Trans Indian Inst Met (2015) 68(Suppl 1):S59–S66
DOI 10.1007/s12666-015-0607-8

TECHNICAL PAPER

Study on the Effects of Squeeze Pressure on Mechanical Properties and Wear Characteristics of Near Eutectic Al–Si–Cu–Mg–Ni Piston Alloy with Variable Mg Content

K. Pratheesh[1] · Allesu Kanjirathinkal[1] · M. A. Joseph[1] · M. Ravi[2]

Received: 15 April 2015 / Accepted: 8 June 2015 / Published online: 14 July 2015

Abstract In the present work, the effects of pressure on the wear resistance characteristics, mechanical properties and the microstructures of Al–Si piston alloys that have variable Magnesium (Mg) content are studied. The paper begins with an explanation of the desirable properties of eutectic Al–Si alloys and why these chemical and mechanical properties are desirable in the fabrication of light weight machine components. The methods for further strengthening the alloys using alloying elements such as Ni, Cu and Mg, and applying heat treatment are also discussed. The paper also emphasises on the addition of Magnesium, and compares the traditional gravity die casting with a novel hybrid technology known as squeeze casting. In the results and discussion section, the microstructure properties of the Al–Si both as-cast and after heat treatment conditions are discussed. The mechanical and wear properties as well as the implications of pressure on the alloys are also discussed in details. SEM analyses of wear surface and fracture behavior on the as cast Al–Si alloys and after heat treatment, reveal that squeeze pressure increases fracture ductility as well as resistance to wear; more so upon heat treatment. It is also determined that the hardness and UTS values increases with increase in Magnesium content and reaches the maximum values when Mg content is at 1 % of the alloy's composition.

✉ K. Pratheesh
mighapratheesh@gmail.com

1 Department of Mechanical Engineering, National Institute of Technology, Calicut 673601, Kerala, India

2 National Institute for Interdisciplinary Science and Technology (CSIR), Thiruvananthapuram 695019, Kerala, India

Keywords Piston alloys · Squeeze casting · Mechanical properties · Electron microscopy · Wear behavior

1 Introduction

The near eutectic Al–Si alloys are applied in areas where qualities such as good mechanical properties, high resistance to wear and tear, reduced density and low thermal expansion are desired [1, 2]. The properties of these alloys are of paramount importance in automobile industries since they are used to fabricate light weight engine components such as pistons, connecting rods, engine blocks and cylinder lines for fuel efficient vehicles [3]. The high resistance to wear and tear, and the good mechanical properties are generally attributed to the existence of hard Si particles that are well distributed in the metal alloy matrix [4].

Improvement of the mechanical properties of the near eutectic Al–Si alloys requires the addition of alloying elements that includes Ni, Mg, and Cu. The alloying elements added lead to the formation of various inter-metallic phases that have very complex chemical and mechanical structures. Some of the inter-metallic phases created includes Al_3CuNi, Al_2Cu, Mg_2Si, Al_7Cu_4Ni, Al_3Ni, and $Al_5Cu_2Mg_8Si_6$ among others [5, 6]. Essentially, the mechanical properties of multi-component pistons made from Al–Si alloys relies heavily on the chemical structure and composition, the evolution of inter-metallic phases, and the morphology features [7, 8]. In order to further improve the wear resistance and mechanical properties of components cast from these alloys, heat treatment can be applied. Sjolander [9] recently performed a summary on the microstructural changes that occur in sequence when treatment solutions proposed by various studies are applied, and also on their implications on the overall mechanical properties. In Al–Si cast alloys, Mg is added to increase the alloys' tensile strength upon heat treatment, since it has been found to have a predominant effect on the material microstructure [10]. In this regard, the effects of Mg on the microstructure are well desired since they have a significant implication on the fracture mechanisms of Al–Si-Cu-Mg-Ni alloys. Lasa and Rodriguez-Ibabe [11] conducted studies focusing on the wear resistance of Al–Si–Mg–Cu–Ni alloys formed through several processing routes using pin on disc techniques with variable speed. The results of wear testing shows that alloys with a high Mg content has improved wear resistance [12]. In general, apart from the composition of the alloy and previous casting procedures such as heat treatment, the wear resistance and mechanical properties of alloys cast from Al–Si is also highly dependent on the casting process.

