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Control of mechanical and wear properties of a commercial Al–Si eutectic alloy

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The properties examined as a function of microstructural modification were ultimate tensile strength, fracture elongation, Vickers hardness and wear resistance. The microstructural modification was achieved by rapid cooling and additions of small amounts of strontium and lithium master alloys into the eutectic melt. In all experiments the commercial ETIAL 140 alloy was cast instead of a high-purity aluminium–silicon eutectic. This allowed determination of the effect of modification treatment, both on silicon and intermetallic phases. It was found that the slowly cooled and unalloyed castings which contained coarse silicon flakes showed highest wear resistance and lowest ultimate tensile strength, fracture elongation and Vickers hardness values. Rapid cooling and also additions of strontium and lithium master alloys reduced the eutectic interphase spacing and refined the silicon phase. This usually corresponded to a significant increase in all properties except the wear resistance. It was noted, however, that the size of the intermetallic phase particles increased abruptly above 0.04% Sr content which resulted in a sharp reduction in all mechanical properties. Unlike the strontium effect, the lithium addition did not influence the intermetallic size significantly and, therefore, the mechanical properties were not impaired. In addition, the wear resistance also remained relatively unaffected because lithium solid solution hardened the primary aluminium dendrites appeared in the modified alloys.

1. Introduction

Eutectic and near-eutectic Al–Si alloys are used extensively in the casting industry. For instance, many parts of a car engine are cast from these alloys [1–4]. In fact, the whole engine block itself can be a hyper-eutectic Al–Si alloy casting instead of the more conventional grey cast iron. This change provides considerable weight savings and, therefore, fuel economy.

During solidification of the Al–Si system, the metallic aluminium phase grows in a non-faceted manner, whereas the covalently bonded silicon phase prefers faceted growth. Such a discrepancy in growth behaviour results in uncoupled growth and hence a so-called irregular eutectic microstructure is developed [5, 6]. This description is afforded to characterize the coarse and flake morphology of the silicon phase in the aluminium matrix [7]. In terms of mechanical properties, such a microstructure is undesirable because it reduces them. The mechanical properties can be increased, however, by refining the silicon phase through a. modification treatment. The details of modification and also the potential modifiers have been studied extensively [5, 6, 8–10]. In most of these studies the Al–Si alloys were prepared using high-purity materials in order to isolate and investigate the effect of the modifier only on the silicon phase.

The commercial alloys, however, are not pure and contain varying amounts of iron, copper, manganese, etc. These elements may form various intermetallic phases within the eutectic microstructure [11, 12] and therefore, are expected to alter the mechanical properties. Moreover, there is the question as to whether a modification treatment which refines the silicon flakes would also have a similar and beneficial influence on the intermetallic particles.

In the present study, a commercial near-eutectic Al–Si alloy (ETIAL 140) was investigated, rather than a high-purity alloy. The ETIAL 140 is still one of the purest near-eutectic commercial Al–Si alloys produced in Turkey. Its composition is given as 11.50%–13.50% Si, 0.60% Fe, 0.40% Mn, 0.10% Cu, 0.10% Mg, 0.10% Zn, 0.10% Ni, 0.10% Pb, 0.15% Ti, 0.05% Sn and the balance is aluminium [13]. The ETIAL 140 corresponds to Alcan 160X, LM6 and G-AlSi13, respectively, in Canada, England and Germany.

2. Experimental procedure

2.1. Casting practice

In each casting practice approximately 200 g ETIAL 140 alloy was melted in a 0.5 kg graphite crucible. To ensure the coarse and flake silicon phase morphology, the eutectic melt at 800 °C was cast into either a schamotte mould containing 75% Al_2O_3 or a graphite mould, which were preheated to 400 and 600 °C, respectively. When chill modification, i.e. rapid freezing, was the intention, the melt was poured into cold moulds. In each casting practice, four 12 mm diameter

TABLE I The effect of casting conditions on the mechanical properties of pure ETIAL 140 alloy

Cast no.	Mould type	Mould temperature (°C)	Tensile strength (MPa)	Fracture elongation (%)	Vickers hardness (H_v)
1	Schamotte	25 (RT)	153	7.5	74
2	Schamotte	400	140	7.3	69
3	Graphite	400	221	10	65
4	Graphite	600	176	7.1	65

and 12 cm long cast bars were produced. Strontium and lithium master alloys were weighed to within 0.001 g accuracy. They were then wrapped in aluminium foil and stirred into the melt using a graphite rod as a stirrer. To ensure homogenization, the casting was made 15 min after stirring the Al–9.6% Sr master alloy into the melt [14]. To prevent its oxidation and loss into the air, the Al–4% Li alloy was stirred into the melt under an argon atmosphere. After stirring, the melt was cast immediately.

