Impact Properties of A356-T6 Alloys

S. Shivkumar, L. Wang, and C. Keller

The Charpy impact energy of A356 alloys has been measured. Instrumented Charpy impact tests have been conducted at 25, 100, 150, and 200 °C. The Charpy specimens were machined from plate castings or tapered cylindrical castings. The plates were produced in sand molds, and tapered cylinders were produced in water-cooled copper molds. Both unmodified and strontium-modified castings were tested. The results indicate that strontium modification improves the impact properties of sand and permanent mold castings. The impact energy increases with solution treatment time. Strontium modification reduces the solution treatment time for attaining a specific impact property level in the casting.

Keywords

A356 castings, Al-Si-Mg alloys, modification, impact properties, heat treatment of Al castings

1. Introduction

ALUMINUM alloy A356 is used in a variety of structural, automotive, aerospace, and engineering applications. The mechanical properties of A356 castings are essentially controlled by the secondary dendrite arm spacing (DAS) and the silicon particle morphology.[1] The effects of these microstructural parameters on tensile properties have been studied extensively.[2-4] The fracture, fatigue, and impact properties, however, have not been the subject of a thorough investigation. Only recently, the users of A356 castings have realized the importance of fracture, fatigue, and impact property data in optimizing design parameters, and several investigations have been initiated.[5,6] All of these studies generally indicate that the mechanical properties of the alloy can be improved significantly by a molten metal processing operation known as modification. The modification process refers to the addition of small quantities (0.015%) of strontium to the melt to change the morphology of silicon crystals from a flake to a fibrous form. Furthermore, recent studies have indicated that strontium modification can be used effectively to lower the heat treatment times substantially.[2,3] Because all A356 castings are used in the T6 condition, a reduction in heat treatment time may lead to a significant decrease in the overall cost of the finished component. In this contribution, the impact properties of unmodified (i.e., no strontium addition to melt) and strontium-modified castings have been measured. The effects of solution treatment time on Charpy impact energy of unmodified and strontium-modified castings have been investigated. Impact data have been acquired over a range of temperatures.

2. Experimental Procedure

The Charpy specimens were machined from A356 castings according to ASTM E23. Two types of castings were used to obtain the Charpy specimens, as shown in Fig. 1. Plate castings were produced in CO_2 sand molds. Tapered cylindrical castings were produced in water-cooled copper molds. The charge consisting of 100% primary A356 ingots was melted in a graphite crucible. The temperature of the metal was increased to about 700 °C. The liquid metal was degassed thoroughly with high purity (99.99%) nitrogen using a graphite tube with circumferential holes. Chemical analysis, vacuum degassing, and thermal analysis samples were cast periodically to monitor the quality of the melt. To grain refine the melt, Al-5Ti-1B master alloy was added to achieve a nominal composition of 0.15 to 0.20% Ti. The metal was filtered through a 20 ppi (pores per inch) ceramic foam filter. The melt was then heated to 750 ± 5 °C. Several tapered cylindrical and plate castings were produced from the melt in the unmodified condition. Al-9.7Sr master alloy was then added to the remaining liquid metal in the crucible to obtain a nominal composition of about 0.015% Sr. After checking for chemistry and gas content, several tapered cylindrical and plate castings were produced. Hence, unmodified and strontium-modified castings were produced from the same melt. Typical chemical compositions in the castings are summarized in Table 1. Most of the castings were heat treated to the T6 condition. The castings were solutionized at 550 °C, quenched in water at 60 °C, naturally aged for 24 h, and artificially aged at 155 °C (plate castings) or 171 °C (tapered cylindrical castings) for 4 h. Experiments were conducted for solution times ranging from 2 to 168 h. The castings were examined by optical and scanning electron microscopy (SEM). Instrumented Charpy impact tests were conducted at Army Ma-

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Table 1 Chemical composition of test castings

	Composition, wt%						
Condition	**Si**	**Mg**	**Fe**	**Mn**	**Cu**	**Ti**	**Sr**
Sand mold, unmodified	7.1	0.39	0.12	0.05	0.10	0.19	0.0003
Sand mold, strontium-modified	7.1	0.40	0.10	0.05	0.09	0.20	0.020
Copper mold, unmodified	7.0	0.38	0.10	0.05	0.11	0.18	0.0004

Materials Testing Laboratory, Watertown, MA. The Charpy impact toughness was measured according to ASTM E23. Measurements were conducted at 25, 100, 150, and 200 °C. The holding time at the test temperature was varied from 1 to 100 h. At least five (and up to ten) tests were conducted under each condition.

