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A Comparative Analysis of Grain Size and Mechanical Properties of Al-Si Alloy Components Produced by Different Casting Methods

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Abstract

This study was carried out to compare cast microstructures and mechanical properties of aluminium silicon alloy components cast by various means. For this purpose, sand casting, chill casting and squeeze casting methods were used to produce similar articles of the same shape and size from an Al-8%Si alloy. It was observed that the grain size of the microstructures of the cast products increased from those of squeeze casting through chill casting to sand casting. Conversely, the mechanical properties of the cast products improved from those of sand casting through chill casting to squeeze casting. Therefore, squeeze cast products could be used in as cast condition in engineering applications requiring high quality parts while chill castings and sand castings may be used in as cast condition for non-engineering applications or engineering applications requiring less quality parts.

Keywords: *Chill casting, microstructure, refinement, sand casting, squeeze casting.*

Introduction

Foundry or metal casting is one of the earliest metal shaping methods known to man, dating back to 2000 B.C. and the process used then was little different in principle from the one used today (Amstead *et al*. 1979). Wright (1990) and Rao (1992) are of the opinion that metal casting came into existence much earlier. Rao (1992) puts the date at 3500 B.C while Wright (1990) observed that casting dates back almost 6000years. He further noted that many developments in casting came from the Orient and that before 1000 A.D., the Chinese had developed ways of casting iron while the method of casting crucible steel was invented later in India. The Oriental developments in casting were exported to Middle East and Europe and the first cast iron gun was produced in England in about 1500 A.D. The first known iron casting made in America was cast iron-cooking pot made in the year 1642 (Jain 1992).

From this lowly beginning, modern foundry industry has grown. Today, there are numerous casting processes, which evolved over the years. These casting processes may generally be classified into two broad classes: sand casting and special casting including die, gravity, investment, centrifugal, pressure castings, etc. each with its own characteristic advantages and disadvantages. Sand casting accounts for about 80% of castings made (Mikhailov 1989). It was estimated in 1979 that 80% of castings made in UK was by green sand moulding (Williams 1979) and in Federal Germany green sand moulding accounted for 67% of casting production in 1986 (Weiss and Kleinheyer 1987).

Engineering and consumer goods are produced by a number of techniques among which are sand casting and die casting. Each alternative technique is characterised by its own distinct capabilities and related costs, which determine specific areas of application. For a good comparison, the production of articles by squeeze casting, pressure die casting, chill casting and sand casting is reviewed.

Making comparison between sand casting and squeeze casting, Lynch *et al*. (1975) observed that although sand cast parts are characterised by rough surface finishes, sand casting as a process offers a cheap means of fabrication which also allows undercuts and channels to be cast into the part and allows the casting of many small-sized parts simultaneously in the same mould, thus increasing productivity. On the other hand, squeeze casting can give full-density parts free of shrinkage or microporosity and with a smoother surface finish and closer tolerance than are possible in sand casting. In addition, it is a cost-effective fabricating process due to its high rate of production and high metal utilisation efficiency.

The maximum weight obtainable by squeeze casting is 19kg for aluminium-base alloys (Clegg 1991; Yue and Chadwick 1996). But the maximum weights attainable by chill casting are 70kg, 25kg, 13.6kg and 9kg for aluminium-base alloys, magnesium-base alloys, cast iron and copper-base alloys, respectively (West and Gruback 1989; Clegg 1991). Clegg (1991) also made comparison between squeeze casting and other similar techniques in the areas of surface finish, dimensional accuracy, minimum section thickness and production volume. The surface finish of squeeze casting is similar to that obtained by pressure die casting, which is within 0.4 to 3.2μm and is better than that obtained by chill casting, which is in the range of 3.2 to 6.3μm.

The dimensional tolerance or accuracy of castings made by chill casting in a single die half is within ±0.25mm. For pressure die-castings with critical dimensions below 25mm, tolerance can be ±0.08mm for zinc-base alloys; ±0.10mm for aluminium-base alloys and ±0.18mm for copper-base alloys. For dimensions within the range of 25 to 300mm, an extra allowance for each 25mm increase of ±0.025mm, ±0.038mm and ±0.051mm should be made, respectively for the three alloy classes earlier mentioned. On the other hand, the dimensional tolerance of aluminium alloy castings made by squeeze casting is 0.2mm/100mm (Clegg 1991).

The reasonable minimum section thickness for chill casting is 5mm while sections as small as 0.5mm in zinc-base alloys, 0.8mm in aluminium-base alloys and 1.5mm in copper-base alloys can be made by pressure die-casting. Squeeze casting is better suited to castings having sections above 6mm, although thin sections of 0.3mm have been made by squeeze casting (Clegg 1991).

