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Effect of Cooling Rate and Heat Treatment on the Microstructure and Impact Resistance of Recycled Aluminium Sand Cast Alloy.

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Abstract In this study the effect of cooling rate and heat treatment on the microstructure and impact resistance of aluminium alloy A356 were investigated. The alloy was obtained from recycled aluminium alloy wheels that were melted, modified and cast in carbon silicate bonded sand moulds. An external chill was placed in the mould and thermocouples attached to a digital data logger were used to capture the cooling rates across the length of the cast after pouring of the metal. Three sections with different cooling rates were identified with the first being adjacent to the chill, followed by a second section and the third farthest from the chill. In the experimental process 5 sets of specimens from each of the sections were solution treated for periods of 30 minutes, 1 hour, 3 hours, 6 hours and one set retained in the as-cast state, respectively. The solution treatment temperature was set at 540^{0}C and was followed by quenching in water at 60^{0}C and precipitation ageing at 170^{0}C for 3 hours. All samples were then prepared for microstructural analysis and charpy impact testing. Results showed the section with the fast cooling rate had finer microstructure and had higher impact resistance energy even after short heat treatment processes. The slow cooling section showed marginal gain in impact resistance even when exposed to solution treatment of 6 hours. Therefore shortened heat treatment processes may be applied on castings with up to 65% improvement in impact resistance energy. This technique can enhance the quality demands of products manufactured in the foundry industry dominated locally by the jua kali practitioners.

Keywords Aluminium Alloy, Cooling Rate, Heat Treatment, Microstructure, Sand Casting.

1. Introduction

The most commonly used methods of casting Al-Si-Mg based alloys (A356 and 357) are sand casting and permanent mould die casting. Sand casting is cheaper to use and easier to develop intricate shapes and forms. Permanent moulds on the other hand are costlier to develop but are suitable in mass production of dimensionally similar components [1]-[4]. In the production of high strength parts such as gear box housings, permanent moulds are preferred as they respond to heat treatment procedures that elevate their mechanical properties by up to 40% [5]. The T6 procedure is one of the most widely applied methods and involves solution treatment at an elevated temperature, quenching and artificially ageing. Sand castings however respond only marginally to heat treatment processes making the benefits of this treatment unfeasible. The reason associated with this distinct behavior is the fact that permanent mould castings have a faster cooling rate that promotes formation of smaller Secondary Dendrite Arms Spacing (SDAS) while sand castings because of their slower cooling rate result in larger spacing between the secondary arms.[6][7]. Aluminium alloys with smaller

SDAS are observed to invariably respond to heat treatment processes resulting in better mechanical properties while those with larger SDAS show only a marginal gain [8]. The T6 heat treatment process that involves solution treatment at 540^{0}C, quenching at 60^{0}C and artificially aging at 170^{0}C is known to provide two beneficial effects. The first benefit is an improved ductility and resistance to fracture and the second benefit is the elevation of the alloy's yield strength and resistance to impact. The first benefit is achieved through the spheroidisation of the eutectic silicon in the microstructure and is realized during the solution treatment time while the second benefit is achieved throughout the entire process of solutionising, quenching and ageing [7]. The addition of either strontium, sodium or any other known modification element is known to change the microstructure morphology of an aluminium alloy from sharp plate-like to one that is more rounded. It has been observed that the rounded structure disintegrates faster during heat treatment than the plate shape resulting in greater mechanical properties [8][9].

While the benefits of permanent mould casting are accepted, the cost related in the manufacture of the permanent mould especially for production of a single part or that of a product with changing profiles can be enormous. The use of sand casting in these cases would therefore be more than appropriate. It is therefore feasible that a sand casting process that responds to heat treatment would add economic value to production of high strength parts.

In this research, a chill was introduced to a sand mould to create a heat sink that accelerated the general uptake of heat from the molten metal thereby promoting formation of a cast with better resistance to impact.

2. The experimental process

The experimental process involved the preparation of 5kg ingots from recycled aluminium alloy wheels using SiC crucibles in an oil fired furnace. The chemical composition analysis of the alloy was carried out using Meta Vision spectrometer. The ingots were re-melted under a cover flux and 0.02% strontium added in the form of a master alloy (Al-10Sr). The melt was then degassed and held at a temperature of 730^{0}C before pouring in sand moulds.