2.2. Metallographic examination

The first few bars were sectioned longitudinally into two pieces and ground on successively fine SiC grinding papers. The ground surfaces were polished with diamond paste, and etching was done in 0.5% HF etchant. The same procedure was repeated for a second time on the transverse sections. It was observed that the eutectic microstructure remained unchanged in any section of a bar. Hence, it was decided that all the metallographic examinations would be made on those transverse sections which were left at the top portions of the cast bars after machining out the tension test samples. The bottom portions of the cast bars were used for wear tests.

The size of the intermetallic phase particles were measured on the images of the samples appeared on the screen of an inverted optical microscope. The silicon interphase spacings, λ, were also determined from those images appearing on the same screen, using the formula [15]

$$\lambda = \frac{1}{M}\left(\frac{A}{N}\right)^{1/2} \qquad (1)$$

where M, N and A are the magnification, number of silicon particles and area containing those particles, respectively.

Scanning electron microscope (SEM) samples, other than the fracture surfaces, were etched deeply in 5% HCl etchant for about 3 h. Graphite was evaporated on to the samples before examining them in a Jeol-JSM T 300 SEM.

2.3. Tension and wear tests

Tension test samples were machined from the cast bars according to the TS 138 (ASTM E8) standard. These samples were pulled and fractured in an Instron 1186 Universal tension test machine. A 2000 kg load and 1 mm min^{-1} crosshead speed were used for all samples. The ultimate tensile strength and fracture elongation were evaluated using the load versus displacement curves obtained in tension tests.

The wear test samples sectioned from the cast bars were first ground down to 1200 grade SiC grinding paper. After drying and weighing, the samples were mounted on to a two-body abrasion resistance apparatus described in detail elsewhere [16]. In this apparatus each sample was worn essentially on a waterproof 1200 grade SiC abrasive paper mounted on the disc of a metallographic polishing machine rotating at 1.7 m s^{-1}. The test sample was kept under a compressive stress of 14 kPa and worn for a travelling distance of 2000 m in each wear test. When a test was completed the worn sample was dried and weighed for a second time. The weight lost due to wear for a constant travelling distance was calculated.

3. Results and discussion

3.1. Pure eutectic

The experimental study was initiated with the pure ETIAL 140 alloy and the results obtained are tabulated in Table I. Only Cast 2, which was made into a preheated schamotte mould, resulted in a typical coarse and flake (i.e. completely unmodified) silicon phase morphology. This microstructure is shown in Fig. 1 where the silicon phase appears darkest in the micrograph. A small group of intermetallic phase particles are indicated with an arrow in the centre of

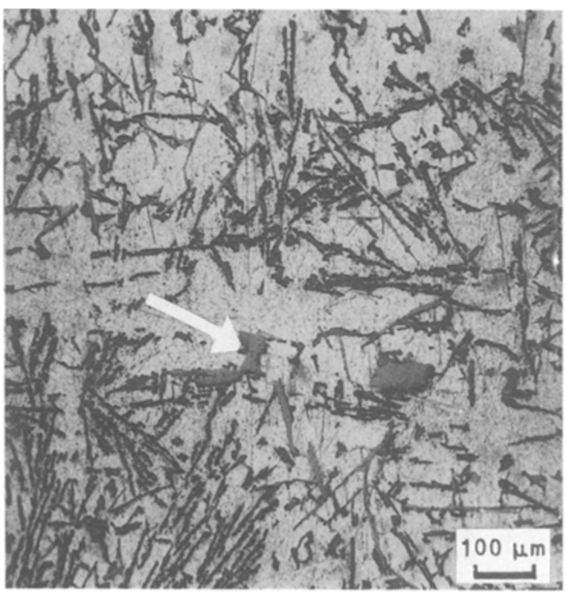

Figure 1 The microstructure of the ETIAL 140 alloy cast into a preheated schamotte mould.

the same micrograph. It is seen that these particles can be found in polygonal and needle-like morphologies. The energy dispersive spectrum (EDS) point analysis during SEM investigations showed that these particles contain primarily aluminium, silicon, iron and copper [17]. Aluminium dendrites appeared whether the eutectic melt was cast into cold or preheated graphite moulds. It is noted also that in these samples the intermetallic phase develops predominantly a more needle-like morphology and appears both within the eutectic mixture and also inside the aluminium dendrites.

