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Effect of Solution Treatment Parameters on Tensile Properties of Cast Aluminum Alloys

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Abstract. The influence of solution heat treatment parameters on T6 properties of unmodified and Sr-modified A356.2 alloys has been studied. The effects of solution temperature and time were investigated with ASTM B 108 test bars cast in sand molds and in permanent molds. Metallographic and image analysis techniques have been utilized to examine the microstructural changes occurring during heat treatment. The results indicate that the effect of Sr modification is to increase the spheroidization rate and lower the coarsening rate of Si particles. The solution temperature has a strong influence on Si particle morphology. Extremely high coarsening rates can be obtained at temperatures greater than 560° C. Solution treatment at these temperatures, however, has a detrimental effect on mechanical properties because of grain boundary melting. It has been established that solution times can be reduced significantly in modified samples. Increasing the solution temperature from 540 to 550° C enhances the strength properties.

INTRODUCTION

Cast aluminum alloys containing about 7% Si and 0.3 to 0.7% Mg are extensively used in many structural, automotive, and aerospace applications requiring a high strength to weight ratio. The cast components are generally heat treated to the T6 condition in order to enhance mechanical properties. Sand castings are solution treated at 540° C for 10 to 18 hr, quenched in water and aged at 154° C for 4 to 8 hr. Permanent mold castings are solution treated at 540° C for 4 to 8 hr, quenched in water, and aged at 171° C for 4 to 8 hr [1]. The primary purpose of the long solution treatment is to thermally alter silicon particle characteristics. The solution treatment changes the morphology of silicon from a polyhedral to globular structure and enhances mechanical properties appreciably. In addition, when the castings are solutionized, magnesium and some silicon dissolve to produce a homogeneous solid solution. The Mg and Si which are in solid solution precipitate as Mg_2Si during the aging treatment. The influence of various parameters on tensile properties of the heat treated product have recently been reviewed by Apelian et al. [2].

In recent years, advancements in molten metal processing technology have facilitated chemical modification of Si particle morphology through the addition of small amounts of Sr or Na to the melt. In this case, chemical and thermal modification may be used in conjunction to reduce the long solution times that are currently being employed in most foundries. It has been reported that modification of the melt with Sr or Na alters the kinetics of spheroidization and coarsening processes during solution treatment [3–5]. As a result, it may be possible to reduce solution times considerably in fully modified castings [6–8]. In the present contribution, the results of a detailed investigation conducted to optimize solution heat treatment parameters in modified and unmodified castings have been reported. This study is part of a larger program on the heat treatment and feeding characteristics of cast aluminum alloys being carried out at the Aluminum Casting Research Laboratory (ACRL), Drexel University.

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EXPERIMENTAL PROCEDURE

The effects of solution treatment time and temperature were evaluated for two different casting techniques: sand casting and permanent mold casting. In both cases, unmodified and Sr-modified ASTM B 108 A356.2 test bar samples were used to examine the influence of selected variables on tensile properties. Sand cast test bars were produced at Littlestown Hardware & Foundry Co., Inc. in Littlestown, Pennsylvania. Permanent mold test bars were cast at Stahl Specialty Co. in Kingsville, Missouri [9].

The castings were heat treated at Drexel University in a resistance heated air circulating box type muffle (Lucifer) furnace. The T6 heat treatment cycle is summarized below:

- Solution treatment: The effect of both solution temperature and time were studied. The solution temperature was varied from 520 to 570°C. The solution time was varied from 25 to 1600 min.
- Quench in water at 60°C.
- Natural age at room temperature for 24 hr.
- Age sand cast bars at 154 ± 2°C for 4 hr.
- Age permanent mold test bars at 171 ± 2°C for 4 hr.

The as-cast and heat treated samples were analyzed by optical and image analysis techniques to assess microstructural changes occurring during heat treatment. The LeMont image analysis system was used to measure structural characteristics of Sr-rich particles. The OASYS linescan algorithm was utilized for this purpose. The fields of observation were selected randomly. At least 10 fields were analyzed from a single specimen. The electrical conductivity of solution heat treated samples was measured in order to monitor structural changes occurring during solution treatment. The Magnaflux FM-140 digital conductivity meter was used for measuring conductivity. The yield strength (YS), ultimate tensile strength (UTS), percent elongation, and Rockwell (F) hardness were estimated from heat treated samples. The yield strength data correspond to 0.2% proof strength. A minimum of 10 bars were tested under each condition. Other pertinent details regarding the experimental procedure are summarized elsewhere [9].