These moulds were made using fine sea sand mixed with 3% sodium silicate and hardened with CO_2 gas. The mould cavity walls were of dimensions 220 mm x150 mm x 20 mm with one of the walls consisting of the cast iron chill. Four k-type thermocouples were assembled in the moulds at distances of 30 mm from each other with first one 3 mm from the chill. These were connected to a digital data logger and temperature readings recorded at 5 second intervals. Using these readings the cast was divided into three parts according to the cooling rate. These sections were cut off and machined to dimensions of approximately 12 mm x 12 mm x 80 mm. Figure 1 shows the assembly where (1) is the casting (2) the riser (3) connecting cables (4) data logger (5) thermocouples and (6) the metal chill. A heat treatment process that included solution heat treatment, quenching in water and artificially ageing was then applied.

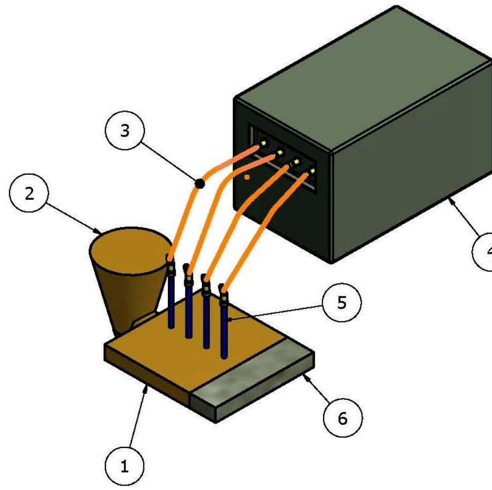


Fig.1. Casting and thermocouple assembly for capturing the cooling temperature.

In solution treatment the specimens were heated in an electric muffle furnace at a temperature of 540^{0}C, followed by quenching in water at 60^{0}C and artificial ageing in an oven at 170^{0}C. At the solution treatment stage a set of five specimens from each of the three sections were heat treated at five different durations namely 30 minutes, 1 hour, 3 hours, 6 hours and one set retained as-cast. They were then immediately quenched in water at 60^{0}C and aged (at 170^{0}C) for three hours. Machining of the impact specimen was done according to ASTM E23-28 for charpy impact testing and those for microstructure analysis prepared according to ASTM E-23. The charpy testing machine had a hammer weight of 25.71kg, arm length of 0.75m and lift angle of 142.5 ^{0}C. The microstructure was carried out using an optical microscope and the specimen etched using Keller's reagent.

3. Results and Discussions

3.1. The Chemical Composition Analysis

Table 1 represents the chemical composition of the cast material obtained by spectrometric analysis. The percentage concentration of the constituent elements determined the material to be of classification A356 aluminium alloy.

Table 1: Chemical composition of aluminium alloy

Al	Si	Fe	Cu	Mn	Mg	Be	Ti
96.8	6.92	0.116	<0.05	<0.02	0.356	<0.05	0.148

3.2. The Cooling Rate

The application of local cooling (chill) at the end of the mold and the riser on the other end as shown in the Fig. 1 resulted in a non-uniform cooling rate across the casting. The cast area closest to the chill cooled fastest and that nearest to the riser cooled slowest. The cooling temperatures were captured by the data logger and cooling rate in the first section determined to be 2.11^{0}C/s (between 625.3^{0}C at 20s and 562.1^{0}C/s at 50s), the second section 1.14^0 C/s (626.6^{0}C at 20s and 563.9^{0}C at 75s) and the third section 0.98^o C/s (627.7^{0}C at 20s and 566.5^{0}C at 80s). Fig. 2 shows the cooling curves of the three different sections. The cast section adjacent to the chill had a faster cooling rate because the chill had a higher rate of heat conductivity compared to the surrounding mold cavity. The second section had a cooling rate lower than the first section but higher than the third. The third section cooled slowest because of its proximity to the riser which retained a large volume of melt.