A new unique approach to component fabrication is made possible using an emerging metal forming process known as squeeze casting. Squeeze casting is a process that combines the desirable features of metal forging and casting processes. In this process the metal is melted and the molten metal is poured into closed die halves and solidified under pressure. The instantaneous contact of molten metal with the die surfaces combined with the pressure causes a rapid heat transfer condition that results a casting which is free of pores and improved wear resistance and mechanical properties. The resulting fabricated components can either be used immediately for service, or after some minor post-fabrication treatment operations. Squeeze casting is usually considered as a near net or net shaped route of fabrication. Lynch and Olley [13] performed some investigations on aluminum squeeze casting and presented some aspects of the process. The objective of the current study is to carry out an investigation on the mechanical properties and wear resistance behavior of Al–12Si–XMg–2Cu–3Ni (X varies between 0.5 and 1.5 wt% Mg) in the as-cast, and after heat treatment conditions respectively. In this work, attempts are also made to compare the wear resistance and mechanical properties when gravity die casting and squeeze casting techniques are used on Al–12Si–1Mg–2Cu–3Ni. A scanning electron microscope is used to conduct wear analysis and fractography studies on the wear surfaces and fractured surfaces of the heat treated Al–12Si–3.10Cu–1Mg–1.78Ni gravity and squeeze die casts.

2 Materials and Methods

2.1 Melting and Casting of Test Specimens

Ingots of an Al–7Si and Al–30Cu, Al–20Mg and Al–75Ni master alloys were used to prepare the experimental alloy. The casting was executed in an 18 kW pit furnace which was of electrical resistance type. The melt was degassed for 60 min by bubbling pure, dry nitrogen gas into it by means of a graphite lance so that the hydrogen dissolved in the melt could be removed. The pouring temperature was kept at 710–720 °C. For squeeze casting, the melt was poured at 680 °C into a die cavity with dimensions of 100 × 100 × 100 mm. Immediately after the melt had been poured into the cavity, a pressure of more than 100 MPa was exerted on the melt in the cavity using a ram for 2 min.

2.2 Heat Treatment of Test Specimens

The specimens used for the tensile and hardness tests (20 × 20 × 20 mm) and the microstructural analysis (20 × 20 × 20 mm), were machined from all the alloys. For solutionisation, the specimens were heated at a temperature of 500 °C for 5 h and quenched in cold water (20 °C). After being quenched, the samples were dried in air and then heated to 180 °C for 9 h in an electric oven for ageing.

2.3 Microstructural Observations

A Leica DMRX 82 optical microscope was employed for observing the microstructures of the specimens

2.4 Tensile Tests and Hardness Tests

The tensile properties of the alloy samples (ASTM standard E8M-04) and Brinell hardness at ambient temperature were evaluated using a universal testing machine (Instron Model 1195-5500R) and a Brinell hardness machine (Indentec).

2.5 Wear Tests

For conducting wear tests, DUCOM TR-20LE pin-on-disc wear testing apparatus under dry sliding conditions in the ambient air at room temperature was used. The main variables of dry sliding wear for Al–Si alloys are sliding distance, sliding distance and sliding velocity. Usually for Al–Si alloys under low velocity (up to 2 m/sec) linear relationship exist between velocities and wear rate [14]. At high load, coarsening of β phase particles occurs leading to increase in the temperature during the sliding of cast Al–Si alloys [15]. For hypoeutectic and hyper eutectic alloy nonlinear relationship exist among applied load and wear rate against steel beyond certain critical load at which transition from mild to severe metallic wear take place [16]. It is observed that when load is above 20 N transition from mild to severe wear may take place [17]. Above a critical load (20 N) load and critical velocity (2 m/sec), wear occurs due to physical failure of metal at interface between mating surfaces. Certain amount of plastic deformation and metal flow always occurs above critical load and critical velocity [18]. Wear rate shows linear relationship up to a load of 20 N and up to a velocity of 2 m/sec [14]. At low velocity and at low load the deformation of subsurface region is not observed because wear is primarily determined by removal of oxide to form wear debris [14]. The strict way by which wear procedure carry on through the oxidation, fracture, removal of oxides and fresh oxidation is not yet very clear [18]. The sliding distance of the pin and the velocity of the disc were fixed at 1800 m and 2 m/s respectively. Each test was for 15 min duration with a load of 20 N.

2.6 Scanning Electron Microscopy (SEM)

To describe the type of wear exhibited by the samples, the worn-out surfaces of the samples subjected to a load of 20 N were viewed using SEM (JEOL JSM 5600LV). Similarly, to study the fracture behaviors of the castings, tensile-fractured samples of the castings were observed using SEM.

3 Results and Discussion

3.1 Chemical Analysis

The composition of the experimental alloy, which was analysed using an optical emission spectrometer, is given in Table 1.

