for their surface quality using physical observation andphotographic analysis. Measurement of surface porosity dimensions of selected casts was carried out. Theroot cause analysis was conducted based on Ishikawa diagram.

Different shaped 21 pieces of aluminum silicon alloy cast components were selected purposively for analysis of the surface defects and after cleaning of the casts 3 geometric shapes of 15samples were selected for surface defect measurement. Purposive sampling method was selected because the method is better sampling method that limits the researcher to specifically use the selected sample/s for the particular designedresearch.

Tools, equipment and instruments that were used for this research were Venire caliper with accuracy of 0.01mm for measuring the dimensions of porosities and surface defects,digital photo camera for analysis , sand casting tools including molding tools and pattern making tools, induction furnace capacity 25tone and other related items.

Experimentally collected measurements were analyzed for degree of surface defect effect and root causes of surface defects were analyzed using Ishikawa diagram. The method is appropriate to analyze the data for this particular research as a result of which remedial actions will be established based on the obtained defects in the castings and the root causes that were sources of defects.

3. RESULT ANDDISCUSSION

3.1. Introduction

This research was carried out using various data collecting methods including, physical observation, photographic methods as well as experiments including casting and measurement of surface porosities dimensions. The case as mentioned earlier was considered on the low alloy aluminum cast products of Akaki Basic Metals Industry. Akaki Basic Metals Industry is producing its products in different sections including foundry section that was observedand where the workers were interviewed randomly. Aluminum silicon castings withvarious surface defects which were experimentally produced types were observed for the degree of their defects in the nonferrous foundrysection.

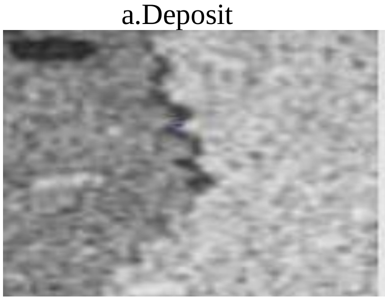
3.2. Observation Analysis Result:

Observation was carried out in nonferrous metals section. The casting process conducted in the case section and the components produced were observed and from the observation it was found that somehow proper sand casting process was carried out fulfilling the required procedure including mechanized molding system using, resin binder or no bake system. However the riser type and size is the same and one for all size castings of different metals, the pouring system is also top pouring system that is processed using overheadcrane at pouring temperature of 730^0C as a result of which the following defects were observed on cast surfaces investigated visually: - Sand sintering (chemical and thermal type), shrinkage cavity, slag inclusion, pin hole, shrinkage porosity, gas porosityand contamination/dirt deposits/. Here it is possible to underline that the pouring temperature was appropriate for the case metal but the riser system and pouring system were not according to the casting and pouring properties of the casemetal, where the vertical shell gating system and trapezoidal shaped riser with predetermined size is required. In addition to the above reasons top gating system is one that is prone to air entrapments, which consequently formporosity.

It was expected that defects may also occurred due to many other factors including skill problemand in proper furnace environments. To investigate the defects of casts in detail, casts were exposed to secondary work and cleaning and finishing of castings were carried out using appropriate cleaning devices particularly portable grinding machine. Next to grinding the surfaces and cutting off the extra metals,riser and gating system parts lathe machine and milling as well as planning machines were also used for further finishing work of the casts as per their geometric shapes that fit to the machinebehaviors.

After cleaning the surfaces and removing extra parts of the casts'photographs of the components were taken using digital camera for further analysis. Figure 1(a-i) shows different defects observed from photographic documents.

a.Deposit



b.Shrinkage Cavity

c. old lap

d. Sand inclusion

e. Pin holes andthermal sand sinters

f. Contaminations and mechanical sandsinters

g. Erosion and mechanical sand sinters

h. Gasporosity

Figure1. Casting defects obtained on low alloy aluminum, casting

2.3. Photographic Analysis Results

Toclearlyidentifythetypesofsurfacedefectsoftheobtainedcasts(castingcomponents)from

low alloy aluminum silicon metal photo graphic analysis was carried out. As seen in the

photographs flat cross sections of various sizes, round and cylindrical shaped casts, rectangular and square cross section and spare part casts have been produced in the factory from low silicon aluminum alloy. Defects like deposits in figure1(a), shrinkage cavity in figure1(b) , cold lap in figure 1(c), slag inclusions in figure1(d), pin holes in figure 1(e), contaminations and mechanical sand sinters in figure 1(f), Erosion and mechanical sand sinters in figure 1(g), gas porosities in figure1(h) , cold shut and lamination in figure 1(i) were seen on the surface of the cast.

Each defects seen in the photograph may be caused dueto many reasons .From own experience and asof[16,19] surface deposits(figure 1(a) are layers of different chemical compositions, thicknesses, distributions and adhesions, which are deposited on the surface of casting that are caused due to burns of different oxides, layer inclusions and slags. These defects can be removed using simple polishing and grinding tools.As of [20] and from physical observation, shrinkage cavities (figure1(b), are open shrinkage defects which are open to the atmosphere,

where the cavities are formed due to entrapment of air from the atmosphere while casting is solidified. The inability of the internal pressure of the liquid metal to push out the gases from the melt create favorite condign to gas to form envelop inside the melt and while solidification takes place the entrapped enveloped gas escapes out from the metal leaving the cavity in the shrank metal. These defects may lead the metal to be rejected as the cast may be under sized. The defects can be improved by using appropriately designed gating system and by using adequate venting system.

