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Process-Composition Design of Hypoeutectic Aluminum-Silicon Alloy for High Performance Wear Resistance Application

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Abstract: *This study investigates the process-composition design of hypoeutectic aluminium-silicon alloys aimed at improving the wear behaviour of the alloy for tribological application. Hypoeutectic Al-Si alloys with percentage composition of silicon ranging from 3 – 7.5% were cast at varying pouring temperatures of 700, 750 and 800^{0}C. The impact of the process-composition parameters on wear rate and the microstructures of the alloy were determined using tribor testing apparatus and scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS) respectively. The results obtained show that increasing silicon content from 3 – 7.5% significantly improved the wear rate of the alloy from 0.0360 – 0.0120 mg/m with optimum pouring temperature value at 700^{0}C. The SEM micrographs indicate that higher percentage composition of silicon yielded the formation of more numbers of primary silicon phases with intermetallic phases that reduced material loss while optimum pouring temperature influenced solidification rate leading to a refined uniform homogeneous phases distributed in the microstructures. It was concluded that process parameter optimization carefully tailored through combination of silicon percentage composition and pouring temperature enhances the wear performance of Al-Si alloys for engineering applications in wear-critical environment.*

Keywords: *Alloys, Temperatures, Composition, Microstructures, Wear rate.*

1. INTRODUCTION

Aluminium alloys are one of the world's most utilized nonferrous alloys especially in engineering applications such as aerospace and automobile industries [1, 2]. This is traced to its excellent qualities which include high strength to weight ratio, corrosion resistance, recyclability and relatively low cost [3, 4, 5]. These properties are explored in the alloy to develop economically sustainable machine component with less weight for integrated functions. Notwithstanding, it exhibits low resistance to wear in tribological application. This has limited its application for production of machine components that have contact surfaces prone to friction forces [6]. The frictional effect generates wears and tears on the components. This in turn leads to replacement of the worn out parts at short intervals which increases maintenance cost [7]. Enhancing the wear behaviour of aluminium alloys is very important in order to improve the reliability of the material and as well extend the service life of machine component it is made of. The process of alloying silicon with aluminium has well been utilized to achieve superior quality of aluminium-silicon alloy, whose properties compare well with those of cast iron that are used in automobile and aircraft engine [8, 9].

Silicon is a good alloying element in aluminium. Its precipitates are hard which distribute in aluminium-silicon matrix with a reinforcing phase that improves abrasion resistance and other related properties of aluminium-silicon alloy [7]. It impedes dislocation movement which improves tribological performance [10]**.** Several process factors influence the wear behaviour of aluminium alloys among which are casting composition, pouring temperature, cooling rate, thermal treatment process, etc. [8, 11]. Solidification route affects the properties of Al-Si alloy. When solidification process is fast, alloy with fine silicon grains are formed. Casting pouring temperature determines grain size, phase transformation and distribution which determine the microstructures [7]. This in turn determines the material properties. Hence, there is need to tailor the wear behaviour of aluminium alloy toward specific engineering application using a definite process-composition design approach. This could enable the alloy to serve as good alternative to other high performance alloys such as steel [10]. The distribution of the silicon particles within the matrix and matrix microstructures determines the mechanical properties of the resultant alloy [12]. Studies observed that solidification route affects the properties of Al-Si alloy. When solidification process is fast, alloy with fine silicon grains are formed [7]**.** Studies using advanced characterization techniques, such as synchrotron X-ray tomography, have further confirmed that the morphology and distribution of primary Si particles are highly sensitive to both composition and cooling dynamics, ultimately dictating the tribological response [18].

Previous works on Al–Si alloys have extensively demonstrated that both silicon content and solidification conditions significantly affect the microstructure, mechanical properties, and wear response [23, 18]. Most of these studies have either focused on isolated factors (composition or cooling rate) or have relied primarily on conventional microstructural characterization and wear tests. Few have integrated a systematic process–composition approach that links solidification dynamics, alloy chemistry, and resulting tribological performance under controlled experimental conditions.