In Table I it is found that the silicon interphase spacing is 42 μm in the unmodified microstructure which resulted in Cast 2. The interphase spacing reduces to 22 μm when the casting is made into a cold schamotte mould at room temperature, i.e. Cast 1 where the melt cools approximately at $0.2\ \mathrm{K\,s^{-1}}$ [18]. The silicon phase, in fact, is present in a partially modified form in all castings except Cast 2.

Vickers hardness measurements were taken on the metallographic samples. It is known that the silicon is about nine times harder than the aluminium [1]. As a result, the hardness of the eutectic mixture is influenced by the size and distribution of the silicon phase in the aluminium matrix. It follows that the hardest eutectic should have a microstructure in which a homogeneously distributed silicon phase is present in the aluminium matrix. Such a eutectic microstructure is obtained in Casts 1 and 2. It is seen in Table I that Cast 1 shows higher ultimate tensile strength and fracture elongation values as compared to Cast 2. The highest tensile properties, however, are shown by Cast 3, which consists of a partially chill-modified fibrous silicon morphology. The coarse, flake silicon phase of Cast 2 is brittle and contains sharp corners inducing a notch effect in the aluminium matrix. The net effect is a reduction in tensile properties. Nevertheless, these drawbacks can be corrected after modification.

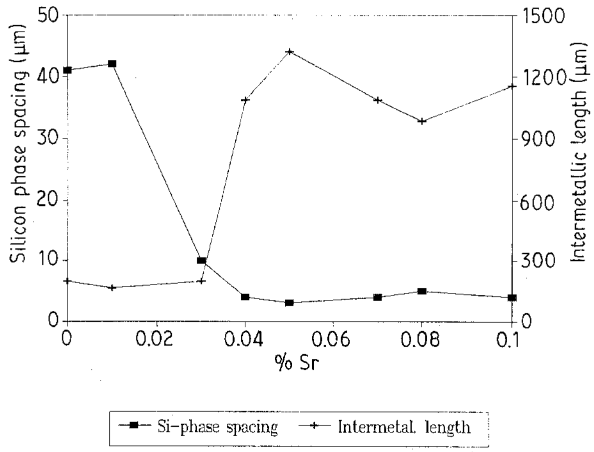

Figure 2 Effect of strontium concentration on the microstructure of ETIAL 140. (■) silicon phase spacing, (+) intermetallic length.

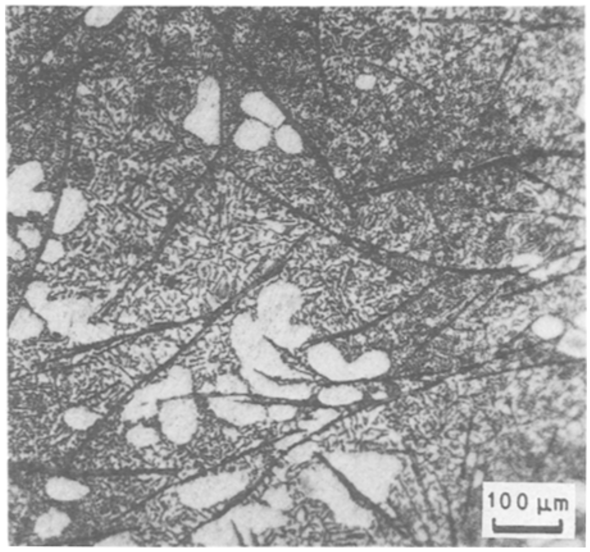

Figure 3 The microstructure of the ETIAL 140 alloy containing 0.05% Sr.

