

Study the Effect of Grain Refinement and Modification on the Dry Sliding Wear Behaviour of Hypereutectic Al-Si Alloys

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ABSTRACT:

The present study deals with an investigation of dry sliding wear behaviour of grain refined and or modified (Al-20Si) alloy by using a Pin-On-Disc. The refining was by grain refinements (Ti and B), modification (Sr, Na and P) and combined action of both (Ti, B + P +chilling). Results indicate that combined grain refined and modified Al-20Si alloys have microstructures consisting of uniformly distributed α -Al grains, eutectic Al-silicon and fine primary Si - particles in the interdendritic region. These alloys (5,6) exhibited better wear resistance (13-15 times) than the same alloy subjected to only grain refinement or modification (1, 2 and 3) . The improved wear resistances are related to the refinement of the aluminum grain size, uniform distribution of fine fibrous eutectic Al-silicon and fine primary Si- particles.

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(dry sliding wear behaviour)

(hypereutectic Al-Si alloys) -

(pin -on- disc) (grain refined and modified)

(α -Al)

(0.09%B) (0.03%Ti) (Al-Si20) -

(Sr)

(Cu3P) (

.(0.3%Cu3P)

()

C°

(20%)

()

1. Introduction

Hypereutectic Al-Si alloys are of commercial interest because of their specific mechanical and physical properties due to presence of primary Si particles in the microstructure. A low thermal expansion coefficient, high wear resistance and elevated hardness are the properties which encourage the application of such alloys in the heavy duty engines and some aeronautic components[2,8,14,15,17].

The casting process and the aluminium alloys have reached a level of quality that makes manufacturing of structural components possible. However, this requires careful control of the casting process, melt quality and a correct selection of aluminium alloys [1].

Use of cast Al-Si alloys as a tribological component in recent years has been expanding widely in military, automobile and general engineering industry. Aluminium-silicon eutectic and near-eutectic alloys are cast to produce majority of pistons and are known as piston alloys. Silicon is probably one of the least expensive alloying additions commonly made to aluminium, which improves castability, enhances corrosion resistance, decreases the coefficient of thermal expansion and imparts wear resistance to aluminium. [3,5,12].

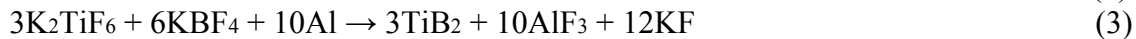
The improvement in sliding wear resistance and mechanical properties is dictated by the type, shape, size and uniform distribution of second phase particles in the matrix and matrix microstructures. Hardness is usually thought of as a wear controlling property, i.e. the higher the hardness, more is the wear resistance of the material. However, it should be emphasized that it is the hardness of the contacting asperities and not the bulk hardness that will control the wear rate. The addition of hard second phase particles to the matrix improves both wear resistance and mechanical properties [2, 3].

Wear of a material is controlled by the material characteristics as well as operating parameters such as applied pressure, sliding speed, environment and the type of sliding interaction. Material characteristics including metallurgical and mechanical properties of alloy significantly affect their wear resistance. It has been reported that grain morphology of the various phases present in alloys appreciably influence the mechanical and dry sliding wear behaviour. Coarse and needle-shaped eutectic and large primary silicon particles increase adhesive wear. In general, fine, spherical and uniformly distributed micro-constituents (alpha aluminium, eutectic, primary silicon) are known to improve the wear and mechanical properties of aluminium alloys [4].

Alloy composition, solidification rate, heat treatment procedures, casting defects, and such microstructural features as grain size and intermetallic phases, are all parameters which closely affect alloy quality since they also influence the mechanical properties of the casting [6].

The cooling rate affects the pore size by the way it affects the local solidification structure (*i.e.* the dendrite arm spacing), which, in turn, controls the threshold cell size and hence the pore size [7].

The mechanical and physical properties of Al-Si alloys were affected by primary Si particle such as particle size and volume fraction, and Si content, *etc.* Therefore, behavior of primary Si particle during solidification should be controlled to acquire desired properties. In literature, it was reported that the primary Si particle was dominantly affected by cooling rate during solidification [8, 9, 16]. Inoculation is the most commonly employed method and is carried out using grain refiners such as Al-Ti, Al-Ti-B, Al-Ti-C, Al-B and Al-Sr-B alloys. The standard method for the manufacture of Al-Ti-B involving the use of K_2TiF_6 and KBF_4 results in considerable fluoride emissions and formation of fluoride salts as slag. [10].