The novelty of the present study lies in its combined investigation of composition–solidification interactions, providing a more holistic understanding of how silicon content and cooling conditions simultaneously govern microstructural refinement and the evolution of intermetallic phases. Furthermore, unlike many earlier works that emphasized only bulk mechanical or wear properties, this study integrates advanced characterization techniques (e.g., SEM/EDS image analysis, to establish direct structure–property relationships. This enables a more predictive understanding of how tailoring both alloy chemistry and processing conditions can optimize tribological behaviour. By addressing these gaps, the study not only validates prior findings but also advances the field by offering a comprehensive framework for microstructural control of Al–Si alloys, which is essential for improving their performance in high-demand applications such as automotive engine parts and wear-resistant components. Hence, the study has simultaneously investigated on composition with solidification conditions alongside with advanced structure–property correlation, providing a more integrated and application-relevant insight than previous works.

2. RELATED WORKS

A lot of studies have been done to determine the wear behaviour of Al-Si alloy with respect to the percentage composition of silicon [13]. Studies have found that the microstructure of Al-Si alloy have significant impact on the wear rate [14]. It was also reported that wear resistance is best obtained in hypoeutectic alloy. Related studies examined the microstructures of an Al-Si alloy with both hypoeutectic, eutectic and hypereutectic structures and found from the differences in their phase amount and morphologies has a direct relationship between the mechanical behaviour and the silicon content in the alloy [12, 13]. Studies have proved that incorporation of Al_2O_3 particles up to 25% in Al-Si matrix composite yields improvement in the wear behaviour [15]. More also, the pouring temperature was also found as a significant factor that affects the wear properties of Al-Si alloys. Therefore, by varying pouring temperatures, grain growth could be regulated. This invariably can either increase or decrease the size of the grain which has direct effect on hardness property [8, 15, 16].

From these previous studies, it was observed that the wear behaviour of Al-Si alloy was explained based on the influence of a one at a time test parameter only [10]. It is obvious that there is a limited study that has utilized composition-process approach to develop high performance aluminium-silicon alloy for tribological application. Hence, there remains a gap in understanding their combined influence and interactions. A detailed experimental and analytical approach is needed to optimize these parameters concurrently to achieve desirable wear performance. Thus; this study aims to investigate on the process-composition design of aluminium-silicon alloy for improving its wear resistance property through multi-parameter optimization framework. The effect of silicon composition and pouring temperature on wear rate of aluminium-silicon alloy is examined with the objective to achieving optimal combined parameter. The results obtained from the study are very useful for design and processing of aluminium alloys for enhanced tribological application.

3. MATERIALS AND METHODOLOGY

3.1 Materials and Alloy Preparation

The base metal utilized in this study is wrought aluminium sourced from aluminium wire cables produced in Curtix Nigeria Company limited, Nnewi Nigeria. The elemental compositions of the wrought aluminium include 99.0% Al, 1.0% Fe, 0.02% Cu, 0.05% Mn, 0.10% Zn and other element in trace quantity. The silicon powder was added as the alloying element at varying percentage composition ranging from 3 - 7.5% in order to study its influence on the wear behaviour of the aluminium alloy. The aluminium cables were charged into the crucible furnace, fired and melted before adding the silicon powder. The molten alloy metal was stirred to get a homogeneous mixture and thereafter poured into a sand mould at specific pouring temperatures ranging from 700 – 800^0C. The cast alloy samples were allowed to cool before removing them from the mould for machining and for subsequent characterization studies. The casting processes were done in foundry workshop of Scientific Equipment Development Institute Enugu (SEDI-E) and the photograph shown in Figures 1 and 2.

3.2 Tribological Test

The wear rate of the samples were tested using a tribometer under dry sliding condition at a constant load of 20N for a given time duration of 20 minutes. The sample was fixed on rotary disc of the tribor testing machine which was rotating at the speed of 2500 rpm. Two emery wheels at the upper part of the machine was made to have direct contact with the test sample within the specified time [17]. The test parameters comprising of constant load of 20N, sliding speed of 1 m/s and sliding distance of 1000m were utilized for the test. The details for the test descriptions and procedures are contained in literature [17]. The wear rate was determined from the mass loss measurements obtained with digital weighing balance and calculated using Equation 1[3].

$$Wear\ rate = \frac{\Delta M}{L\ X\ SD} \tag{1}$$

$$SD = 2\pi NDt \tag{2}$$

Figure 1: Furnace charging process in the foundry workshop

Figure 2: Melting and casting process in the foundry workshop

Figure 3: Cast samples of the Aluminum-Silicon alloy

Where ΔM is the mass loss, L is the applied load, SD is the sliding distance, N is the radial speed, D is the disc diameter and t is the time the specimen was exposed to wear.