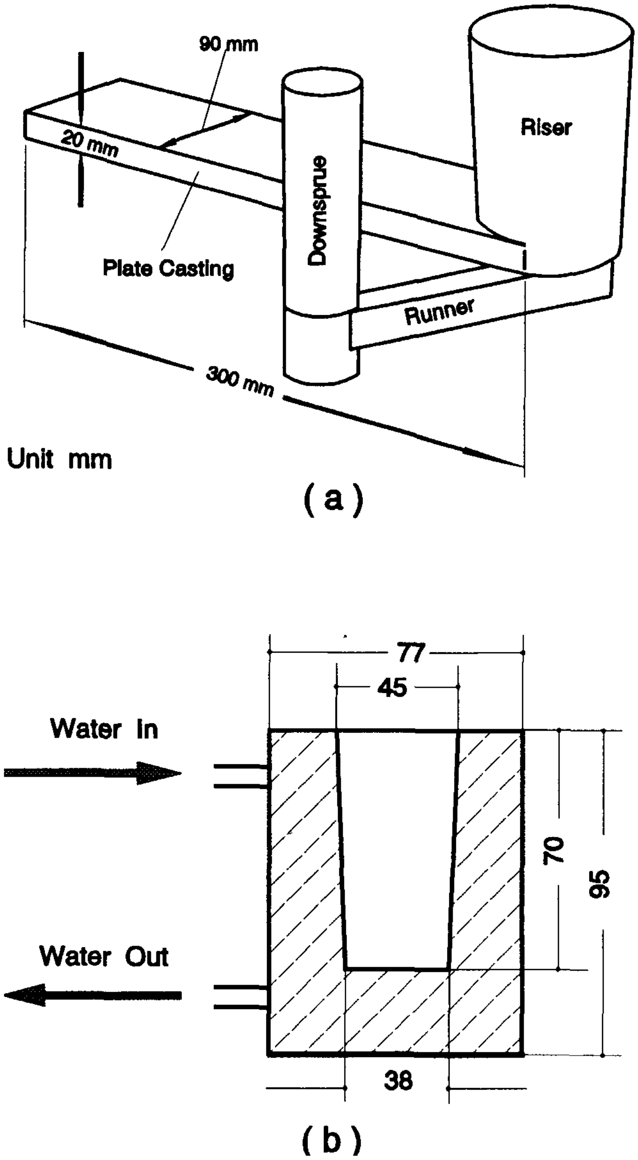

Fig. 1 Schematic of the casting design used in the experiments. Plate castings were produced in sand molds. (a) Tapered cylindrical castings were produced in water-cooled molds. (b) Charpy specimens were machined from these castings.

3. Results and Discussion

Typical microstructures in the test castings are shown in Fig. 2. Unmodified sand castings consist of coarse, branched, and interconnected silicon flakes. A fibrous silicon structure is observed upon modification (Fig. 2b). This refinement of the silicon structure by impurity elements has been explained based on the twin plane re-entrant edge (TPRE) mechanism.[7,8] According to this model, growth of plate-like silicon in unmodified alloys occurs by repeated nucleation of new layers on the re-entrant edges and grooves created by the intersection of {111} twins at the solidifying interface. When strontium is added to the melt, it may get preferentially absorbed at the silicon interface and lead to a poisoning effect, whereby the attachment of silicon atoms onto the re-entrant edges and grooves is prevented. Castings poured into metallic molds contain much finer silicon particles than sand castings (Fig. 2c and d). This refinement of silicon at high growth rates is often referred to as "quench modification" and results from a change in the molecular attachment kinetics.[8] Average values of DAS and grain size in the test castings are shown in Table 2. Within the limits of experimental scatter, strontium modification does not have any significant effect on DAS or grain size. Typical DAS values for sand and metallic mold castings are on the order of 47 and 23 μm, respectively.