3.2 Microstructure

The microstructure of the permanently molded (using 32 × 200 × 250 plate casting) Al–Si alloy with a variable Magnesium content in its as-cast form is as shown in the Figs. 1, 2, 3, 4 and 5. The microstructure comprises of α-aluminum dendritic halos that have eutectic Silicon (Si) and complex intermetallic compounds that are segregated into the primary Si and inter-dendritic regions. The primary irregular eutectic Si particles and the primary polygonal Si are dark grey, while the intermetallic phases have a light grey color. In the micrograph in the as cast condition, the eutectic Si flakes have lamellar and rod style shapes while the intermetallic phases occur in blocky or fibrous morphologies in the inter-dendritic regions.

The alloy has some other coexisting elements such as copper, nickel, magnesium, and iron which forms the intermetallic Al_2Cu, Al_7Cu_4Ni, $Al_4Cu_2Mg_8Si_7$ and Al–Si–Fe–Ni–Cu. The solubility of these elements in aluminium usually increases with increasing temperature. This decrease from high concentrations at elevated temperatures to relatively low concentrations during solidification as well as during heat treatment results in the formation of secondary intermetallic phases [19].

The features of the microstructures of the alloy in T6 condition undergoes changes upon heat treatment. Figures 1, 2, 3, 4 and 5 shows the comparison between the microstructures of the alloy in as-cast and T6 heat treatment condition. Microstructure observation reveals that the secondary arm spacing is reduced for the heat treated alloys. Most of the intermetallic phases dissolves and tends to spheroidize, i.e., sharp corners become rounded. The morphology change of the eutectic Si is obvious after heat treatment. The plate-like eutectic Si in as-cast case is broken into small particles. Spheroidization and coarsening of the discontinuous phase occur at elevated temperatures, because the interfacial energy of a system decreases with the reduction in interfacial surface area per unit volume of the discontinuous phase. Solution heat treatment results in the microstructural changes due to the instability of the interface between two phases. Plate-like eutectics are more resistant to interfacial instabilities and subsequent spheroidization than the fibrous kind. Spheroidization and coarsening of the discontinuous phase occur at elevated temperatures, because the interfacial energy of a system decreases with the reduction in interfacial surface area per unit volume of the discontinuous phase [20]. Thus combination of alloying elements and heat treatment is a satisfactory option for obtaining improved control on the microstructure and hence on improving the properties of the alloy. Actually, due to heat treatment both the primary silicon crystals and eutectic silicon needles show some spheroidizing. Increasing in Mg content results in the precipitation of intermetallic particles of Mg_2Si. Heat treatment promotes rounding of the eutectic Si particles particularly for high Mg content alloys. The micro structure

Table 1 Chemical composition of the experimental alloy (wt%)

	Si	Cu	Mg	Ni	Fe	Mn	Ti	Al
Alloy 1	12.2	2.89	0	1.77	0.16	0.03	0.01	Bal
Alloy 2	12.02	3.10	0.52	1.81	0.17	0.04	0.01	Bal
Alloy 3	12.09	3.10	1.13	1.78	0.19	0.04	0.01	Bal
Alloy 4	11.55	3.10	1.54	1.67	0.18	0.04	0.01	Bal
Alloy 5	12.2	2.89	2.12	1.77	0.16	0.03	0.01	Bal

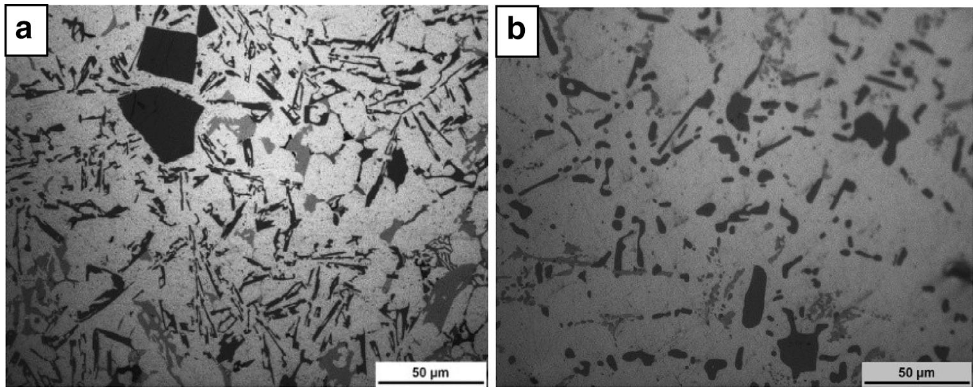


Fig. 1 Microstructure of the Al–12.12Si–3.14Cu–0Mg–1.77Ni alloy (gravity die casting) **a** As-cast **b** Heat treated condition