3.3 Microstructural Characterization

The specimen samples were cut from the aluminium-silicon alloy which were further polished and etched an etchant solution (kellers reagent). Computerized scanning electron microscope with energy dispersion spectrometer (SEM/EDS) JEOL JSM-IT200 Series was used to study the microstructures and its elemental constituents.

4. RESULTS AND DISCUSSIONS

Table 1: Effect of percentage composition of silicon and pouring temperature on the wear behaviour of aluminium-silicon alloy

Percentage Composition of Si in Al-Si Alloy	**Pouring Temperature (^{0}C)**	**Wear rate (mg/m)**
Control sample	700	0.0945
3.0	700	0.0301
3.0	750	0.0326
3.0	800	0.0360
4.5	700	0.0205
4.5	750	0.0223
4.5	800	0.0264
7.5	700	0.0120
7.5	750	0.0135
7.5	800	0.0151

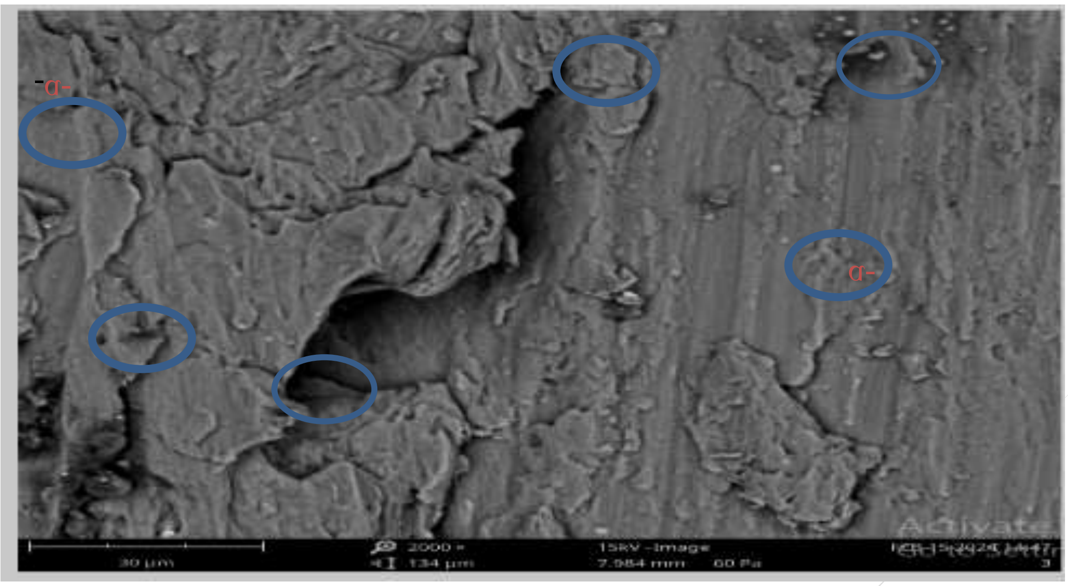


Figure 4: Aluminum control sample dominated with dendritic shaped α-Al phase

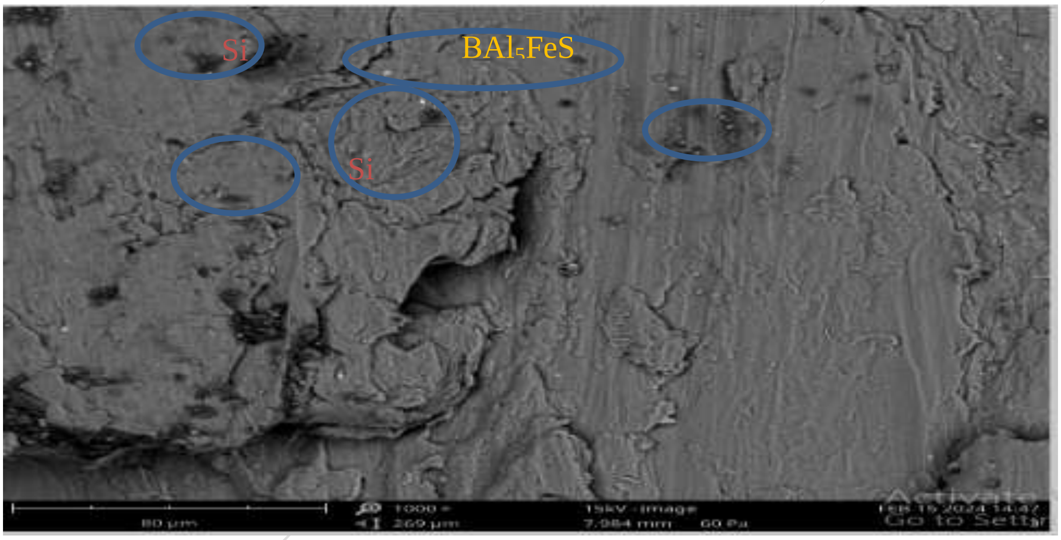


Figure 5: Al-Si alloy with 3% composition of silicon with dispersed bright dark angular shaped primary silicon phase

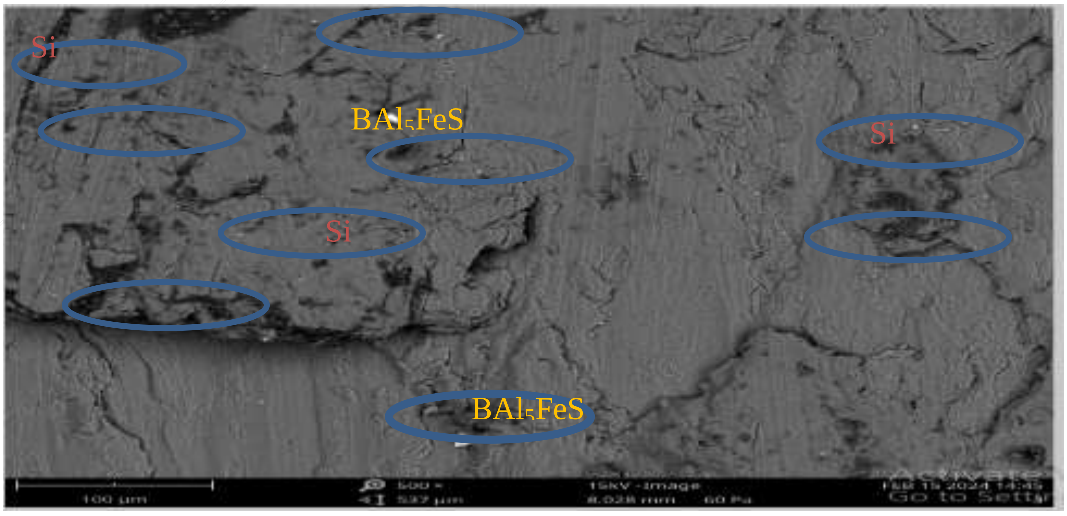


Figure 6: Al-Si alloy with 7.5% composition of silicon with more number of dispersed primary silicon phase