Flux treatment leads to *in-situ* generation of the nucleants such as AlB_2 and TiB_2 ; the production of master alloys based on the above chemical equations results in a fine dispersion of the borides in aluminium which can be subsequently added to aluminium alloys [10].

In order to achieve fine silicon phase with beneficial shapes and distribution, modification is usually acquired by the addition of phosphor or phosphorous compound to the melt before casting, which can obtain a uniform distribution of AlP ($Al[l] + P[l] \rightarrow AlP[s]$) particles [5,6] that can promote nucleation of primary silicon with a cube-cube orientation relationship [11].

For the purpose to increase the industrial applicability, microstructure modification is necessary through adding elements, such as Ti, P, Na, Sr, directional solidification, or rapid cooling, such as in surface treatment with high-energy beams, which can result in dramatic increase in mechanical properties. Thus, morphologies of the primary and eutectic silicon phases are paid particular attention for obtaining a refined microstructure and less faceted silicon morphologies in order to increase the strength and ductility of the alloy. They vary with different composition and processing conditions. Reported primary phase morphologies include [14, 16, 18, and 19]: hexagonal plate shaped crystals, equi-axed octahedral crystals, equi-axed crystals containing parallel twins, star-like crystals containing two to five radiating twin planes, and spherical Crystals [13].

The role of the silicon content in Al-Si alloys has been investigated intensely by several researchers. Although increasing the silicon content of the alloy has usually been found to improve the wear resistance, under certain experimental conditions, high silicon content alloys have performed worse than their low silicon counterparts [17]. From the foregoing discussion, it is clear that many mechanisms can play a significant role in the sliding wear behaviour of complex polyphase alloys. Many previous studies on the fundamental metallurgical mechanisms of friction and wear in pure metals and single phase alloys have provided a basis for interpreting their sliding wear behaviour, but investigators only rarely have pursued the more rigorous questions involved with understanding the mechanistic details of sliding wear behaviour of the complex microstructures typical of many grain refined and modified materials. If timely

progress is to be made in this area, more tools of basic metals research need to be focused on the alloys of current technological significance.

The main purpose of the present work is to investigate the relationship between the microstructure and the solidification parameters (such as cooling rate, composition, modifiers, grain refiners) and sliding wear behaviour of hypereutectic Al–20Si cast alloys in dry sliding against a steel counter face by using Pin-On-Disc wear tests.

2. Experimental details

Al–20Si alloy was prepared by melting commercially pure aluminum (99.8%) with commercially pure silicon in clay graphite crucible in gas furnace under a cover flux (45%NaCl + 45% KCl + 10% NaF) and the melt was held at 900 °C with continuous mechanical mixing by graphite mixer until all the Silicon quantity are dissolved in the aluminium melt. After degassing with 1% solid hexachloroethane, pure titanium powder, strontium nitrate, Cu₃P, NaF, duly packed in aluminum foil were added to the melt for grain refinement and modification. The melt was stirred for 3 minutes after the addition of grain refiner and/or modifier.

Melts were held for 5 min and poured into a cylindrical steel mould with 15×15×200 mm.

The sample 6 was prepared by pouring the melt in opened metal mould surrounded by ice. The details of the alloys, grain refinement and modification treatment and the condition of solidification of various alloys are given in [Table 1](#). All casting processes carried out in Babylon university/metallurgical laboratory.

Table 2 Chemical analysis and hardness values of cast alloys

Alloy	Wt%Si	Wt%Fe	Wt%Sr	Wt%Na	Wt%Ti	Wt%B	Wt%P	Al		Hardness (HB) Kgf/m ²
1	20.6	0.21	-----		----- -	----- -	-----	balance	normal	75
2	20.4	0.18		0.12						75
3	20.06	0.19					0.008			94
4	20.3	0.19	0.009		----- -	----- -	----- -	balance	normal	76
5	20.5	0.22	-----		0.03	0.09	0.0042	balance	normal	110
6	20.1	0.16	-----		0.035	0.11	0.0045	balance	chilled	135

The microstructures of the samples that had been cut in the cross-sectional direction were studied using Nikon optical microscope in science & technology ministry in Iraq. Grain size analysis was carried out by the linear intercept method after etching the polished surface with Keller's reagent (2.5% HNO₃, 1.5% HCl, 1% HF and 95% H₂O). Samples for optical microscopy were polished using in mechanical

grinding and polishing equipment. The microstructures for each alloy are given in Fig.2 to Fig.9.