The effects of solution heat treatment on silicon particle structure in sand castings are shown in Fig. 3. During solution treatment, silicon crystals gradually undergo several morphological changes, all driven by a reduction in interfacial energy. In unmodified alloys, the large silicon particles undergo necking, and separation can occur at several corners and thin growth steps. During this stage, the average particle diameter decreases. The fragmented particles gradually begin to spheroidize. Prolonged solution treatment leads to classical particle coarsening, as predicted by the Liftshitz-Sloyozov-Wagner (LSW) model.[9,10] In unmodified alloys, spheroidization rates are very small, and even after 168 h of solution treatment, several silicon particles with large aspect ratios can still be detected in the microstructure (Fig. 3c). In strontium-modified alloys, however, a highly spheroidized structure is observed for solution times of 4 h (Fig. 3d). The data of Shivkumar et al.[2] and Parker et al.[11] indicate that solution times less than 1 h may be sufficient to spheroidize silicon particles in modified alloys. It has generally been established that fibrous eutectics, such as observed in modified alloys, are susceptible

Table 2 Microstructural and pore parameters in test castings

	Sand mold		Copper mold	
Parameter	**Unmodified**	**Strontium-modified**	**Unmodified**	**Strontium-modified**
DAS, μm	48	47	24	23
Grain size, μm	850	800	200	180
Porosity, %	0.48	0.61	0.14	0.21
Maximum pore area, μm^2	53,000	85,000	2300	15,000