As seen in figure1(c)cold laps were formed on the surface of the cast. This is because of low pouring temperature and /or because of poor gating systemdesigns which leadthe liquidmetal unable to fill the mould cavity completely and consequently leaves on the surface of the cast miss run .Such defects mostly lead to rejection of the cast from theproduct.

The sand inclusions (figure1 (d)) and slag inclusionsocalled scab or blacking scab are occurred in the sub surface and surfaces of castings and under the cast portion that probably caused due to erosion of mold, charring of sand metallic oxides and slag as well as burns. Mostly theses defects are difficult to see on the surface and can be seen while machining and are difficult to avoid.

Pin holes and thermal sand sinters are displayed in figure 1(e).Authors (15, 16) agree that the cause of pinhole is gas entrapment in the metal during pouring and solidification. Such gases arise from moisture, binders and additives containing hydrocarbons, blacking and washes from sand cores. Uneven solidification often occurs when mold is designedmissing the rule of directional solidification. Many authors agree that directional solidification rule is such thatthe thinnest pieces of the cast shape should solidify first, and the thickest pieces solidify last, to ensure shrinkage doesnot alter or damage thepiece.

Sand sinters are caused by erosion of the mold wall dueto turbulent flow and sand particle mixed with molten metal and remaining stacked with the metal at the cold state affecting the surface quality,especially when the sintering is mechanical nature, which cannot be removed easily.

Contaminations and mechanical sand sinters which are displayed in figure1(f)are caused by the interaction of metal and the environment especially at the hot state of the solid cast. Such defects may cause part of the cast surface different in color.

As seen in figure1(g),erosion and mechanical sand sinters affected the surface of the cast. In view of [18] and from existing experience sand is eroded and washed around the mold and stack with the metal surface causing sand sintering. The, cause of erosion are design and utilization of poor gating systems, the mold is too dry, pouring was turbulent. Some other factors for such defects can be low skill of the foundry operator, the weak ramming of molding sand and others.Figure1 (h) demonstrates gas porosity,which is one of the most common and difficult defect occurred on the aluminum cast surface. From literature [17] it is possible to underline that gas porosity on aluminum alloy casting occurs due entrapment of air from the atmosphere while pouring, from the moistened metal, lubricants and from the furnace as well as mold itself.Most probable cause of porosity on aluminum cast surface is dissolving of hydrogen gas that form steam and form bubbles of gas envelop that can be escape out while solidification takes placeleaving vacant, which leads to mechanical degradation of the cast in service. Prevention of aluminum cast from hydrogen is the best way to minimize suchdefects.

The cause of lamination (figure 1(i)) is thin metallic layer/skin formation with different microstructuresformedfromthemetals and alloys of the cast and sometimes from partly separated oxide films. The defect can be removed by grinding if the depth of the layer is not affecting the dimension of the cast.

3.4. Pores Dimension MeasurementAnalysisResults

While conducting this research, casts produced with different geometric shapes including round ingot of diameter 30mm and 500mm length, rectangular shaped casts of 50x30x250 as well asflat shaped cast of piece200x25x300 were purposively selected for determination of surface defectdimensions and their level of effects on the cast quality.

The dimensions were measured using Vernier caliper.According to the measurement obtained, 6 porosities on the round piece, 5 porosities on the rectangular piece and 4 porosities on flat pieces were observed (Table3).Depth and diameters were measured considering the shape of the porosities was round and spherical.

Table 3some dimensions and porosity depths of cast low alloy aluminum silicon components

Part	Number of porosities	Depth of porosity (mm)	Diameters of porosity (mm)
Round piece	6	1.01	4.2
		0.85	6
		0.5	22.25
		0.38	10
		0.22	12
		1.0	4
Rectangular piece	5	0.5	14
		0.7	15
		1.1	11
		1.0	16
		0.4	15
Flat bar	4	1.0	17
		0.8	9
		1.6	14
		1.4	13

As seen in table 3,numbers of porosities are large in a specified area of the cast surface and are out of the standard. The world experience recommends 2 poreswith a diameter of maximum 1mmin1^{2}mm area of the cast surface or only 1 pore with a diameter of 2mm in a 1^{2}mmarea on the cast surface is considered porosity free casting surface.In this regard the surfaces of the casts were affected highly and should be minimized by identifying and analyzingthe root causes and factors based on Ishekawa diagram.

3.5. Cause and Effect Analysis Using IshikawaDiagram

Various causes may be sources of surface defects of aluminum silicon alloys casting. When the causes are complicated, Ishikawa diagram displayed in Figure 2 helps to analyze the root causes and leads to suggest remedial actions. Based on this the causes are analyzed (Figure 2) in detail.