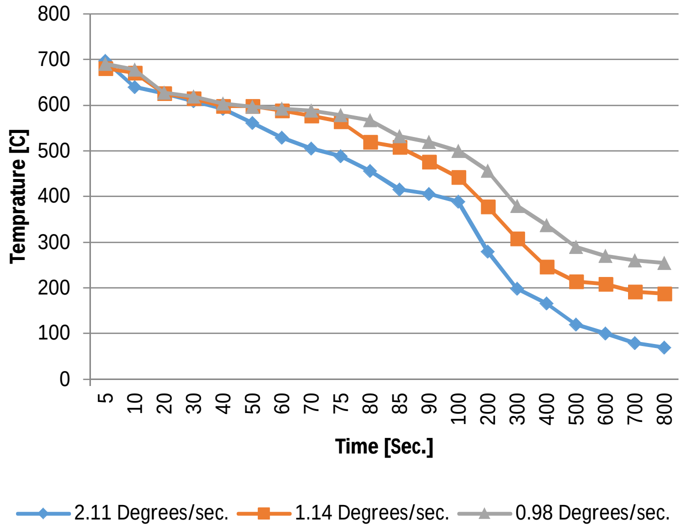
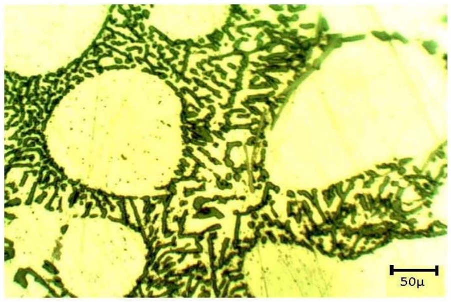


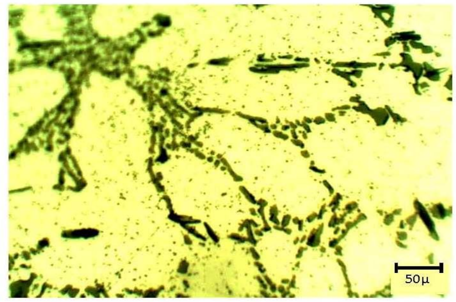
Fig. 2. Cooling curves of sections I, II and III.

3.3. The Microstructure Evolution after Heat Treatment

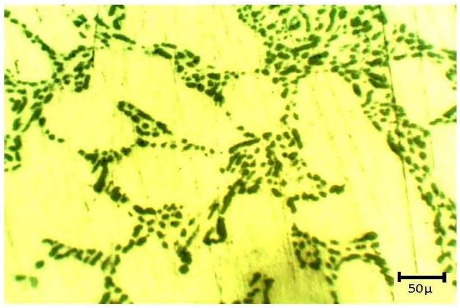
The microstructures of the test samples were examined using the optical microscopes in the as-cast condition and after heat treatment at varying solution treatment times. As expected, micrographs were dominated by the image of the primary alpha-aluminium dendrites, interdendritic irregular Aluminium-Silicon eutectic regions, Iron rich intermetallics and magnesium-silicon particles. In all the micrographs, the eutectic silicon particles were in fine globular morphology, a clear indication of structural modification resulting from strontium addition in the casting process. Fig. 3 shows the micrographs of the specimen from the section adjacent to the chill (cooling rate of 2.11^{0}C/s). In Fig. 3(a) the material is in the as-cast state and illustrates the well established physical explanation of the effect of a fast cooling rate in thin walled castings or permanent mold castings. It is seen that the microstructure is finer as a result of faster nucleation and growth and this is associated with better mechanical properties [10][11]. After 30 minutes of solution treatment, the eutectic silicon fibres are observed to have fragmented and are also spheroidised. This is also a well documented phenomenon as silicon is known to spheroidise when exposed for a few minutes to temperatures of about 540 ^{0}C (Fig. 3b) [12]-[13]. After 1 hour and 3 hours of solution treatment the silicon particles are more spheroidised and substantially coarser (Fig. 3c and Fig. 3d respectively). With solution treatment of 6 hours the spheroidisation has changed little, the particles still appear coarse, but the interparticle spacing has increased (Fig. 3(e)).