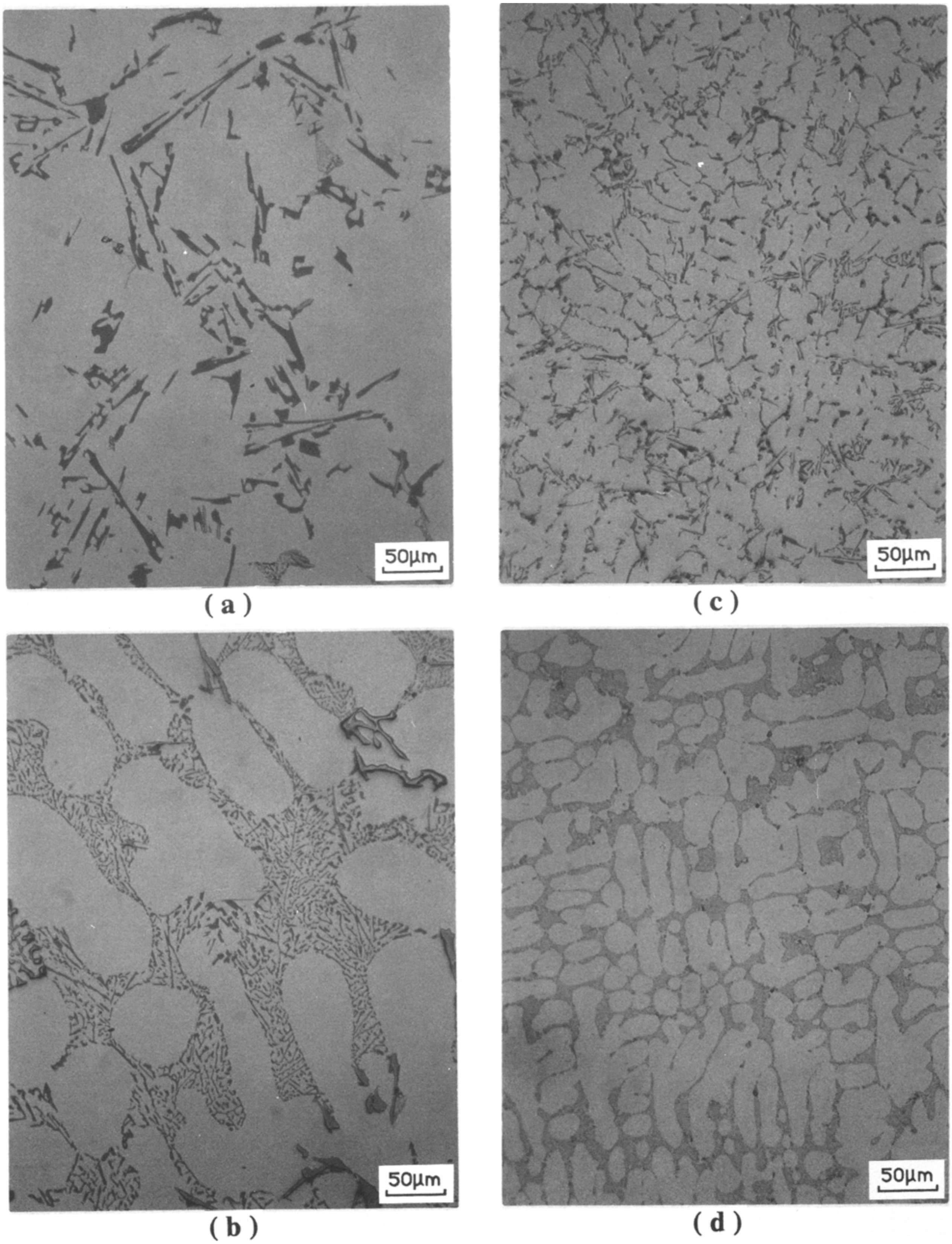

Fig. 2 As-cast microstructures in test castings. Sand castings: (a) Unmodified. (b) Strontium-modified. Metallic mold castings: (c) Unmodified. (d) Strontium-modified.