Squeeze casting which is a relatively new casting method, compared with other manufacturing processes, has a number of advantages one of which is that the microstructure of the castings can easily be manipulated by process control to achieve the required optimum properties. Furthermore, nucleating agents can also be used but they are not usually required (Yue and Chadwick 1996). Lynch *et al*. (1975) observed that squeeze castings have refined microstructure with fine grains, close dendrite arm spacing and small constituent particles. The combined effect of high pressures and metal mould (die) leads to high heat transfer coefficients which in turn results in alterations in microstructures due to high rate of nucleation and subsequent growth rate of nuclei. This assertion was supported by Yong and Clegg (2004).

In spite of the fact that a lot of research works have been carried out to improve casting process more works on the process are still required for better understanding of the process. This study was conducted to compare the grain size of microstructures and mechanical properties of aluminium silicon alloy components cast by sand, chill and squeeze casting methods.

Materials and Methods

Materials and Equipment

In this study, an Al-Si alloy scrap was used. The composition of the scrap was determined using energy dispersive X-ray fluorescence (EDXRF) and classical (wet analysis) methods and it is as presented in Table 1. Other materials used were a prepared lubricant consisting of 10% graphite in lubricating oil of the type 20W/50, proprietary "Foseco" flux and hexachlorethane tablets.

Table 1. Chemical composition of Al-Si alloy used.

Material	Composition, %							
	Si	Sn	V	Cr	Mn	Fe	Co	Ni
Al-Si Alloy	8.081	<1.980	<0.182	<0.110	0.173	0.686	<0.027	0.086

Table 1. (continued)

Material	Composition, %							
	Cu	Zn	As	Pb	Zr	Nb	Mo	Al
Al-Si Alloy	1.920	0.511	<0.007	0.073	0.004	<0.001	<0.001	Rem.

A 2kW electric resistance furnace, an immersion pyrometer, a 150T hydraulic press, squeeze casting rig and die heater were the main equipment used for the study. Others include metal polishing machine, Roll grinder, optical microscope, Rockwell hardness tester and universal tensile testing machine.

Experimental Methods

The aluminium-silicon alloy was melted and heated to required pouring temperatures using the methods in Raji and Khan (2005; 2006). Squeeze casting was carried out at pouring temperatures of 650-750^{o}C, squeeze pressures of 75-150MPa, punch velocity of 9.45mm/s and pressure period of 30s using the method specified in Raji and Khan (2006). Sand castings were made at pouring temperatures of 650-800^{o}C according to the method in Raji and Khan (2005) while chill castings were made at pouring temperatures of 650-750^{o}C according to the method in Raji and Khan (2006).

Tensile test was done on a universal testing machine while hardness was determined using Rockwell machine as par Raji and Khan (2006).

Metallographic Examination

Preparation of Al-Si samples for micro-examination involved mainly sampling, grinding, polishing and etching. Samples measuring 26mm x 15mm x 10mm were cut from the castings with the help of a hacksaw as shown in Fig. 1. The samples were filed and ground. Grinding was done in succession on a Roll grinder using silicon carbide abrasive papers of 220-, 320-, 400-, and 600-grits. Rough polishing and final polishing were done using a paste made from silicon carbide powder (1,000 grit) and a paste made from pure heavy grade of magnesium oxide (MgO) respectively on a billiard cloth on the circular disc machine polisher. The speed of the wheel was maintained at 600rpm and 350rpm for rough and final polishing respectively. Final rinsing was done with warm water and the specimens were blown dry with a hand dryer and then kept in a desiccator.

Etching of the specimens was done using approximately 0.24% Hydrofluoric acid (HF) made from 1ml HF (48%) and 199ml water. The specimens were etched for a period of 60s each in a porcelain dish and then rinsed in running water, immersed in a boiling ethanol for 60s and then blown dry with the dryer. Each specimen was then mounted on a Pol Jenalab optical microscope and the microstructure observed and photographed at a magnification of x125.

Results and Discussion

Metallographic Studies of Cast Samples

The results of metallographic studies of the cast samples showed that in all cases, the microstructure of the cast samples were of hypoeutectic structure consisting of primary alpha solid solution of silicon in aluminium (α) in a matrix of eutectic (α+Si). However, the grain sizes differed for various castings. The quantitative grain sizes of the various castings based on American Society for Testing and Materials (ASTM) grain size number *n* are presented in Table 2.