As seen in figure 2 the root causes of the case metal casts in the particular industry are pouring process related problems ,molding process and molding materials associated problems, cast

materials property related problems, skilled man power problem and solidification process instability.

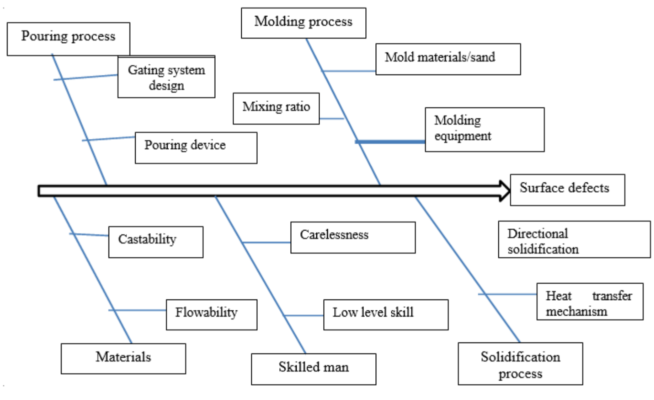


Figure2.Ishikawadiagram for surface defect analysis

Looking in to detail the gating system design in the case industry was not well calculated and the only top gating system which is mostlyexposed to air trapping have been used,laminar flow characteristics was not secured, erosion of mold was observed and the separated sand particles mixed with liquid metal, as a result porosity, sand inclusions and sintering and other related defects were formed on the surface of the cast samples.The riser design is also not well analyzed as per the metal type and size.The only cylindrical open riser system was utilized .Thus proper metal compensation could not be achieved, in which case shrinkage cavity and shrinkage porosities were the results.Pouring was done using ladles with the help of overhead crane,but the ladles were not preheated and consequentlymoisture from the dirt and non-driedladle combined with the molten metal and cause surface defects.

The main mold material used in the case industry is silica sand which is obtained from Tungabhadra River.The sand was mixed with resin binders.For the particular metal cast selected for this research and for market consumption of the industry products in this industry green sand has been used as the main mold material. The mixing ratio was taken in a trial and error method, that there was no standard mix ratio for the particular metal. While the mold filling took place the moisture of the sand evaporated in a steam form forming gas bubbles in the molten metal. Whenthepouringprocessendedandwhensolidificationcommencesthegasenvelop inside the metal escaped out leaving pores on the surface of the metal. More over large amount of hydrogen is dissolved in aluminum alloys and consequently causes porosity.Molding is carried out in a mechanized system, however the devices and flasks were not cleaned well, contaminations,lubricants and moistures were not removed,hence additional source of inclusions and air entrapment are the results and ultimately porosity,burn on, deposits and similar defects increased on the surface of thecast.

Aluminum is considered as foam forming metal and has a short freezing range.If the this metal melt is not properly super-heated fluidity of the metal is reduced,flow ability and cast ability become low,the mold cavity may not be filled completely,overcoming viscosity problem and surface energy is difficult and early solidification,scab and lap could be the cases .

Each metal needs its own pouring temperature, but in the case factory temperature control is limited or not existed, thus pouring was donein non-standardized time and temperature, as aresult early solidification,shrinkage and shrinkage cavities were magnified on the surface of the case casting.Other defects like lamination also were observed.Attention was not given for the pouring system that follows directional solidification,thus turbulent flow cause entrapment of airin to the molten metal, the entrapped gases cause porosity and slag inclusions.

Employees of the factory are not well trained andskill in performing casting process is low.In addition employees are not seriously attending each process and consequence.Negligence and carelessness was identified from among the employees.Thus selection of charging materials were not done properly,dirt,colored and moistenscraps were charged .The product thus became full of deposits,slag inclusions and porosities. Reversing the above mentioned root causes by developing well designed scientifically correct casting method may maximize the production quality of the casts of low aluminumsilicon alloy and can save20000 .00US per year for Akaki Basic Metals Industry.

4. Conclusions

Experimental investigation of low alloy aluminum silicon casting surface defect was conducted at Akaki Basic Metals Industry.

Physical observation, photographic analysis, cause and effect analysis, measurement of depth and diameter of defects of the selected cast low alloy aluminum silicon components confirmed that all casts including the round bar, rectangular bar and the flat bar components selected as a sample were affected by various surface defects. The pore sizes obtained by measurements confined that the pores were above the standard limit and the casts became under dimension.Measurements were taken using Vernier caliper of accuracy 0.01 accuracy.According to the measurement obtained number of porosities are large in a specified area of the cast surface and is out of the standard that the world experience recommends 2 pores with a diameter of maximum 1mm in1^2mm area of the cast surface or only 1 pore with a diameter of 2mm in a 1^2mm area on the cast surface can be accepted as a good qualitycast.

From the root cause analysisusing Ishikawa diagram it was clear that molding process, molding material property, melting and solidification temperature, pouringprocess includinggating system design, skilled man power problems were the main factors affected the surface of the casts.

Solving the mentioned problems may improve the quality of products and can save over 20000.00 USD per year for the caseindustry.

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