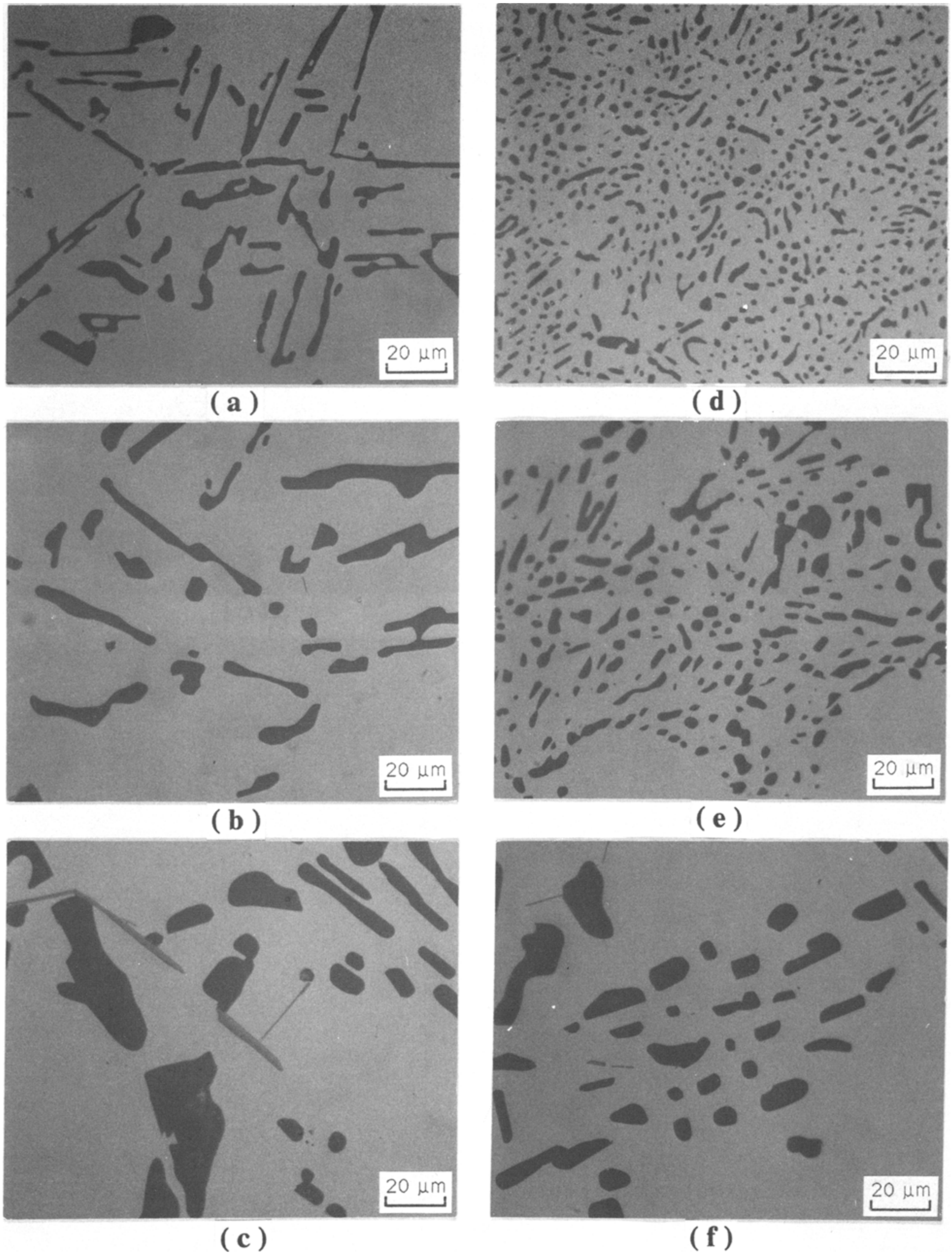

Fig. 3 Microstructures in heat treated sand castings as a function of solution time. Unmodified: (a) 4 h, (b) 16 h, (c) 168 h. Modified: (d) 4 h, (e) 16 h, (f) 168 h.

Table 3 Charpy impact energy of A356 alloys at 25 °C as a function of solution time

	Charpy impact energy, J			
	Sand mold		Water-cooled copper mold	
Solution time, h	Unmodified	Strontium-modified	Unmodified	Strontium-modified
As cast	1.1 ± 0.1	2.3 ± 0.2	2.0 ± 1.1	10.8 ± 2.7
2	1.0 ± 0.1	2.0 ± 0.1	5.6 ± 0.8	12.9 ± 1.1
4	1.2 ± 0.1	2.8 ± 0.1	6.8 ± 1.1	12.9 ± 1.1
8	1.4 ± 0.2	...	7.8 ± 0.5	13.1 ± 1.4
12	1.8 ± 0.4	3.1 ± 0.3	...	...
16	2.7 ± 0.2	2.9 ± 0.4	8.8 ± 1.1	13.9 ± 0.5
24	...	2.9 ± 0.3	...	...
48	2.7 ± 0.3	5.5 ± 1.3	...	...
96	2.9 ± 0.5	7.3 ± 1.6	...	...
168	...	...	26.1 ± 0.5	20.3 ± 0.9

Table 4 Elevated temperature Charpy impact energy of A356 castings in the T6 condition

	Charpy impact energy, J			
	Sand mold		Water-cooled copper mold	
Holding time, h	Unmodified	Strontium-modified	Unmodified	Strontium-modified
Test temperature, 100 °C				
1	1.2 ± 0.1	1.8 ± 0.2	6.8 ± 1.9	11.2 ± 0.5
10	1.3 ± 0.2	1.7 ± 0.3	...	...
100	1.3 ± 0.2	1.8 ± 0.4	6.1 ± 0.9	14.0 ± 1.9
Test temperature, 150 °C				
1	1.1 ± 0.2	1.6 ± 0.2	4.4 ± 0.5	9.8 ± 0.5
10	1.2 ± 0.2	1.6 ± 0.3	...	...
100	1.3 ± 0.1	1.7 ± 0.1	4.7 ± 0.1	8.8 ± 0.9
Test temperature, 200 °C				
1	1.3 ± 0.4	1.7 ± 0.2	...	...
10	1.7 ± 0.2	1.9 ± 0.1	...	...
100	2.0 ± 0.1	2.2 ± 0.1	...	...

to shape perturbations and can be spheroidized more easily than plate-like structures.[12] Castings produced in metallic molds exhibit quench modification, and hence, spheroidization occurs very rapidly in both unmodified and modified alloys upon solution heat treatment (Fig. 4). These results indicate that the effects of strontium modification are more significant at low cooling rates such as those observed in sand castings or in thick sections of permanent mold castings.