3.2. Strontium modification

3.2.1. Microstructure

Al–9.6% Sr master alloys of appropriate weight were stirred into the eutectic melt before casting into a schamotte mould preheated to 400 °C, as for Cast 2 of Table I. The strontium concentration in the melt was varied over a wide range from 0.00%–0.10% Sr. The silicon interphase spacing as a function of strontium concentration is plotted in Fig. 2. Hence, whilst the interphase spacing is about 42 μm in the unmodified condition, it is reduced to about 10 and 3 μm after adding, respectively, 0.03% and 0.04% Sr. Microscopic examination reveals that the silicon phase is modified partially at 0.03% Sr addition. The fully modified, i.e. fine and fibrous silicon phase, is found when the strontium concentration is increased to 0.04%.

The silicon interphase spacing remains little changed above 0.04% Sr. The size of the intermetallic phase particles, however, increases abruptly above the 0.03% Sr level, as noted also in Fig. 2. The SEM–EDS point and area analyses indicate that these particles contain primarily aluminium, silicon, iron and copper, but not strontium [17]. Fig. 3 is a micrograph of 0.05% Sr-added casting containing the fully modified fibrous silicon phase, the aluminium dendrites and large aspect ratio intermetallic particles. The length of the intermetallic particles at this particular strontium concentration reaches almost 1200 μm, as compared to approximately 200 μm in the strontium-free castings. We are of the opinion that the intermetallic phase morphology is influenced by strontium chemisorption during freezing of the eutectic alloy in a manner that is known to be responsible for the modification of the silicon phase [6, 18, 19]. This effect, however, is expected to be exactly in the reverse direction, leading to coarsening instead of refining of the intermetallic phase.

Fig. 4a and b are scanning electron micrographs of the fracture surfaces of two tensile test samples. Fig. 4a reveals that the sample containing 0.03% Sr fractures predominantly in a ductile manner as noted also for a hypoeutectic alloy [18]. The 0.05% Sr-containing sample, however, displays sharp cleavage facets indicating the brittle nature of fracture, Fig. 4b.

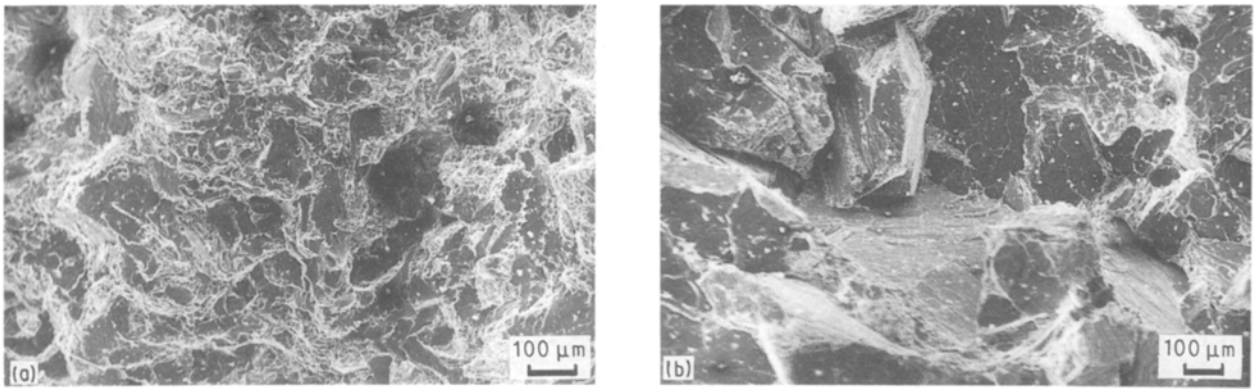

Figure 4 Fractography of ETIAL 140 tension test samples containing (a) 0.03% and (b) 0.05% Sr.

3.2.2. Mechanical properties

Fig. 5 illustrates the variation of ultimate tensile strength and Vickers hardness with respect to the strontium concentration. An identical trend is revealed also in the fracture elongation versus strontium concentration relationship. It is noted that all three properties increase steadily until about 0.03% Sr and then suffer a sudden decrease at higher strontium levels. The transitions can be related directly to the changes in the microstructure described above. As noted in Fig. 2 the intermetallic size remains unaffected whereas the silicon phase is gradually refined up to 0.03% Sr concentration. A sharp increase is observed, however, in the intermetallic phase length above 0.03% Sr. Hence, above this strontium level the microstructure consists of a small, fibrous silicon phase, and a large, plate-like intermetallic phase together in the aluminium matrix. In terms of mechanical properties, the formation of such an intermetallic morphology offsets the benefits gained from refining of the silicon phase.