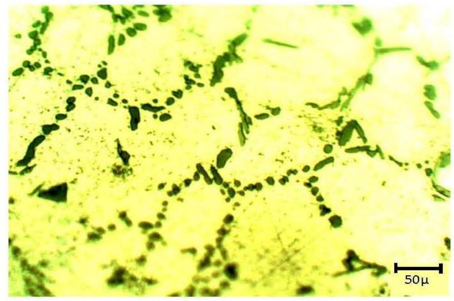
(a) As-cast



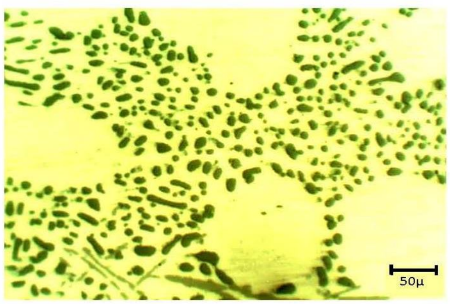
(b) After 30 Minutes Solution Treatment



(c) After 1 Hour Solution Treatment



(d) After 3 Hour Solution Treatment



(e) After 6 Hour Solution Treatment

Fig. 3. Microstructures for the section with the cooling rate of 2.11^0C/s (a) in the as cast state (b) after solution treatment of 30 minutes (c) 1 hour and (d) 3 hours and (e) 6 hours at 540^0C.

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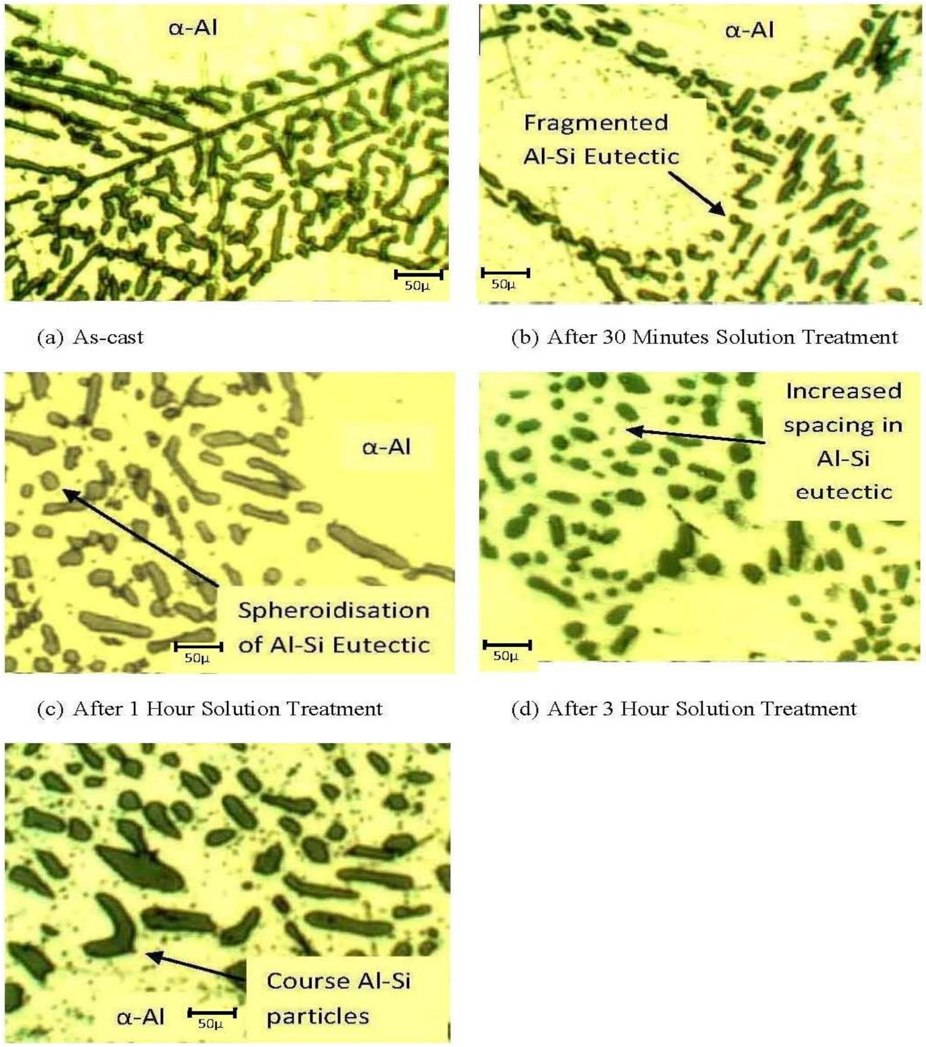
Fig. 4. shows micrographs of the section of cooling rate 1.14^0C/s. Fig. 4(a) represents the as cast state; the silicon phase in the microstructure exhibits a fibrous morphology due to strontium modification during casting. After 30 minutes of solution treatment the silicon fibres are observed to have fragmented and spheroidised as expected (Fig. 4(b)). In Fig. 4 (c) solution treatment was conducted for one hour; little change in the spheroidisation was observed but a slight increase in coarsening was noted. After 3 hours and 6 hours of solution treatment the particles had substantially increased in particle spacing and become coarser as seen in Fig.s4 (d) and 4(e) respectively.