The Charpy impact energy (CIE) values at 25 °C are shown in Table 3. In the as-cast condition, strontium modification increases the impact energy from 1.1 J to 2.3 J in sand castings. Similarly, in metallic mold castings, the impact energy of the as-cast alloy increases from 2 to 10.8 J upon strontium modification. The effect of solution treatment on the impact energy at 25 °C is shown in Fig. 5. In sand castings, the impact energy increases slowly with solution treatment time. The impact energy of modified alloys is higher than in unmodified alloys for all solution times. Commercial A356 sand castings are typically solution treated for times ranging from 8 to 12 h. The increase in CIE attainable during this period is on the order of 30 to 35%. Typical impact energies in the T6 condition are on the order of 1.5 and 3.0 J for unmodified and strontium-modified alloys. The castings have to be solution treated for extended periods to obtain a significant increase in CIE. For example, after 96 h of solution treatment, CIE of sand castings increases by about 200 to 300% from the as-cast value. Castings produced in metallic molds, however, exhibit a significant increase in CIE even after relatively short solution times. For example, after a 2 h solution treatment, CIE increases from 2.0 to 5.6 J and from 10.8 to 12.9 J in unmodified and strontium-modified alloys, respectively. Permanent mold A356 castings are typically solution treated for 3 to 6 h. Under these conditions, CIE of A356-T6 alloys are on the order of 7 and 13 J in unmodified and strontium-modified alloys, respectively. The impact energy continues to increase with solution time, and CIE values as high as 26 J have been measured after 168 h. Modified alloys exhibit significantly higher CIE than unmodified alloys, for solution times typically used in commercial practice. At long solution times (>100 h), however, CIE values of unmodified and strontium-modified alloys are comparable.

Elevated temperature CIE values are shown in Table 4. The results show that holding sand cast samples at temperatures of up to 150 °C for times on the order of 100 h does not affect the CIE significantly. Table 4 shows that the CIE of A356-T6 (solution time, 8h) castings at 25 °C and after 100 h at 150 °C is on the order of 1.3 J. The CIE is essentially equal to the room-temperature value after 1 h at 200 °C. However, a slight increase in CIE is observed at holding times greater than 1 h at 200 °C. In metallic mold castings, the CIE at 100 °C does not vary significantly from the room-temperature value. For example, the impact energy of A356-T6 castings (solution time, 4h) at 25 °C and after 1 h at 100 °C is 6.8 J. At 150 °C, a decrease in