To summarize, it becomes obvious that the optimum strontium concentration is approximately at 0.03% and large intermetallic particles can lower the mechanical properties even below those values found for the strontium-free eutectic.

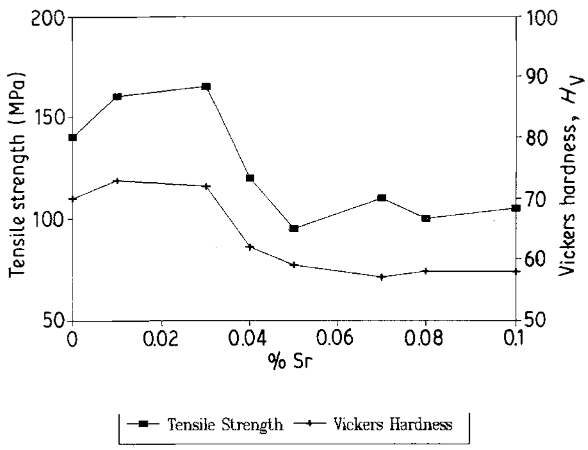

Figure 5 Effect of strontium concentration on some mechanical properties of ETIAL 140. (■) Tensile strength, (+) Vickers hardness.

3.3. Lithium modification

It was Kim and Heine [8] who first examined systematically the effect of various potential modifiers (impurities) on the Al–Si eutectic microstructure but found no effect of lithium. However, more recently, Clapham [9] reported that lithium modifies the silicon phase, provided that it is introduced into the eutectic melt at larger concentrations and also under a protective atmosphere. Clapham, nevertheless, worked with only the high-purity materials and did not study the mechanical properties of the lithium-modified alloys.

In the present investigation, Al–4.0% Li master alloys were stirred into the eutectic melt under an argon atmosphere and cast immediately into a graphite mould preheated at 600 °C. The amounts of the master alloys stirred in were adjusted so that the lithium concentration in the melt was varied from 0%–0.30% Li.

3.3.1. Microstructure

From microstructural investigation it was found that the silicon phase is modified partially after 0.05% Li addition. Complete modification is achieved when the lithium concentration stirred into the eutectic melt was increased to 0.10%. Therefore, it appears that due to its higher solid solubility in the aluminium matrix and also its evaporation tendency, much larger lithium levels are necessary for modification as compared to those lower strontium levels. It was noted also that the intermetallic phase was less sensitive to the lithium additions. The size of the intermetallic particles tended to increase above 0.10% Li, nevertheless, this increase is much less significant than that found in the presence of strontium. The intermetallic particles appeared either in plate-like or polygonal forms and are present mostly within or between the side branches of aluminium dendrites, Fig. 6.

3.3.2. Mechanical properties

The variation of ultimate tensile strength and Vickers hardness with lithium concentration are plotted in Fig. 7. It is seen that the two properties attain their maximum values at approximately 0.10% Li, then tend to degrade at higher lithium concentrations. It is noteworthy that this behaviour coincides with the increase in intermetallic phase size as found with

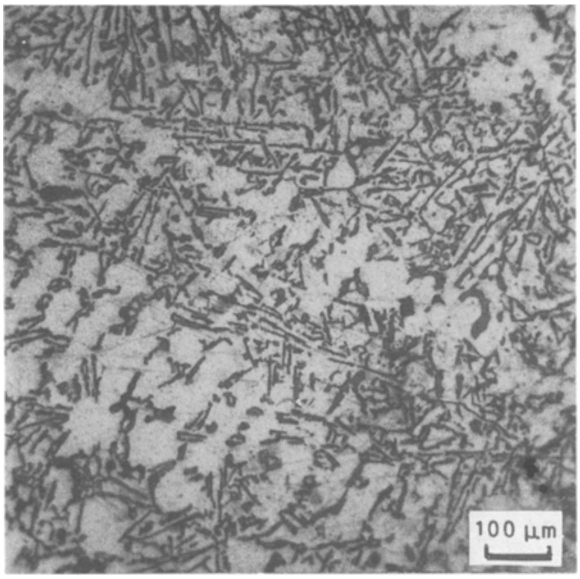

Figure 6 The microstructure of the ETIAL 140 alloy containing 0.10% Li.