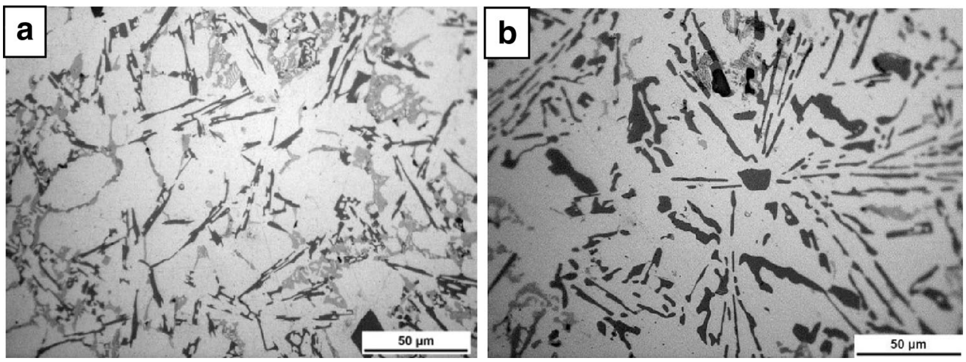


Fig. 2 Microstructure of the Al–12Si–3Cu–0.5Mg–1.7Ni alloy (gravity die casting) **a** As-cast **b** Heat treated condition

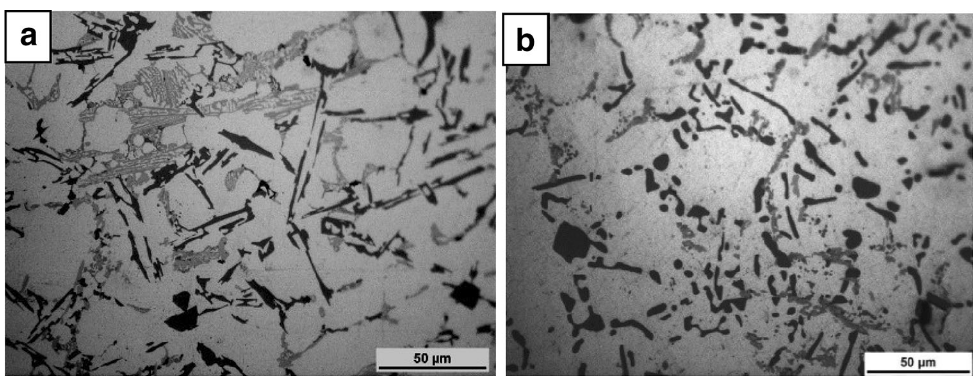


Fig. 3 Microstructure of the Al–12Si–3Cu–1Mg–1.7Ni alloy (gravity die cast) **a** As-cast **b** T6-condition

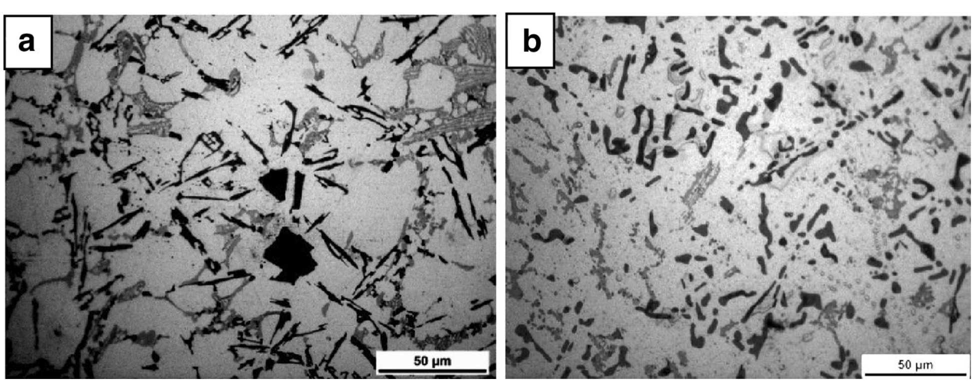


Fig. 4 Microstructure of the Al–12Si–3Cu–1.5Mg–1.7Ni alloy (gravity die cast) **a** As-cast **b** T6-condition

of the sample under squeeze cast is shown in Fig. 6. The applied pressure increases the cooling rate as it improves the thermal contact between the casting and the die, resulting in a refined grain structure and the almost complete elimination of all shrinkage and gas-related porosities. This accelerates the mechanical and wears