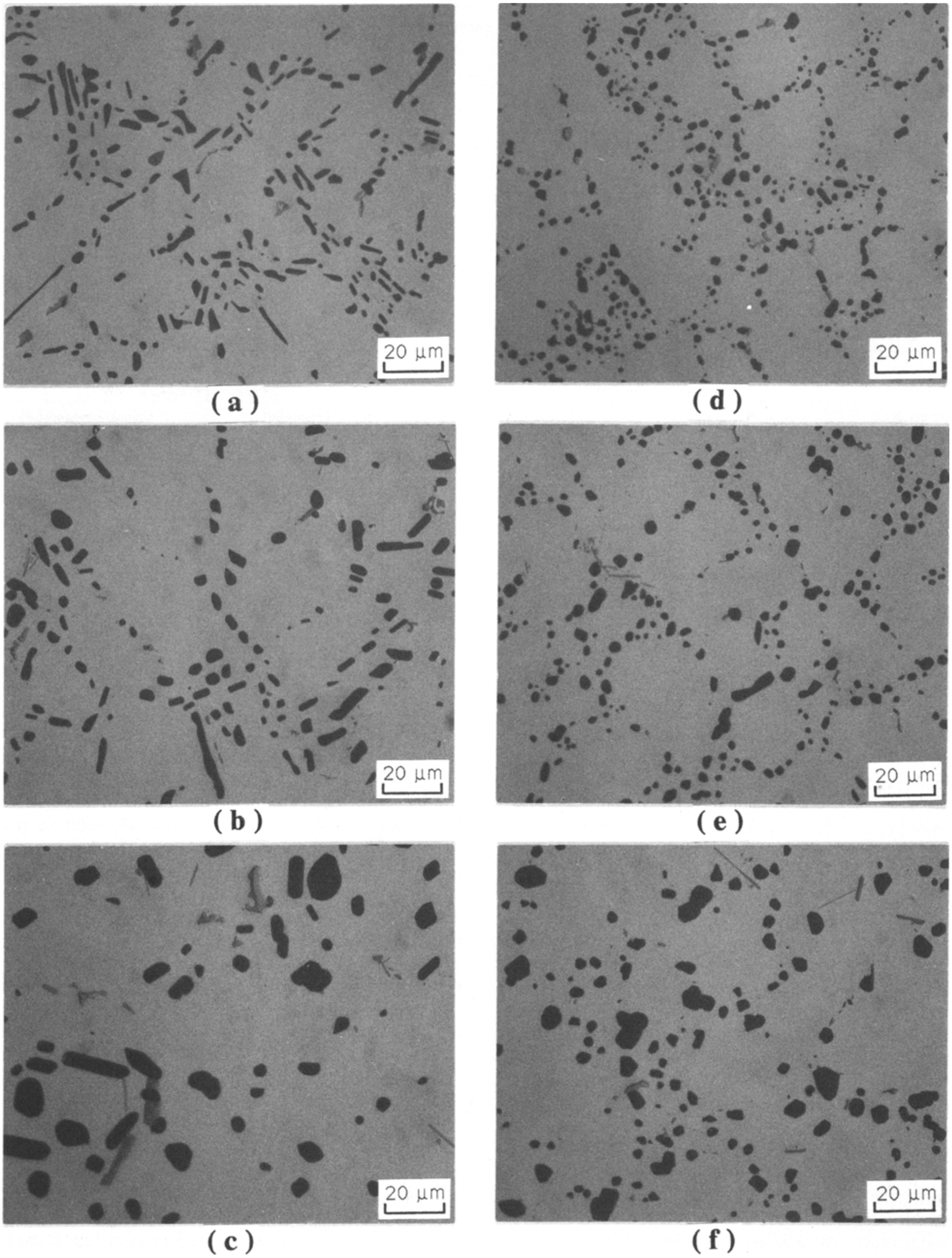

Fig. 4 Microstructures in heat treated metal mold castings as a function of solution time. Unmodified: (a) 4 h, (b) 16 h, (c) 168 h. Modified: (d) 4 h, (e) 16 h, (f) 168 h.

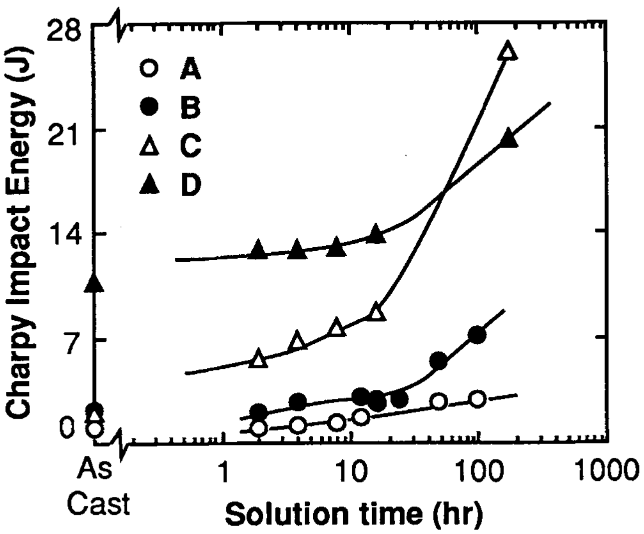

Fig. 5 Variation of Charpy impact energy in A356-T6 castings as a function of solution time. Sand castings: A, unmodified; B, strontium-modified. Metallic mold castings: C, unmodified; D, strontium-modified.

CIE (from the value measured at 25 °C) is observed even for holding times of 1 h.