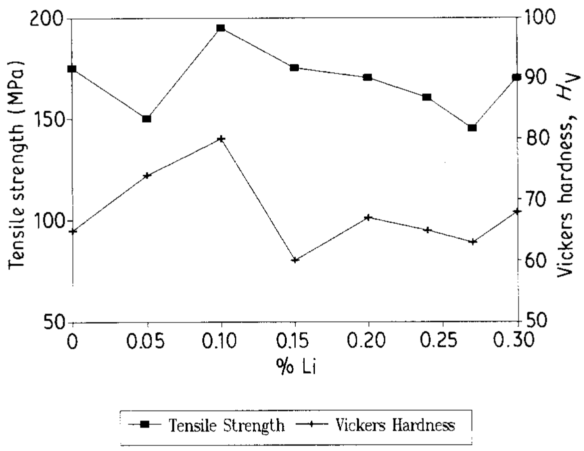

Figure 7 Effect of lithium concentration on some mechanical properties of ETIAL 140. (■) Tensile strength, (+) Vickers hardness.

strontium modification. A larger scatter in Vickers hardness is observed because, during a hardness test, an indentation might be taken only on a soft aluminium dendrite rather than on the harder eutectic mixture.

3.4. Wear properties

The Al–Si alloys and particularly the hypereutectic compositions, are well recognized for their wear resistance [1]. As mentioned earlier, however, a universal and a standard wear test procedure has yet to be developed. With this in mind, the wear resistance of the alloys investigated here can be compared among themselves using the wear test apparatus explained in Section 2.3. It should be remembered that the test results presented in Tables II and III can be used to compare only the wear properties of the alloys listed in each table. Moreover, the wear conditions here are much different from those arising in practical situations.

TABLE II The wear properties of ETIAL 140 alloy containing strontium and cast into schamotte moulds

Cast no.	Mould temperature (°C)	Sr (%)	Weight loss ($10^5\,g\,m^{-1}$)
1	25(RT)	–	284
2	400	–	247
3	400	0.01	392
4	400	0.03	418
5	400	0.04	556
6	400	0.05	392
7	400	0.06	422
8	400	0.08	469
9	400	0.10	493

TABLE III The wear properties of ETIAL 140 alloy containing lithium and cast into preheated graphite moulds

Cast no.	Mould temperature (°C)	Li (%)	Weight loss ($10^5\,g\,m^{-1}$)
1	600	–	594
2	600	0.05	631
3	600	0.10	671
4	600	0.15	619
5	600	0.19	655
6	600	0.24	627
7	600	0.27	656
8	600	0.30	613

Among all ETIAL 140 castings given in Tables II and III, Cast 2 of Table II offers the highest wear resistance. It is understood from microstructural evidence that the best wear property is obtained with the coarse and flake silicon phase morphology shown in Fig. 1. When ETIAL 140 is cast into a cold schamotte mould at 25 °C, the silicon phase is chill modified partially, as mentioned already in Section 3.1. A modified morphology also contains aluminium dendrites within the eutectic morphology. These changes result in a reduction in wear resistance, contrary to the improvements obtained in the mechanical properties listed in Table I. The addition of strontium also introduces simultaneous modification and reduction in wear resistance. The fully modified eutectic morphology observed in Cast 5 of Table II suffers the lowest wear resistance of all the casts in the same table.

The lowest wear resistance among all three pure ETIAL 140 castings are found in Cast 1 of Table III. This is expected, because the graphite mould cools faster than the schamotte mould, resulting always in a partially modified silicon phase and aluminium dendrites in the microstructure. It is noted in Table III, however, that the reduction in wear resistance is less serious following lithium additions.

Aluminium dendrites free of any hard silicon particles in the modified morphologies are much softer than the eutectic mixture. Hence, modification produces an undesirable microstructure in terms of wear resistance. Owing to its appreciable solid solubility in aluminium, the lithium should harden the aluminium dendrites and also the aluminium phase of the eutectic mixture. Consequently, the lithium modification is found to be less harmful as compared to either chill or strontium modification when the wear resistance is considered.

4. Conclusions

The mechanical and wear properties of the commercial ETIAL 140 aluminium–silicon eutectic alloy were investigated in relation to microstructural modifications induced by strontium and lithium additions. It was found that in terms of mechanical properties, the intermetallic size should not increase whilst the silicon phase was being modified. This was achieved, however, only in the presence of lithium. The lithium modification was also less undesirable when wear resistance was considered.

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