Dry sliding wear tests were conducted using a conventional pin-on-disc testing machine in metallurgical laboratory of material engineering collage in Babylon University. A scheme of the testing configuration is shown in Fig. 1.

The pins of ($a = 6$ mm) diameter and 25 mm length were fabricated ,in mechanical workshop of mechanical engineering collage in Babylon University by center lathe , from the castings against a hardened and ground ($R_a = 0.1$ μm) cast iron disc [Dia-110 mm and (8 mm) thickness] with a hardness value about HRC 63. The mating surfaces of the pins and the disc were polished to a roughness of $R_a = 0.1$ μm before start of the wear test.

The wear tests were run under constant load ($p=12.5$ N) and constant sliding speed ($R=500$ rpm) and 30 minute time. The pins were weighed, using Mettler 4-digits balance, before and after the tests to obtain the coefficient of wear, according to Eq. (1):

$$w = \Delta m / d \cdot p_i \quad \text{----- Eq. (1)}$$

Where w is the coefficient of wear (g/Nm), p the load (N), Δm denotes mass loss of pin (g) and d is the distance (m). A minimum of two samples were tested for each condition. If the difference between the two samples was greater than 10%, a third and even a fourth pin were tested.

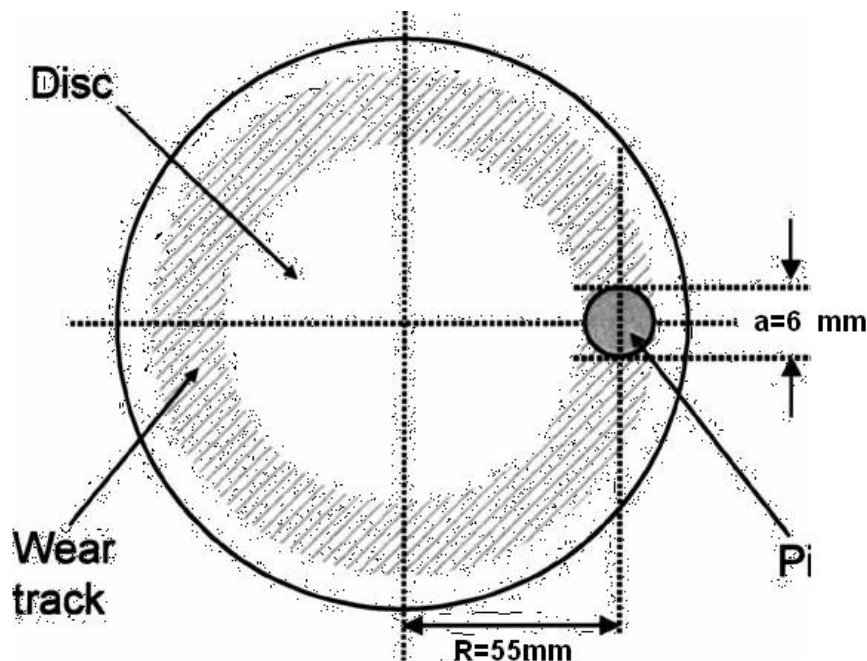


Fig. 1 Scheme of the testing configuration of the pin-on-disc machine.

3. Results and discussion

3.1. Microstructure study:

Optical micrographs of cast Al–20%Si alloy are shown in(Fig.2 - Fig.9). It can be seen from micrograph of conventional cast alloy (Fig.2) that polyhedral-shaped primary silicon particles are present in the matrix of aluminium–silicon eutectic apart

from eutectic silicon which is long interconnected and needle-shaped .Average size of primary silicon particle is about 120 μ m and the fraction of primary Si particles about 30%. Microstructures of treated Al–20%Si alloy with strontium (Sr) and sodium (Na) are shown in (Fig.3 and Fig.4). It can be easily seen that no considerable influence of refining or modification. The micrograph in (Fig.5) reveals important influence of phosphor on the morphology of Al-Si eutectic and primary Si- particles because the formation of AlP particles which have significant role in heterogeneous solidification. The fraction of primary Si-particles increases to about 60% and the average size of these particles about 50 μ m.