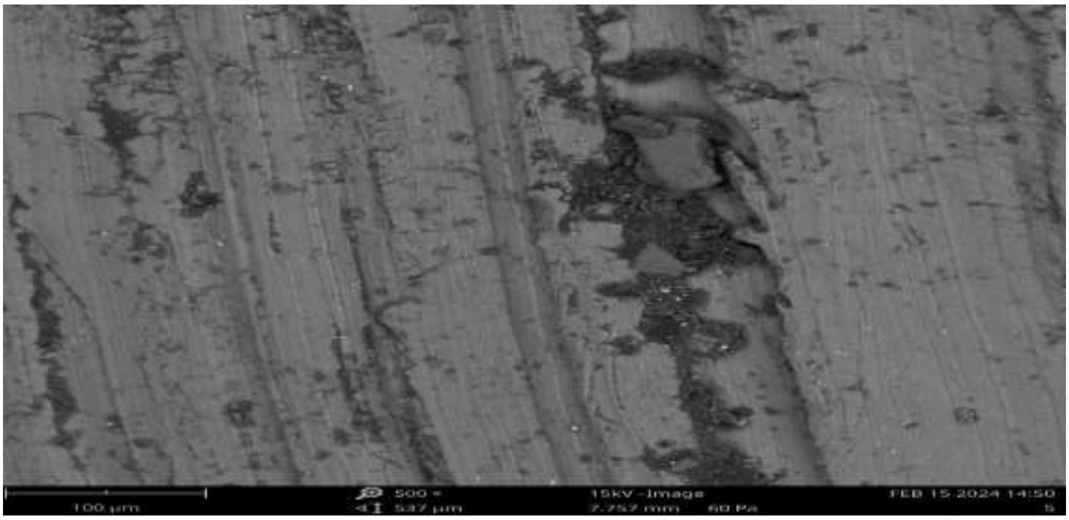
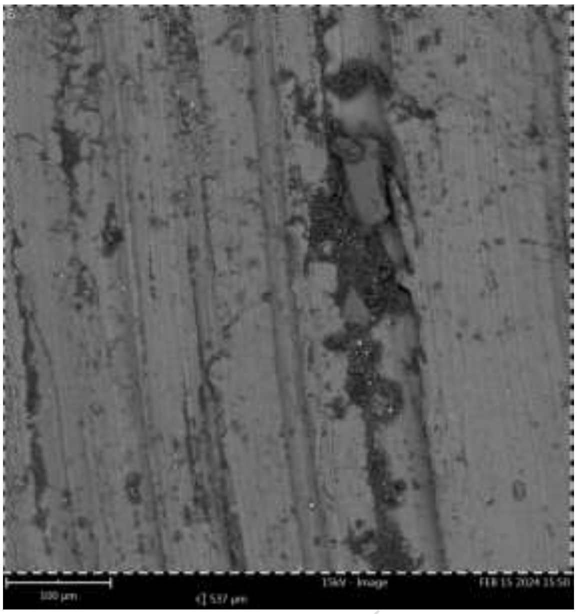


Figure 7: Al-Si alloy with finer grain size due to low pouring temperature



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
13	Al	Aluminium	92.40	91.65
14	Si	Silicon	3.34	3.45
11	Na	Sodium	1.10	0.93
12	Mg	Magnesium	0.90	0.80
17	Cl	Chlorine	0.58	0.75
26	Fe	Iron	0.34	0.69
16	S	Sulfur	0.42	0.50
19	K	Potassium	0.31	0.45
15	P	Phosphorus	0.38	0.43
20	Ca	Calcium	0.23	0.33
22	Ti	Titanium	0.00	0.00

FOV: 537 µm, Mode: 15kV - Image, Detector: BSD Full, Time: FEB 15 2024 15:50

Figure 8: SEM/EDS showing the elemental composition of the alloy

4.1 Effect of Alloy Composition on the Micro-structures and the Wear Behaviour of Aluminium-Silicon Alloy

From the results shown in Table 1, it was observed that the wear rate value of 0.0945 mg/m was obtained in wrought aluminium. This value was relatively higher when compared to those of aluminium-silicon alloys that ranges from 0.0360 to 0.0120 mg/m. It shows that silicon addition to aluminium improved its wear resistance property. It was also noted from the results obtained that as the percentage composition of silicon in the alloy increased from 3 to 7.5%, the wear rate showed a decrease 0.0360 to 0.0120 mg/m. This indicates that silicon composition has significant effect on the wear behaviour of the alloy.

The improvement in the wear resistance property observed in the alloy is traced to so many phase changes obtained in its structure as a result of silicon addition and also due to the variation in the alloy composition. The SEM micrographs presented in figures 4 - 6 show good comparison of the microstructures of both wrought aluminium and aluminium-silicon alloys. In plate 1**,** which represent the control sample, the presence of α-aluminium matrix (α-Al) was identified in dark coloration with continuous dendritic shape. This phase formed the background phase that yielded the matrix from which other phases were embedded in the alloy system. The α-Al phase is reported to be a soft and ductile phase which could provide toughness but very limited in hardness and wear resistance [2]. This correlates with the results shown in Table 1 which showed a relatively high wear rate value of 0.0945 mg/m in the control sample compared to those of the aluminium-silicon alloys which ranges from 0.0360 – 0.0120 mg/m.