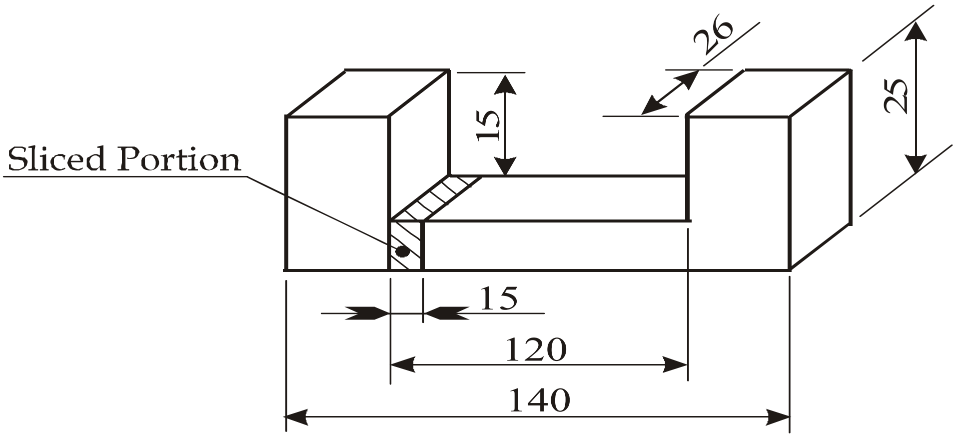

Fig. 1. Sliced portion of castings for metallographic test; dimensions are in mm.

Table 2: Properties of Aluminium-Silicon alloy produced by various casting methods in as cast condition.

Squeeze Pressure, MPa	Pouring Temperature, °C	Number of Grains at Magnification x125				Number of Grains at Magnification x100, N	ASTM n*	UTS, MPa	Proof Stress, MPa	Hardness, HRF	Elongation, %
		N_{g1}	N_{g2}	N_{g3}	Average N_g						
Sand Cast Products											
0	650	9	6	8	7.67	11.98	4.58	102	40	35.5	2.3
	700	7	7	5	6.33	9.89	4.31	88	38	34.5	2.2
	800	7	4	5	5.33	8.33	4.06	65	35	33.0	2.0
Chill Cast Products											
0	650	12	14	16	14.00	21.88	5.45	115	105	39.5	2.7
	700	13	11	15	13.00	20.31	5.34	115	106	40.0	2.4
	750	14	10	13	12.33	19.27	5.27	114	104	40.5	2.5
Squeeze Cast Products											
75	650	30	32	33	31.67	49.48	6.63	146	128	46.0	3.4
	700	33	35	29	32.33	50.52	6.66	182	147	50.0	3.6
	750	34	30	35	33.00	51.56	6.69	209	147	53.5	3.4
100	650	36	38	42	38.67	60.42	6.92	158	136	46.5	3.4
	700	41	45	43	43.00	67.19	7.07	219	153	55.0	3.8
	750	44	40	42	42.00	65.63	7.04	215	150	54.5	3.6
125	650	44	43	42	43.00	67.19	7.07	184	140	50.0	3.6
	700	55	58	56	56.33	88.02	7.46	232	156	58.0	3.8
	750	47	50	47	48.00	75.00	7.23	226	152	57.5	3.8
150	650	47	44	46	45.67	71.36	7.16	210	145	53.5	3.6
	700	53	60	57	56.67	88.55	7.47	232	156	58.0	3.8
	750	51	49	46	48.67	76.05	7.25	225	152	58.0	3.6

* Large value indicates fine grain size.

The quantitative grain sizes were determined using ASTM grain size number calculated from Eq. 1 (Askeland 1985):

$$N = 2^{n-1}, \qquad (1)$$

where: N - number of grains per square inch (25.4mm x 25.4mm) at magnification x100; n - ASTM grain size number.

The number of grains per square inch is normally determined from photograph of metal taken at magnification x100. For microphotograph at different magnification other than x100, the N in equation 1 is determined by Eq. 2:

$$N = \left(\frac{g}{100}\right)^2 N_g, \qquad (2)$$

where: g - specified magnification; N_g - number of grains at specified magnification.

The micrographs of some selected sand casting, chill casting and squeeze castings are shown in Figs. 2-5. The primary solid solution of silicon in aluminium (α) is shown in the micrographs as white patches while the eutectic (α + Si) is shown as dark patches.

The results of micro-examination showed that sand castings were characterised by coarse grains (4.06-4.58) due to slow cooling rates of the sand moulds with the coarseness increasing with increase in the pouring temperature. This increase in the grain size of sand castings with increase in the pouring temperature may be explained by increased mobility of the atoms at high temperatures. Solidification is a process of nucleation and growth and it is affected by the rate of heat transfer which in turn affects the structure and properties of the casting (Yong and Clegg 2004). Chill castings were characterised by fairly fine structures (5.27-5.45) brought about by the high cooling rate of the moulds only. The structures were however, coarser than those of the squeeze castings.