Careful observation to micrographs in (Fig.6 and Fig.7) revealed that the eutectic silicon and primary Si-particles are refined and modified by (Ti, B and P) all together, and the aspect ratio of eutectic silicon fiber about 3 .This alloy comprise soluble $TiAl_3$ particles and insoluble boride particles in an aluminum matrix which has significant role in refining the Al-Si structure. Average size of primary silicon particles is about 5 μ m and the distribution of these particles is uniform. Refinement of eutectic silicon and modification of primary Si-particles was observed in the micrograph in (Fig.8 and Fig.9). Very fine and uniform Si-eutectic and primary Si-particles reveals the influence of combination of modifiers and refiners with the chillers on the morphology of the microstructure of Al-20Si cast alloys, and the aspect ratio of the eutectic silicon fiber is about 2 . In quench-modified eutectic forms the Si-eutectic fibers are much finer than slowly grown flakes and are finer than impurity-modified fibers [40].

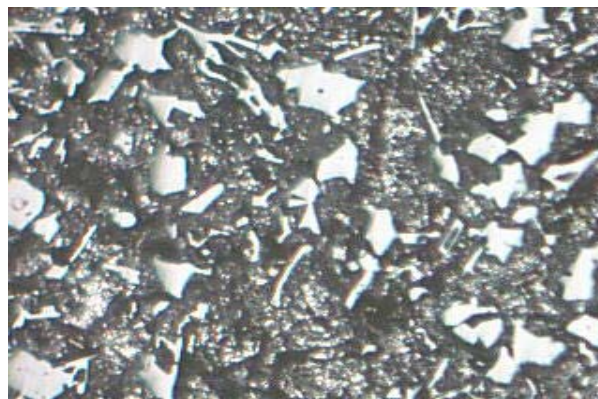


Fig.2 - Conventional cast Al-20Si alloy (alloy no.1)
X200



Fig.3 Al-20Si modified by Sr (sample 2) x200

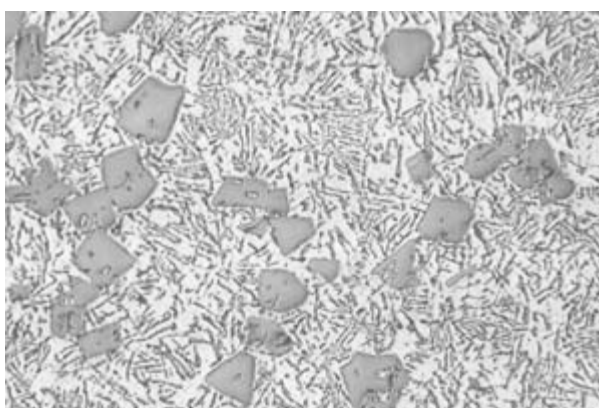


fig.4 Al-20Si modified by Na (sample 3) X200

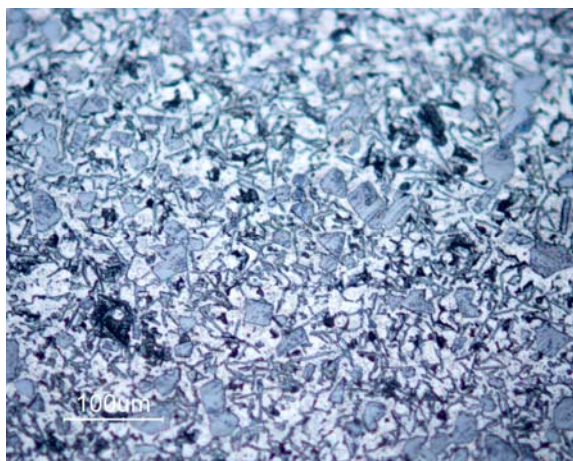


Fig.5 Al-20Si modified by 0.09%p(sample 4) X200

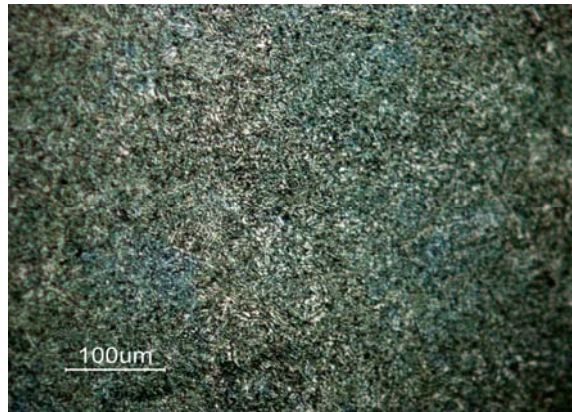


Fig.6 Al-Si Alloy refined by Ti, B