The presence of primary silicon phases were also observed in the structure of the alloy shown in figures 5 - 7**.** They are very bright and dark in colour with angular, blocky and polygonal shape [18]. Their dispersions throughout the entire matrix in isolated form were very visible in the micro-structure which is evident for the significantly improved wear resistance of the aluminium-silicon alloy. More numbers of these phase were observed in the SEM micrograph of plate 3 of the sample that has higher percentage composition of silicon which yielded better wear resistance property as observed in the result shown in Table 1. The modified eutectic silicon phase was observed in figure 7, where the needle-like acicular aluminium phase was modified to finely fibrous phase with the constituent elements that formed a network around the dendrites of σ-Al. This is trace to the low pouring temperature used to cast the sample. The lower pouring temperature slowed down the solidification rate, which yielded finer and more uniform refined microstructures. The fine morphology of the phase obtained in plate 4 is strongly believed to have impacted a better wear behaviour in the aluminium-silicon alloy. The presence of the Al-Fe intermetallic phases were found in figures 5 and 6, which comprise of σ and β-Al_5FeSi phase observed in small whitish colour. These are aluminium-silicon intermetallic which is a multicomponent system of the alloy with other elements such as iron formed through precipitation [19]. The EDS results shown in figure 8 identified some of these elements in their compositions as constituents of the alloy confirms the presence silicon as the alloying element with constituent element in trace quantity that make up the intermetallic phases. They were shown as a very bright/white located at the interdendritic regions and as well at the grain boundaries [20]. These are coarsen and hardened micro constituent of the alloy which contributed to enhance the wear resistance of the alloy.

4.2 Effect of Varied Pouring Temperature on the Micro-Structures and the Wear Behaviour of Aluminium-Silicon Alloy

The results presented in Table 1 also showed that varied pouring temperatures alongside with alloy composition had effect on the wear rate of the aluminium-silicon alloy. These effects were based on the solidification rates and the corresponding microstructures obtained at various pouring temperatures. From the SEM micrographs presented in plates 5 - 7, it was found that at higher pouring temperature value of 800^0C, larger coarse grains were obtained compared to those cast at lower pouring temperatures value of 700^0C. This could be traced to the fact that at higher pouring temperature, the molten alloy had more thermal energy. Hence, it must have taken longer time to cool to its solidification range. This was considered to have delayed nucleation and solidification processes which eventually yielded coarser grain. Grain size has been reported to have significant effect on wear rate [21, 22]. Hence, at lower pouring temperatures, finer grains with more numbers of grain boundaries were obtained as shown in plate 4. This was considered to have yielded higher strength with better resistance to plastic deformation which was attributed to the more numbers of the grain boundaries. This consequently improved the wear resistance as seen in the result shown in Table 1.

4.3 Comparative Assessment of the Study's Outcome with Previous Related Literatures

Previous works on aluminum–silicon alloys have established that both composition (Si content) and solidification conditions (cooling/ pouring temperature) strongly control microstructure and therefore mechanical and tribological behaviour. The comparative assessment of the results obtained in this study with other results reported by previous researchers were considered in three perspectives:

Based on the manufacturing routes, it was found that in this study, the wear rate of sand-cast Al–Si alloys decreased with increasing silicon content and was further influenced by pouring temperature. At 3% Si, the wear rate ranged from 0.0301–0.0360 mg/m, while at 4.5% Si, improved resistance was observed (0.0205–0.0264 mg/m). The best performance occurred at 7.5% Si, where wear rates dropped to 0.0120–0.0151 mg/m. Additionally, alloys cast at lower pouring temperatures (700 °C) consistently showed lower wear rates than those solidified at higher temperatures (800 °C), due to a finer microstructure resulting from slower growth of eutectic Si [8].