(a) As-cast

(b) After 30 Minutes Solution Treatment

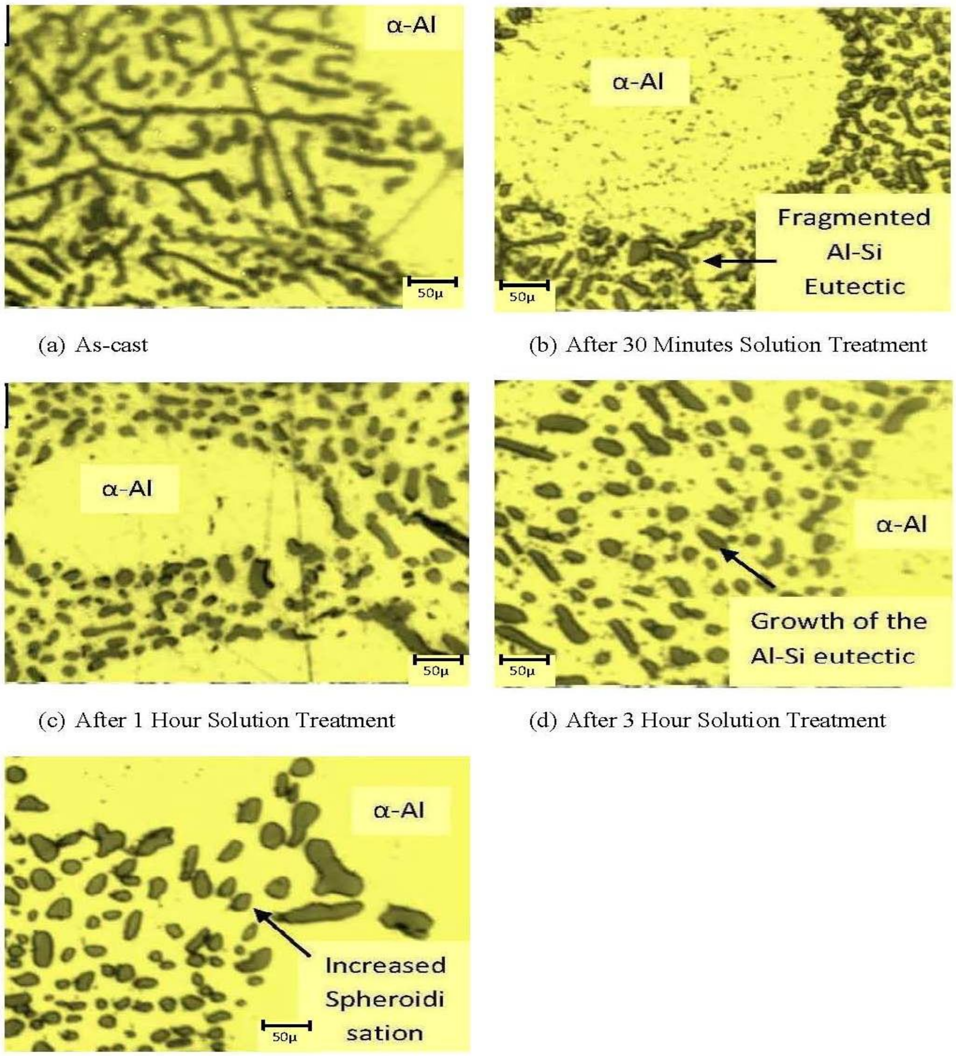
(c) After 1 Hour Solution Treatment

(d) After 3 Hour Solution Treatment

(e) After 6 Hour Solution Treatment

Fig. 4. Microstructures for the section with the cooling rate of 1.14^0C/s (a) in the as cast state (b) after solution treatment of 30 minutes (c) 1 hour and (d) 3 hours and (e) 6 hour sat 540^0C.