The effects of strontium modification on mechanical properties can be analyzed based on the fracture behavior. In Al-Si alloys, cracks are initiated by fracture of silicon particles and propagate primarily through the interdendritic regions. A fine silicon structure produced either by high solidification rates (quench modification) or by the addition of strontium to the melt (chemical modification) promotes fracture resistance. Extended solution heat treatments enable blunting of sharp edges in the eutectic silicon particles, especially in unmodified castings produced at low solidification rates. This refinement in the silicon structure increases the amount of strain associated with crack propagation and thereby improves ductility and toughness. In addition, prolonged solution treatment also leads to a coarsening of silicon particles, and the particle spacing increases. As the silicon particle spacing increases, larger ligaments of the aluminum matrix can provide an effective barrier for crack growth, thereby improving toughness properties. Hence, in an unmodified metallic mold casting, CIE values of 6.8 and 26.1 J were measured for average particle spacings of 3.9 and 8.2 μm, respectively. All of the CIE values were correlated with the average silicon particle spacing, λ. Best fits from the regression analysis for both values of DAS indicated that CIE is proportional to $\lambda^{0.89}$. This result is in general agreement with the data of Meyers and Lyons,[13] which indicate that fracture toughness (K_{IC}) of A357-T6 alloys is proportional to λ. In other alloy systems, several other investigators have also shown that fracture toughness is proportional to $\lambda^{0.5}$.[14,15] The different values of the exponent may arise from differences in microstructural features of the alloys.

Cast aluminum alloys may contain several interdendritic phases depending on chemical composition. Mechanical properties are strongly influenced by the distribution and morphology of these interdendritic phases. A356 generally is considered to be a relatively pure alloy with strict limits on impurity concentrations. For example, the maximum specified iron (a major impurity element) concentration is 0.2%. Consequently, the mechanical properties of A356 alloys are generally superior to most other cast aluminum alloys. The CIE values for strontium-modified A356 and alloy 319 (a common automotive alloy) in the T6 condition after 8 h of solution treatment are 13.1 and 1.8 J, respectively, for castings produced in metallic molds.[16] The corresponding values after 168 h of solution treatment are on the order of 20 and 2.4 J, respectively. It appears that the toughness and CIE values of alloy 319 are limited by the iron-containing interdendritic phases, which do not undergo significant changes during solution treatment.

One of the problems encountered with strontium modification is the apparent increase in the amount of porosity in the casting (Table 2). The exact reasons for the increase in porosity have not been clearly understood. It has been suggested in the literature that several factors may contribute to the increase in porosity.[17] The addition of strontium to the melt may reduce the surface tension and may facilitate the nucleation of the pore. Strontium may also increase the inclusion content of the melt and thereby provide additional sites for the nucleation of the pore.[18] Despite the increase in porosity, however, it has been shown that modified castings possess better impact, tensile,[2] and fracture[16] properties than unmodified castings. From a practical point of view, chemical modification can be used as a relatively inexpensive technique to lower solution treatment times. Optimum solution times for maximizing tensile[2,3] properties in strontium-modified alloys have been measured to be on the order of 1 to 2 h for permanent mold castings and about 3 to 6 h in sand castings. These times are significantly lower than the values listed in heat treatment specifications, which were developed several decades ago for unmodified castings. The Charpy impact data presented here also show that the time required to attain a specific property level is significantly lower in strontium-modified alloys than in unmodified castings. These results highlight the beneficial effects of strontium modification in aluminum foundries.

4. Conclusions

The mechanical properties of cast aluminum alloys are strongly influenced by the morphology of interdendritic phases. Refinement of the silicon structure through the addition of strontium-containing master alloys to the melt improves the impact properties of A356-T6 castings. The impact energy increases with solution treatment time. Typical impact energies for sand castings in the T6 condition are on the order of 1.5 and 3.0 J for unmodified and strontium-modified alloys. Sand castings need to be solution treated for extended periods to obtain a significant increase in CIE. Impact energies for permanent mold castings in the T6 condition are on the order of 7 and 13 J in unmodified and strontium-modified alloys, respectively. Permanent mold castings exhibit an appreciable increase in CIE even after relatively short solution times (<2 h). Impact energies as high as 26 J have been measured in permanent mold castings solution treated for 168 h. Strontium modification can be used effectively to lower the solution treatment times for attaining the desired impact energy levels in the casting.

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