RESULTS AND DISCUSSION

Effect of Solution Time

The influence of solution treatment time on Si particle morphology of sand cast test bars is shown in Figure 1. It can be seen that as the solution time increases, Si particles undergo necking and are broken down into smaller fragments. The fragmented particles are gradually spheroidized. Prolonged solution treatment leads to extensive coarsening of the particles. Modification has a strong influence on spheroidization and coarsening of Si particles. A high degree of spheroidization is observed in modified alloys after only 50 min of solution treatment. In unmodified specimens, however, even after 800 min and solution treatment several long needles of silicon are visible. A similar behavior is observed in permanent mold test bars. In this case, the time required for spheroidization is much smaller than in sand cast specimens. These results can be explained from theoretical considerations which indicate that interfacial instabilities cannot readily occur in platelike (unmodified) eutectics and hence, the structure is resistant to spheroidization [10]. Fibrous eutectics (modified), however, are susceptible to shape perturbations and the particles are easily spheroidized. The spheroidization and coarsening processes occur because of the instability of interfaces between two different phases and are driven by a reduction in the total interfacial energy.

Image analysis data for both sand cast and permanent mold test bars are shown in Figure 2. In this figure, Si particle characteristics such as average particle diameter, aspect ratio, and number of particles are plotted as a function of solution time. The average diameter initially registers a decrease because of fragmentation of the particles. Subsequently, particle coarsening leads to a significant increase in the average diameter. Because of the higher cooling rate, average equivalent diameter is much larger in permanent mold than in sand cast specimens. The average silicon particle diameter is much smaller in modified than in unmodified samples. The large diversity in particle size and shape in unmodified alloys provides a greater driving force for coarsening of Si particles than in modified samples. Consequently, higher growth rates are observed in unmodified than in modified alloys. Typical growth rates have been estimated to be of the order of 0.04 to 0.1 μm/hr and 0.02 to 0.05 μm/hr in unmodified and modified alloys, respectively. In modified castings, particle growth obeys equations developed for diffusion controlled growth and particle volume is proportional to $t^{1/3}$ [11]. In unmodified sand castings, the dependence of particle size on $t^{1/3}$ is observed only after large solution times (>200 min). In this case, the assumption of spherical morphology for Si particles is not valid at short solution times. Spherical particles begin to dominate only after the casting has been solutionzed for extended periods. Meyers [4] has conducted a detailed study of the coarsening process in unmodified A357 samples and has shown that the $t^{1/3}$ dependence of particle radius is valid after a solution time of 5