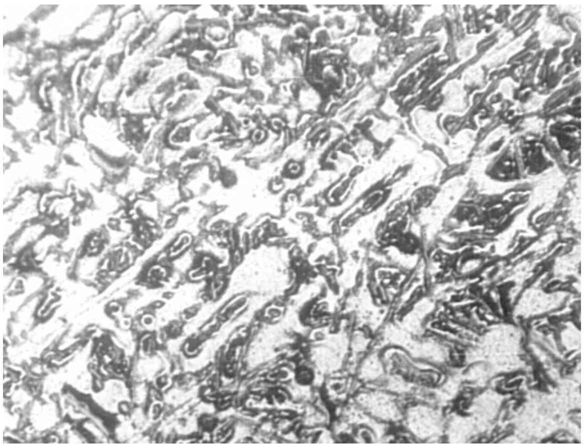

Fig. 2. Micrograph of Al-8%Si Alloy Sand Cast at a Pouring Temperature of 700°C (x125); white patches are primary α while dark patches are eutectic, α + Si.

Fig. 3. Micrograph of Al-8%Si Alloy Chill Cast at a Pouring Temperature of 650°C (x 125); white patches are primary α while dark patches are eutectic, α + Si.

Fig. 4. Micrograph of Al-8%Si Alloy Squeeze Cast at a Pouring Temperature of 650°C and a Squeeze Pressure of 100MPa (x 125); white patches are primary α while dark patches are eutectic, α + Si.

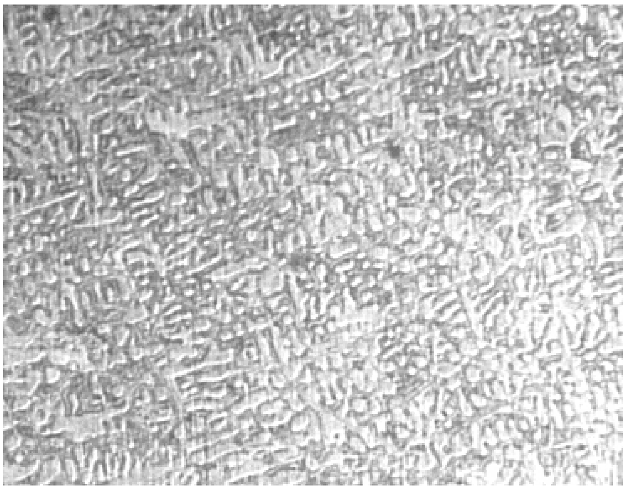

Fig. 5. Micrograph of Al-8%Si Alloy Squeeze Cast at a Pouring Temperature of 750°C and a Squeeze Pressure of 125MPa (x 125); white patches are primary α while dark patches are eutectic, α + Si.

The results of micro-examination revealed that the grains of squeeze castings are fine with the fineness increasing with increase in squeeze pressure for all pouring temperatures. The grain sizes of squeeze cast products made at squeeze pressure of 75MPa were 6.63, 6.66 and 6.69 for pouring temperatures of 650, 700 and 750°C, respectively. Increasing the squeeze pressure to 125MPa yielded finer grain sizes of 7.07, 7.46 and 7.23 for pouring temperatures of 650, 700 and 750°C, respectively. Further increase in squeeze pressure to 150MPa did not yield any meaningful refinement for pouring temperatures of 700 and 750°C while for pouring temperature of 650°C it yielded further refinement of grains (7.16). The fine structures of squeeze castings were brought about by the high cooling rates of the dies aided by the squeeze pressure as was observed by Yong and Clegg (2004). These results agree with the findings of Lynch *et al.* (1975), Yue and Chadwick (1996) and Yong and Clegg (2004).

Mechanical Properties of Squeeze Cast, Chill Cast and Sand Cast Samples

The results of mechanical properties of the castings in as cast condition are presented in Table 2. The results showed an increase in hardness of Al-8%Si alloy from HRF39.5-40.5 for chill castings to a maximum of HRF58.0 for squeeze castings which constitutes about 43 to 47% increase over those of chill castings. The increase in the hardness of squeeze cast products is brought about by the faster cooling rates giving rise to grain refinement and elimination of porosity and hence increased hardness of squeeze cast products. Compared with the hardness of squeeze and chill castings, the hardness of the sand castings was smaller. It ranged from HRF35.5 down to HRF33.0 with increase in the pouring temperature.