In contrast, studies on die-cast Al–Si alloys have shown that the rapid solidification characteristic of the process refines silicon particles and intermetallic phases, leading to higher hardness and lower wear rates compared to sand-cast alloys of similar composition [20]. For instance, refined eutectic silicon morphologies in die-cast alloys suppress microcrack formation and delamination during sliding, resulting in wear rates frequently reported below 0.010 mg/m [5]. In conclusion, it was found that while sand casting offers simplicity, cost-effectiveness, and flexibility in adjusting composition and pouring conditions, it generally produces coarser microstructures that increase wear susceptibility. Conversely, die casting ensures finer microstructures and superior wear resistance but comes at higher cost and reduced processing flexibility [18].

More also, considering alloy chemistry adjustments, it was noted from this study that by varying Si wt% in the hypoeutectic range, higher Si content is believed to have increased hardness which consequently lowered specific wear rate. This is in line with prior chemistry-adjustment studies which attribute improved wear resistance to the larger volume fraction of eutectic Si acting as a hard reinforcement within the Al matrix. Research studies reported similar trends in hypoeutectic Al-Si alloys, and correlated reduced wear with refined microstructures produced by alloying and increased cooling rate. However, unlike some reports that used modifiers or different casting routes, the combination of lower pouring temperature and optimized Si% achieved the improved wear without adding costly modifiers, demonstrating that process control and composition together can match some benefits of chemistry changes. ”

On the account of melt and solidification control, the present study demonstrates that both silicon content and pouring temperature significantly affect the wear resistance of sand-cast Al–Si alloys. At constant composition of 3% Si alloy, lowering the pouring temperature from 800 °C to 700 °C refined the microstructure and consistently reduced wear rates from 0.0360 mg/m to 0.0301 mg/m. This trend is attributed to slower solidification at lower pouring temperatures, which suppresses coarse eutectic growth and promotes a more homogeneous microstructure [8]. Similarly, increasing Si content from 3.0% to 7.5% enhanced wear resistance, as higher silicon promotes hard phase formation that resists material removal during sliding [5].

Comparatively, die-casting routes employ much higher cooling rates, which strongly influence solidification dynamics. The rapid solidification promotes finer dendritic structures, smaller silicon particles, and a reduced volume fraction of shrinkage porosity compared to sand casting. These refined microstructures improve hardness and suppress microcrack initiation at Si–matrix interfaces, resulting in superior wear performance, often with wear rates lower than 0.010 mg/m for alloys of similar composition [20, 18]. Thus, while sand casting with controlled pouring temperature allows tailored investigation of composition–solidification interactions and provides cost-effective processing, it's relatively slower cooling leads to coarser microstructures and higher wear rates. In contrast, die casting inherently optimizes melt and solidification control, producing refined and more wear-resistant alloys but with higher processing cost and lower flexibility in controlling cooling gradients.

5. CONCLUSIONS

The wear behaviour of hypereutectic aluminium-silicon alloys has been studied under composition-thermal influenced microstructure for wear-critical applications. It has been well established that the alloying element composition and pouring temperature have significant effect on the wear behaviour of hypereutectic aluminium-silicon alloys. Increasing the percentage composition of silicon from 3 – 7.5% significantly enhanced the wear resistance from 0.0360 – 0.0120 mg/m which was attributed to the presence of dispersed hard silicon particles in the structure of the Al-Si alloy. The optimum process condition that yielded maximum wear resistance performance of the alloy was obtained at 7.5% and 700^{0}C for percentage composition of silicon and the pouring temperature respectively. In the development of a hypereutectic Ai-Si alloy for a critical wear component, lower pouring temperatures are preferred due to the resulting finer microstructure with optimal pouring temperature value just above the liquidus specific to the silicon content in the alloy. Hence, a practical design for hypoeutectic Al-Si alloy formulation and processing for superior wear resistance application has been established.

6. RECOMMENDATIONS

From the findings obtained in this study, it is recommended that future studies should explore minor alloying and modifier additions. The study on the combined effect of trace additions with controlled pouring temperature would clarify whether process control alone or combined chemistry with process control produces the most reliable wear resistance. More also, further studies should extend composition range and solidification conditions alongside with heat treatment studies as a post manufacturing process.

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