and modified by P(sample 5) X200

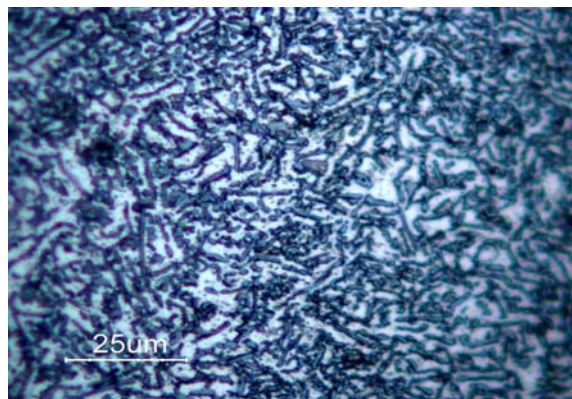


Fig. 7 Al-20Si Alloy refined by Ti, B
and modified by P(sample 6) X200

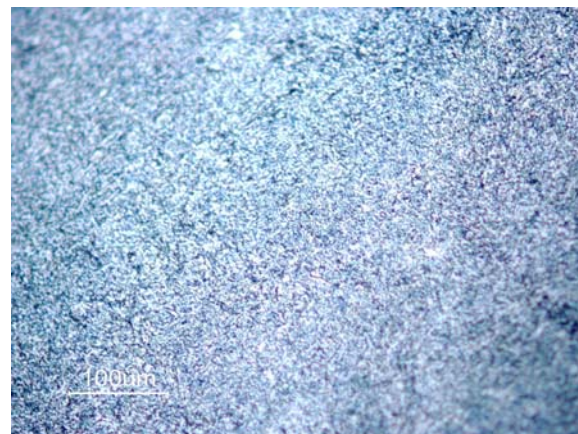


Fig.8 Al-20Si Alloy refined by Ti, B
and modified by P and chilled (sample 6) X1000.

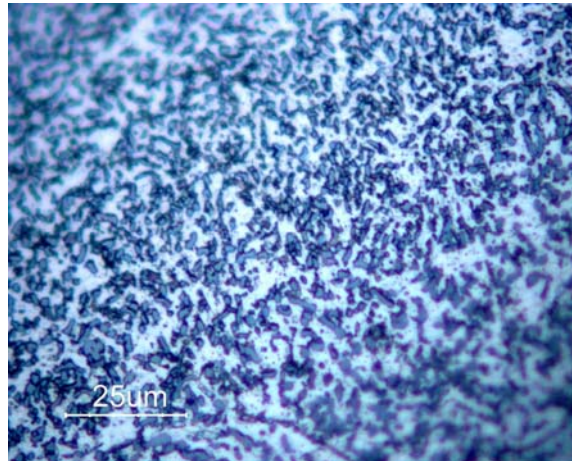


Fig. 9 Z3-EK-X1000 Al-20Si Alloy refined by Ti, B and modified by P and chilled

3.2. Hardness:

The hardness of treated and untreated alloys was investigated. It was observed that the hardness of modified and /or refined, (samples 3, 5 and 6), in the range (94-135 HB) is higher than unmodified and unrefined (samples 1, 2,3 and 4) in the range (75-76 HB). However, sample 6 refined and modified by (Ti, B, P and quenched has about (135HB), sample 5 modified and refined with out quenching has (110 HB), sample 3 treated by phosphor has (88HB) and samples 2 and, sample 4) treated by (Na and Sr) have (76,75HB), respectively. Such improvements in hardness can be attributed to two basic factors i.e. reduced average primary silicon particle size and marginal modification of eutectic silicon needle into fine fibrous form apart from increased uniform and homogeneous Si-eutectic and primary silicon caused by modifiers and refiners [16,20]. It is evident from Fig.(9)that primary silicon particles in modified, refined and quenched alloy is 60 times finer than that of conventional Al-20Si cast alloy Fig. 2.