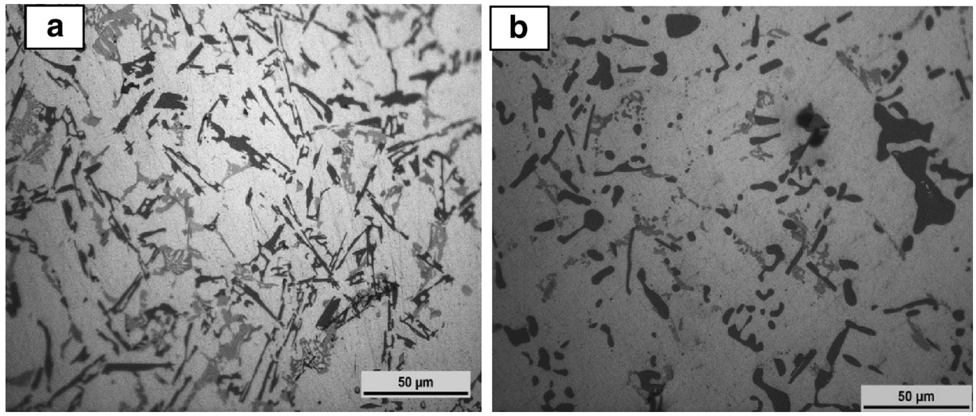


Fig. 5 Microstructure of the Al–12.2Si–2.89Cu–2.12Mg–1.77Ni alloy (gravity die cast) **a** As-cast **b** Heat treated condition

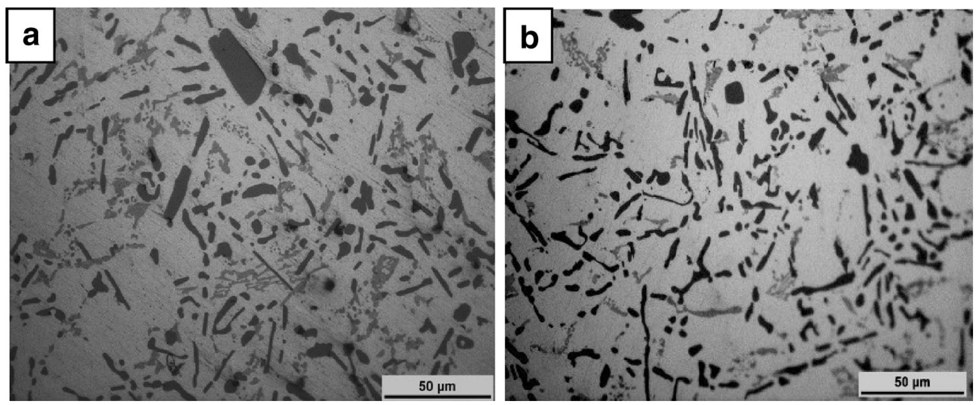


Fig. 6 Microstructure of the Al–12Si–3Cu–1Mg–1.7Ni alloy (squeeze cast) **a** As-cast **b** T6-condition

characteristics of the cast alloy. Also application of pressure causes the rounding of the eutectic Si particles Hence, it is acknowledged that squeeze-cast components have superior mechanical properties and wear characteristics compared to those fabricated using conventional casting methods.

3.3 Mechanical Properties and Wear characteristics

The tensile properties and hardness of as cast and heat treated gravity die cast and squeeze cast samples obtained are shown in Figs. 7 and 8. It is observed that the hardness and ultimate tensile strength (UTS) values are found to rise with increase in Mg content. Alloys with increased Mg level exhibits a micro structure in which the Si particles are inherently refined and well distributed. When Mg level increases, large Mg_2Si particles tend to form and their number and size rises with increased Mg. The Mg_2Si phase is desirable in Al alloys because of its high melting point (1085 °C), low density (1.9 gm/cc), high hardness (4.5 GPa), low coefficient of thermal expansion (7.5×10^{-6}/K) and reasonably high elastic modulus. Its presence in the form of large blocky particles significantly detracts from the alloy's mechanical properties. The UTS and hardness values are higher than that of as cast alloys.

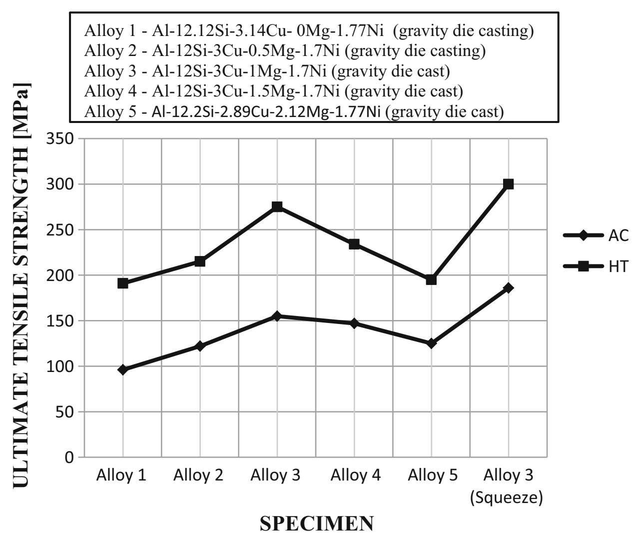


Fig. 7 Plot showing the variation of ultimate tensile strength for different alloys