From the micrographs of the section of cooling rate 0.98^0C/s in the as-cast state observed in Fig.5 (a), it is evident that the microstructure exhibited is not as fine as that obtained from the section with the cooling rate of 2.11^0C/s and 1.14^0C/s. This is attributed to the slow nucleation and growth of cells and is likely to result in lower mechanical properties. In the micrographs of Fig. 5 (b, c and d) of specimen solution treated for 30 minutes, 1 hour and 3 hours respectively, it is observed that there is fragmentation and spheroidisation of the silicon particles but slight increase in coarsening and particle spacing. Fig. 5 (e) of specimen solution treatment of six hours shows increased spheroidisation of the eutectic particles.



(a) As-cast

(b) After 30 Minutes Solution Treatment

(c) After 1 Hour Solution Treatment

(d) After 3 Hour Solution Treatment

(e) After 6 Hour Solution Treatment

Fig. 5. Microstructures for the section with the cooling rate of 0.98^{0}C/s (a) in the as cast state(b) after solution treatment 30 minutes at (c) solution treatment of 1 hour and (d) solution treatment of 3 hours (e) solution treatment of 6 hours at 540^{0}C.

3.4. The Impact Resistance

Fig. 6 shows the impact energy obtained from the charpy impact tests as a function of solution treatment at 540^{0}C for 30 minutes, 1 hour, 3 hours, 6 hours and in the as-cast state. The energy recorded for the cooling rate of 2.11^{0}C/s, 1.14^{0}C/s and 0.98^{0}C/s in the as-cast state were 1.62 J, 1.14 J and 0.93 J respectively. After 30 minutes of solution treatment the impact energy recorded for the section with the cooling rate of 2.11^{0}C/s increased to 1.95 J and to 3J after 6 hours of the treatment. This meant that solution treatment for 30 minutes improved the impact energy 20% from the as-cast state and achieved 65% improvement of the impact energy of the same treatment carried out for 6 hours. For the section with the cooling rate of 1.14^{0}C/s the impact energy after 30 minutes solution treatment was 1.42 J, an increase of 24.6% from the as-cast state. A 48.7% improvement in the impact energy was obtained after solutionising for 6 hours. For the section of cooling rate 0.98^{0}C/s there was an increase of 14.9% in impact energy from 0.94 J to 1.07 J. On further solution treatment of 6 hours, the impact energy improved marginally to 1.12 J, a 19.2% improvement from the as-cast state.

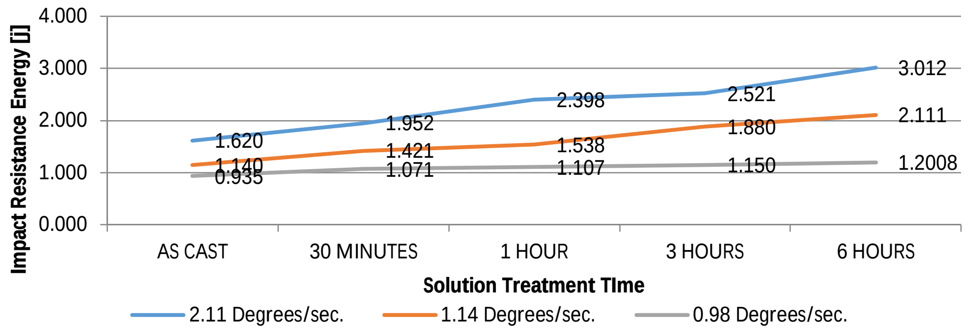


Fig. 6. The impact energy as functions of solution treatment time

4. Conclusions

The following conclusions were derived from the research work.

a. The impact energy of Al-7%wtSi-0.3%Mg alloy casting of cooling rate 2.11^{0}C/s is found to improve to 65% after 30 minutes of solution heat treatment. The cooling rate of 2.11^{0}C/s is typical of a thin walled casting or one cast in a permanent mould. This means that a short period solution treatment can be employed with significant gain in impact resistance.

b. An Al-7%wtSi-0.3%Mg alloy of cooling rate 1.14^{0}C/s obtained a fine microstructure and showed spheroidisation, coarsening of particles and increase in particle spacing after 30 minutes of solution treatment. It also achieved 49% of the impact energy of that solution treated for 6 hours. This means that it is feasible to substantially elevate the mechanical properties of sand castings by coupling with external chills.

c. The region of cooling rate 0.98^{0}C/s reflects cooling rates typical to those in sand mould casting. The slow cooling rate resulted in low impact resistance energy values in the as-cast state and an improvement of only 19%. This means that a lot of energy would be expended in the solution treatment with only marginal gains.

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