3.3. Coefficient of wear:

The coefficients of wear of all alloys tested at (2.61m/s) are shown in Fig.9. Comparing the coefficient of wear of samples 1 and 2, (1.5, 1.45 respectively) it is clear that no influence of Sr and Na on the coefficient of wear. The beneficial effect of phosphor is clear on the sliding wear behavior of sample 3 (0.5×10^7 g/Nm) because the formation of AlP particles which act as nucleate and encourages heterogynous solidification, the heterogynous don't allow growth [21].

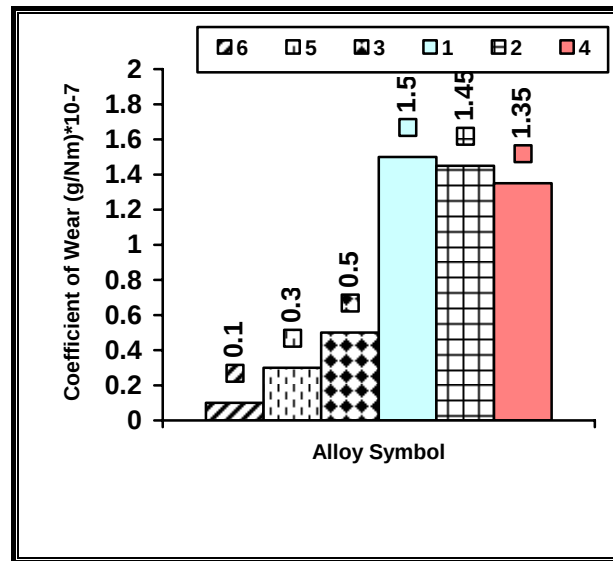


Fig.9 Average coefficient of wear of the alloys

In the case of samples 6 and 7, ($0.3, 0.1 \times 10^{-7} \text{g/Nm}$ respectively), very fine structure help to increase the hardness and wear behavior by decreasing the coefficient of wear to $0.1 \times 10^{-7} \text{g/Nm}$. the quenching and Ti, B refiners and P modifiers play a significant role in refining the structure of hypereutectic Al-Si alloys because comprise soluble TiAl_3 particles and insoluble boride and AlP particles in an aluminum matrix . Optimum wear resistance require a fine and uniform distribution of primary silicon particles and these requirements are reveal clearly in micrograph of sample 6 .

4. Conclusions:

From the experimental results, following conclusions can be drawn.

1. The refined, modified and quenched hypereutectic cast Al–20%Si–0.035%Ti–0.11B–0.0045P alloy results in finer and more uniformly distributed primary silicon particles compared to that of conventional Al-20Si cast alloy. Besides the refinement of primary silicon particles, modification of eutectic silicon particles was also observed.
2. Higher Sliding wear resistance of sample 6 was found .
3. higher hardness of sample 6 was found.
4. No influence of Sr and Na on morphology of hypereutectic Al-Si alloys.
5. The Phosphor plays a significant role in modification of primary silicon particles.
6. Quenching from about 150°C above the melting point of Al-Si Alloys treated with refiners and modifiers play a significant role in refining and uniform distribution of eutectic and primary silicon particles, and increases the hardness and sliding wear resistance.
7. Average size of eutectic and primary silicon particles decreases about 60 times.
8. The coefficient of wear decreased about 15 times in sample 6.