Heat treatment of Al–Si–Cu–Mg–Ni shows cumulative effect of precipitation hardening(Mg_2Si), breaking of cast dendritic structure, reducing segregation of alloying elements, spheroidization of silicon crystals and improved bonding between the second phase particles and matrix aluminium. To get the benefits of precipitation hardening it

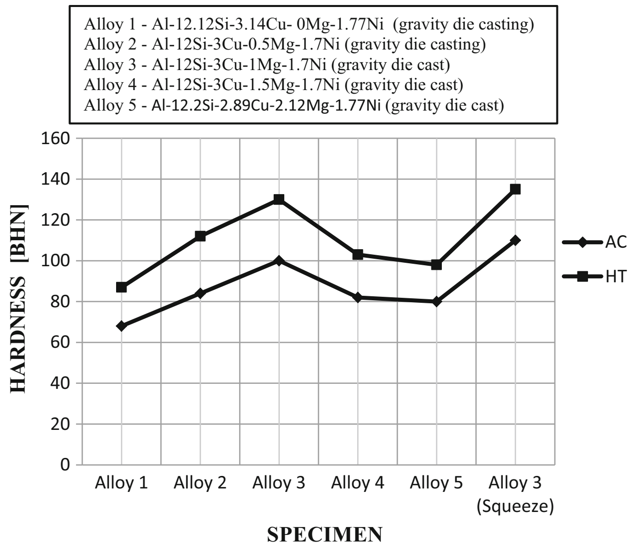


Fig. 8 Plot showing the variation of hardness for different alloys

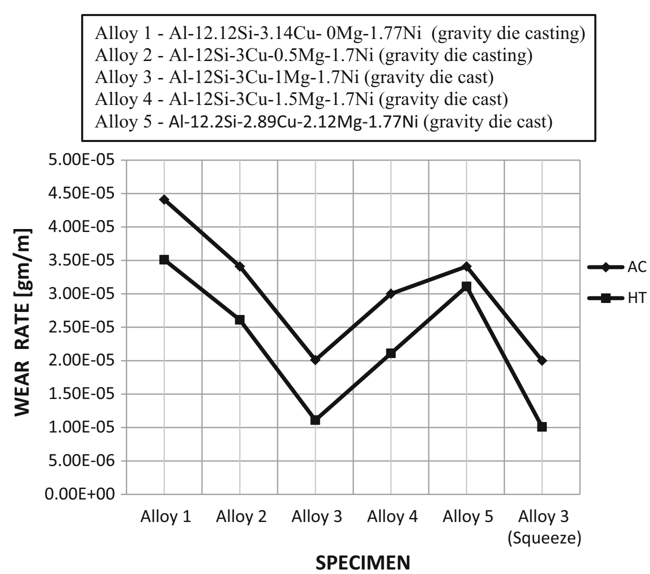
is necessary that alloy elements are dissolved in aluminium matrix during the solutionizing. Solution temperature determines diffusion and solubility limits of alloying elements in the aluminium. An increase in temperature (500 °C) increases both the parameters which inturn increases the effect of age hardening and their effect on mechanical and wear resistance. Enhanced distribution of refined and spheroidizaised silicon crystals would retard the crack nucleation and propensities and can be attributed to improvement of wear resistance with heat treatment. The wear rate of as cast and heat treated gravity die cast and squeeze cast samples obtained are shown in Fig. 9. Wear rate decreases with increase in Mg content for both as cast and heat treated alloy. After heat treatment the wear resistance of all samples are improved. Harun et al. [21] have also found that the wear resistance of Al–Si–Cu–Ni–Mg alloys is affected by heat treatment in a favourable way. Improvement of yield strength obtained after heat treatment is also known to delay or inhibit wear.

3.4 Effect of Pressure

The application of pressure during solidification has resulted in increase in hardness, increase in UTS and decrease in wear rate. The rate of increase in hardness and UTS which is the result of both increase in heat transfer rates and decrease in inter atomic distances. Squeeze cast components are characterised by a refined micro structure having fine grains, close dendrite arm spacing and small constituent particles. The applied pressure increases the cooling rate as it improves the thermal contact between the casting and the die, resulting in a refined grain structure and almost complete elimination of all shrinkage- and gas-related porosities. This accelerates the mechanical and wears characteristics of the cast alloy. Hence, it is generally acknowledged that squeeze-cast components have superior properties compared to those fabricated using conventional casting methods. The fine grain size results from a high level of nucleation and subsequent growth rate. Nucleation occurs initially in the under cooled region at the die wall and is enhanced as metal movement which promotes back melting and, dendrite sharing mixed with rapid cooling. The mechanical shock encountered at the instant of the die closer is felt to contribute further to nucleation.