The UTS of sand castings were smaller than those of the squeeze castings and it varied from 102 to 65MPa with increase in pouring temperature from 650 to 800°C. The reduction in UTS of sand castings with increase in pouring temperature is due to grain growth as a result of over heating and “burning” of the alloy. The UTS of chill castings was about 115MPa while those of squeeze castings ranged between 146 to 232MPa depending on temperature and squeeze pressure. The results of UTS showed that squeeze casting enhances the strength of cast materials. The increase in the strength of squeeze cast products is due to higher cooling rates leading to grain refinement. The reduction in the grain size leads to increase in the number of grains and hence increase in the amount of grain boundary. Subsequently, any dislocation moves only a small distance before reaching a grain boundary and the strength of the product is thus increased (Askeland 1985).

The pattern of 0.2% proof stresses is similar to those of UTS of squeeze and chill castings, although with different values. The reasons for the increase in proof stress are the same for those advanced for increase in UTS. The proof stresses of sand castings made at various pouring temperatures were almost the same. They ranged from 35 to 40MPa.

The percentages of elongation for the squeeze castings varied between 3.4 to 3.8% as compared to those for chill castings which ranged from 2.4 to 2.7%. The increase in elongation of squeeze cast products is brought about by rapid cooling leading to grain refinement and reduction in secondary dendrite arm spacing so as to speed the evolution of the latent heat. The reduction in secondary dendrite arm spacing is accompanied by increase in strengths and ductility (Askeland 1985). The percentage elongation of Al-8%Si alloy sand castings was found to be smaller than those of the squeeze castings and chill castings. It ranged from 2.0 to 2.3%.

Conclusion

The following conclusions were made based on the study:

1. The microstructures of castings increase in degree of fineness from sand castings to chill castings to squeeze castings.
2. Generally, the mechanical properties of squeeze castings are higher than those of chill castings and sand castings with those of sand castings being the least.

3. Squeeze casting significantly improves the mechanical properties of squeeze castings over those of chill and sand castings.

4. Sand castings could be used in as cast condition in non-engineering applications and engineering applications which require low mechanical properties. Chill castings and squeeze castings could be utilised in as cast condition in engineering applications which require medium and high mechanical properties, respectively.

References

Amstead, B.H.; Ostwald, P.F.; and Begeman, M.L. 1979. Manufacturing processes. 7th ed., John Wiley and Sons, New York, NY, USA.

Askeland, D.R. 1985. The science and engineering of materials. PWS Publishing Co., Boston, MA, USA.

Clegg, A.J. 1991. Precision casting processes. Pergamon Press PLC, Oxford, UK.

Jain, P.L. 1992. Principles of foundry technology. 3rd ed., Tata Mc Graw-Hill Publishing Co., Ltd., New Delhi, India.

Lynch, R.F.; Olley, R.P., and Gallagher, P.C.J. 1975. Squeeze casting of brass and bronze. Paper No.75-90. AFS Trans. 83: 561-8.

Mikhailov, A.M. 1989. Metal casting. Mir Publishers, Moscow, USSR.

Raji, A.; and Khan, R.H. 2005. Effect of pouring temperature on the properties of Al-8%Si alloy sand cast components. Global J. Engin. Res. 4(1&2): 1-4.

Raji, A.; and Khan, R.H. 2006. Effects of pouring temperature and squeeze pressure on the properties of Al-8%Si alloy squeeze cast components. AU J.T. 9(4): 229-37, April.

Rao, P.N. 1992. Manufacturing technology: Foundry, forming and welding. Tata McGraw-Hill Publishing Co., Ltd., New Delhi, India.

Weiss, R.; and Kleinheyer, U. 1987. Current trends in the use of moulding and core making processes. Casting Plant Technol. 3(4): 10-9.

West, C.E.; and Gruback, T.E. 1989. Permanent mold casting. *In*: ASM. 1989. Metals handbook (Casting). vol. 15, pp. 275-85, ASM, Metal Park, OH, USA.

Williams, R. 1997. The present status and future of green sand in the foundry industry. The British Foundryman 72(6, Special Supplement): 53-62.

Wright, R.T. 1990. Manufacturing systems. The Goodheart-Willcox Co., Inc., Tinley Park, IL, USA.

Yong, M.S.; and Clegg, A.J. 2004. Process optimisation for a squeeze cast magnesium alloy. J. Materials Process. Technol. 145(1): 134-41, January.

Yue, T.M.; and Chadwick, G.A. 1996. Squeeze casting of light alloys and their composites. J. Materials Process. Technol. 58(2-3): 302-7, March.