References

1. C. Dřum, H.I. Laukli, O.S. Hopperstad, M. Langseth, Structural behaviour of Al–Si die-castings: Experiments and numerical simulations, *European Journal of Mechanics A/Solids* 28 (2009) 1–13.
2. K.G. Basavakumar, P.G. Mukunda, M. Chakraborty, Dry sliding wear behaviour of Al–12Si and Al–12Si–3Cu cast alloys, *Materials and Design* 30 (2009) 1258–1267.
3. T.M. Chandrashekharaiya, S.A. Kori, Effect of grain refinement and modification on the dry sliding wear behaviour of eutectic Al– Si alloys, *Tribology International* 42 (2009) 59– 65
4. T.V.S. Reddy, D.K. Dwivedi, N.K. Jain, Adhesive wear of stir cast hypereutectic reciprocating sliding conditions, *Wear* 266 (2009) 1–5.
5. Chirita, I. Stefanescu, D. Soares, F.S. Silva G, Influence of vibration on the solidification behavior and tensile properties of an Al-18wt%Si alloy, *Materials and Design* xxx (2008) xxx–xxx
6. H.R. Ammar, C. Moreau, A.M. Samuel, F.H. Samuel, H.W. Doty, Effects of aging parameters on the quality of 413-type commercial alloys, *Materials and Design* 30 (2009) 1014–1025 ,
7. Moa, A.M. Samuel, F.H. Samuel, H.W. Doty, S. Valtierra , A study of tensile properties in Al–Si–Cu and Al–Si–Mg alloys: Effect of β -iron intermetallics and porosity , *Materials Science and Engineering A* 490 (2008) 36–51.
8. Omid Lashkaria, Frank Ajerschb, Andre Charettec, X.-Grant Chend, Microstructure and rheological behavior of hypereutectic semi-solid Al–Si alloy under low shear rates compression test, *Materials Science and Engineering A* 492 (2008) 377–382.
9. Min Ryouly, Chul-Hyun Kim and Myung-Ho Kim, Microstructure and Mechanical Properties of Hyper-eutectic Al-Si Alloys Fabricated by Spray Casting, *J. Mater. Sci. Technol.*, Vol.24 No.1, 2008.
10. T.R. Ramachandran, P.K. Sharma and K. Balasubramanian, Grain Refinement of Light Alloys, 68th WFC - World Foundry Congress 7th -10th February, 2008, pp. 189-193 .
11. C.L. Xu, H.Y. Wang, Y.F. Yang, Q.C. Jiang, Effect of Al–P–Ti–TiC–Nd₂O₃ modifier on the microstructure and properties of hypereutectic Al–20 wt.%Si alloy , *Materials Science and Engineering A* 452–453 (2007) 341–346 .
12. a, S.D. McDonald, A.K. Dahle, Modification of Al-Si Alloys, *MATERIALS FORUM VOLUME 28* - Published 2004. pp. 954-950.
13. L.L. Ge,R.P. Liu, G.Li, M.Z. Ma, W. K. Wang , Solidification of Al–50 at.%Si alloy in a drop tube, *Materials Science and Engineering A* 385 (2004) 128–132,
14. S. Spigarell, E. Evangelista, S. Cucchieri, Analysis of the creep response of an Al–17Si–4Cu–0.55Mg alloy, *Materials Science and Engineering A* 387–389 (2004) 702–705.
15. C.M. Chen, C.C. Yang, C.G. Chao, Thixocasting of hypereutectic Al–25Si–2.5Cu–1Mg–0.5Mn alloys using densified powder compacts, *Materials Science and Engineering A* 366 (2004) 183–194.
16. D.M. Stefanescu, "Casting", **ASM**. Volume 15 of the 9th Edition *Metals Handbook*.1992, pp348-360.
17. L. Lasa, J.M. Rodriguez-Ibabe, Wear behaviour of eutectic and hypereutectic Al–Si–Cu–Mg casting alloys tested against a composite brake pad, *Materials Science and Engineering A* 363 (2003) 193–202.

18. Liao Hengcheng, Sun Yu, Sun Guoxiong, Restraining effect of strontium on the crystallization of Mg₂Si phase during solidification in Al-Si-Mg casting alloys and mechanisms, Materials Science and Engineering A358 (2003) 164- 170 .
19. K. Narayan Prabhu, B.N. Ravishankar, Effect of modification melt treatment on casting/chill interfacial heat transfer and electrical conductivity of Al- 13% Si alloy, Materials Science and Engineering A360 (2003) 293- 298.
20. Peter J. Blau," Friction, Lubrication, and Wear Technology", Volume **18** of the ASM Handbook, 1992, pp.1599-1917.
21. George F. Vander Voort,"Metallugraphy and Microstructures"ASM Handbook, Volume 9 , 2004,pp.249.,1703-1712.