The effect of the pressure could be expressed using the equation suggested by Ghomashchi [22].

Fig. 9 Plot showing the variation of wear rate for different alloys



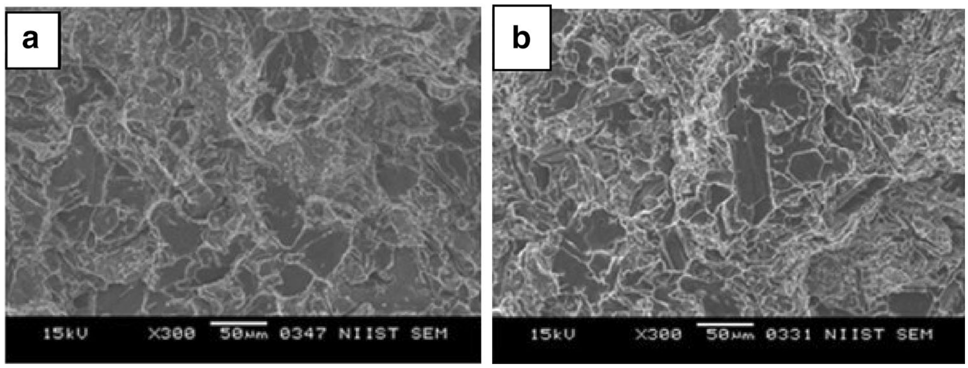


Fig. 10 SEM images of the fractured surface of the heat-treated, alloys subjected to the tensile test **a** Al–12Si–3Cu–1Mg–1.7Ni (gravity die casting) **b** Al–12Si–3Cu–1Mg–1.7Ni (squeeze casting)

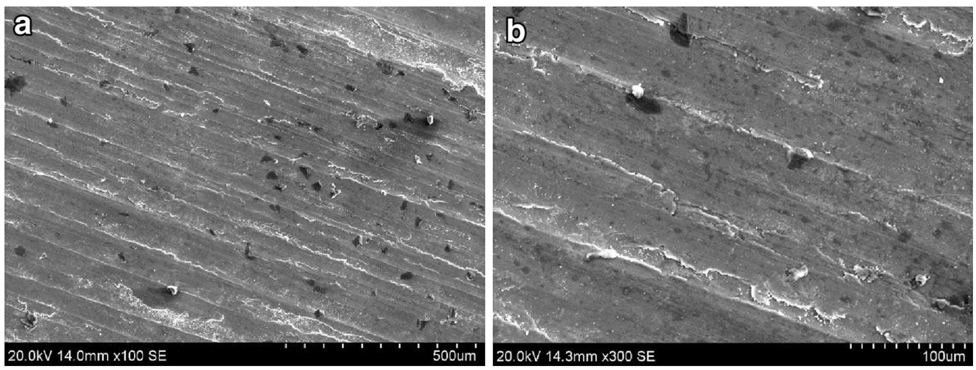


Fig. 11 SEM images of worn surface of heat treated alloys, subjected to wear test **a** Al–12Si–3Cu–1Mg–1.7Ni (gravity die casting) **b** Al–12Si–3Cu–1Mg–1.7Ni (squeeze casting)

$$P = P_0 \exp\left(\frac{-\Delta Hf}{RTf}\right) \quad (1)$$

where ΔHf is the latent heat of fusion and P_0 and R are constants. Thus, the freezing point (Tf) of the alloy is directly proportional to the pressure applied. The application of pressure increases the freezing point, which results in an increase in the degree of under cooling of the initially superheated alloy. The frequency of nucleation increases, and a finer microstructure evolves [22]. The intimate contact between the melt and the die wall leads to a higher degree of heat transfer, resulting in a higher cooling rate. This causes the formation of a fine microstructure in the squeeze-cast alloy specimens [23]. The wear data obtained shows that the improvement in the microstructure achieved by applying a squeeze pressure results in the Si particles becoming more rounded and uniformly distributed. This, in turn, results in the squeeze casted alloy showing superior wear resistance, in keeping with what has been reported previously [20].

3.5 SEM Analysis of Fracture Behaviour and Wear Surface

Figure 10 reveals the SEM micro graphs of the typical fracture surfaces of heat treated gravity die cast and squeeze casted samples. The morphologies of the eutectic and primary Si phases primarily control the nature of the fracture process. A mixed mode of brittle cleavage and ductile fracture with dimples is observed at both heat treated and as cast samples. The initiation and propagation sites of the cracks formed are determined by the coarse Si particles. Application of squeeze pressure improves the fracture surfaces. The fractured surfaces are smoother in the case of the squeeze-cast alloy specimen. It indicates more ductile fracture mode for the squeeze-cast alloy. The fracture behaviour of the alloys is affected by the size of α particles and Si morphology. Figure 11 shows SEM images of worn surfaces of heat treated gravity die cast and squeeze cast Al–Si–Cu–Mg–Ni. These images shows that the nature of the wear of the specimens is metallic, because the test strips are smooth, and the grooves become smaller with plastic deformation. Nucleation of cracks in Al–Si–Cu–Ni–Mg alloy mostly occurs at particle matrix interfaces. The mechanism of material removable in the alloy is found to be micro cutting. The material accumulated around the groove, deformed plastically and subsequently detached from the wear surface by nucleation and propagation of the cracks. The silicon particles for the high Mg alloys are surrounded by Mg_2Si particles resulting in a better bonding of Si particles to the matrix. The Inferior wear properties of low Mg alloy may be attributed due to the debonding of large primary Si at their interface with the matrix.

4 Conclusions

From the above study, the following conclusions are made:

1. The UTS and hardness values are found to increase with increase in Mg content and attain the maximum at 1 % Mg content alloy.
2. Heat treatment increase the strength of the investigated alloys. The eutectic silicon particles start to fragmentize and spherodize almost immediately with heat treatment. This leads to pronounce improvement in mechanical properties and reduces the wear rate.
3. Increase in squeeze pressure promotes rapid solidification and refined cell structure, decreases the α-Al grain size and modifies the eutectic Si, which increases the mechanical properties and decreases the wear rate.

Acknowledgments The financial support received from CSIR-Network Project ESC0101 is acknowledged. Support received from Dr. M.T Sebastain, Dr. M.L.P. Reddy, Chief Scientists NIIST, Trivandrum is also acknowledged. Help provided by Mr. K.K. Ravikumar, Mr. Chandran, Sr. Technical officers and Mr. V. Antony Sr. Technician, NIIST, Trivandrum is greatly appreciated.

References

1. Timmermans G, and Froyen L, *Wear* **230** (1999) 105.
2. Rohatgi P K, Asthana R, and Das S, *Int Met Rev* **31** (1986) 115.
3. Dwivedi D K, *Mater Sci Technol*. **19** (2003) 1091.
4. Clarke J, and Sarkar A D, *Wear* **54** (1979) 7.
5. Belov N A, Eskin D G, and Avxentieva N N, *Acta Mater* **53** (2005) 4709.
6. Zeren M, *Mater Des* **28** (2007) 2511.
7. Qian Z, Liu X F, and Zhao D G, *Mater Lett* **62** (2008) 2146.
8. Mohamed A M A, Samuel A M, Samuel F H, and Doty H W, *Mater Des* **30** (2009) 3943.
9. Sjolander E, and Seifeddine S, *J Mater Technol* **210** (2010) 1249.
10. Gruzleski J E, and Closset B, *The Treatment of Liquid Aluminium Silicon Alloy*, AFS, Inc., Illinois (1990).
11. Lasa L, and Rodriguez-Ibabe J M, *Mater Sci Eng A* **363** (2003) 193.
12. Hekmat-Ardakan A, Liu X, Ajersch F, and Chen X G, *Wear* **269** (2010) 684.
13. Lynch R S, and Olley R P, *Am Foundrym Soc Trans* **122** (1975) 569.
14. Diwivedi D K, *Mater Des* **31** (2010) 2517.
15. Yaseen R S, and Dwarkdas E S, *Wear* **84** (1983) 372.
16. Rabinowitcz E, *Friction, Wear and Lubrication*, John Wiley and Sons, New York (1965) p 70.
17. Saka N, Eleiche A M, and Suh N P, *Wear* **44** (1977) 109.
18. Spurr R T, *Wear*, **55** (1979) 283.
19. Ye H, *ASM Int JMEPEG* **12** (2003) 288.
20. Mohamed A M A, Samuel A M, Samuel F H, and Doty H W, *Mater Des*, **30** (2009) 3943.
21. Harun M, Tilib I A, and Daud A R, *Wear* **194** (1996) 54.
22. Ghomashchi M R, and Vikhrov A, *J Mater Process Technol* **101** (2000) 1.
23. Lee J H, Kim H S, Won C W, and Cantor B, *Mater Sci Eng A* **338** (2012) 182.