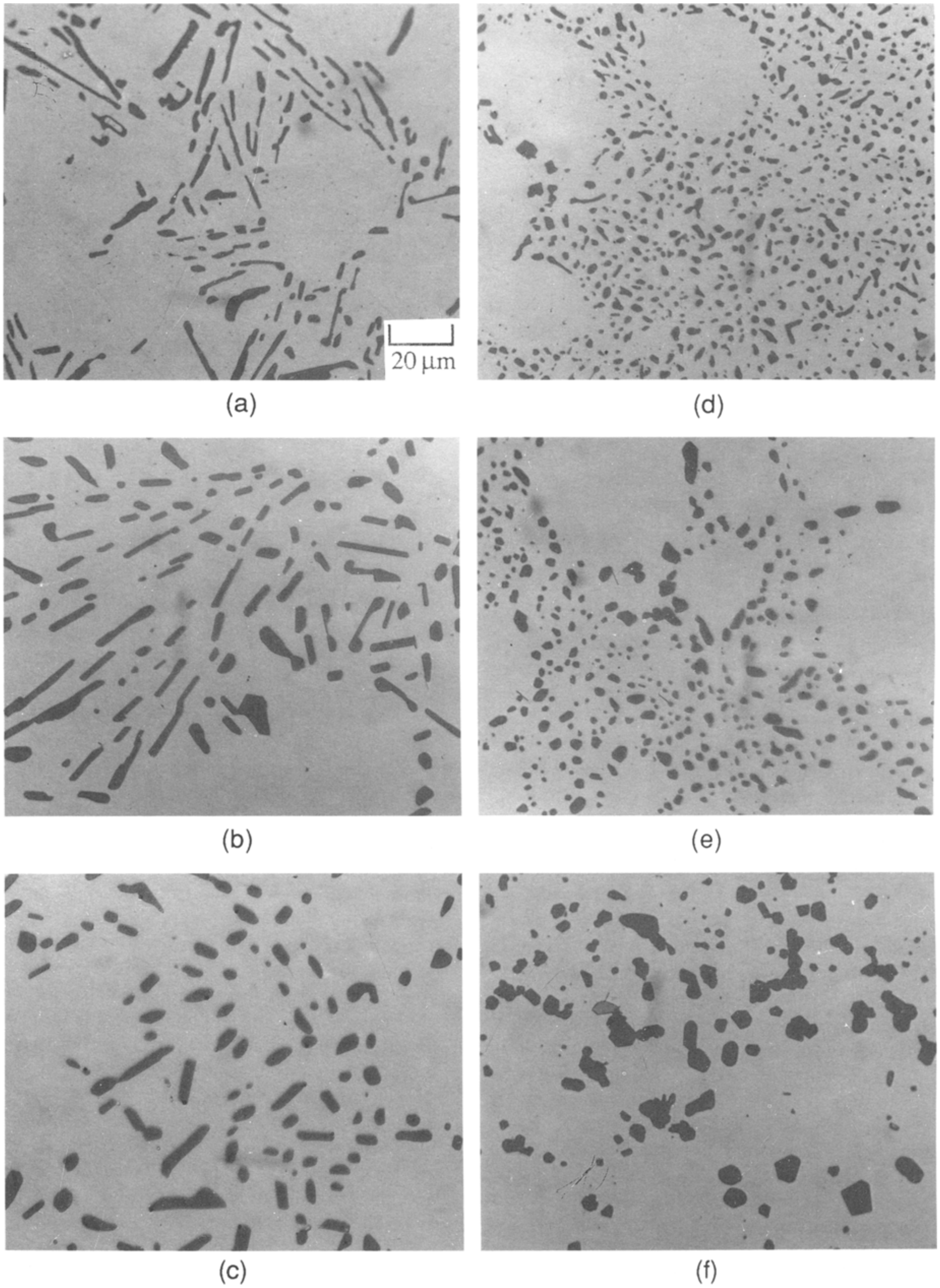


Fig. 1. Typical microstructures of sand cast test bars as a function of solution time (solution temperature = 540° C (500X). Unmodified: (a) 50 min (b) 400 min (c) 1600 min Modified: (d) 50 min (e) 400 min (f) 1600 min.

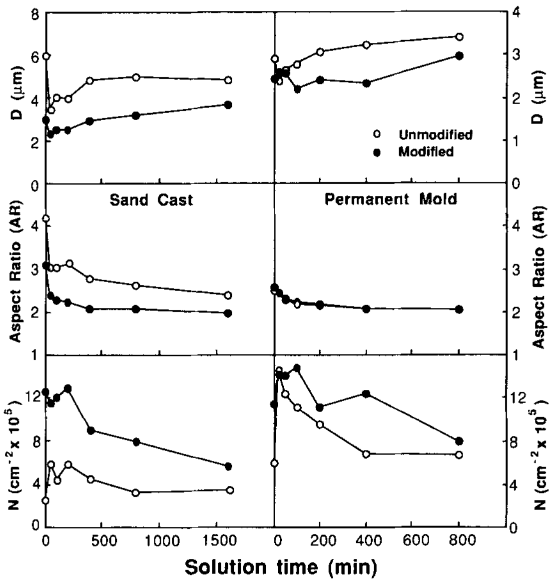


Fig. 2. Variation of silicon particle average diameter (D), aspect ratio, and number of silicon particles (N) with solution time (solution temperature = 540° C).

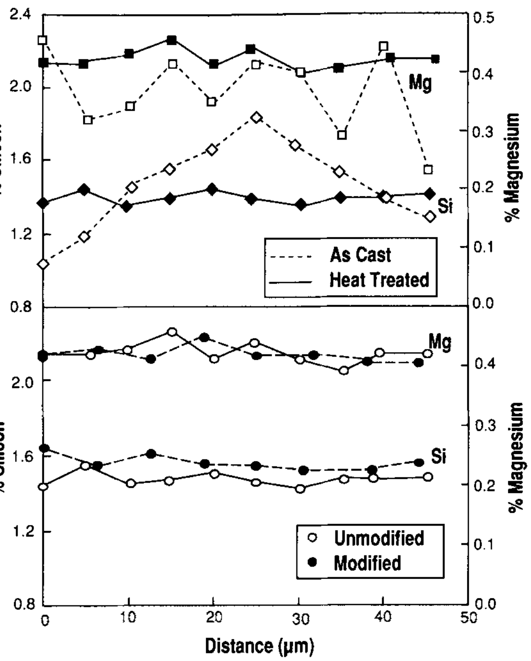


Fig. 3. Si and Mg concentrations across a dendrite in as-cast and solution treated (50 min at 540° C) test bars. The Si and Mg profiles for modified and unmodified alloys solutionized for 50 min are also plotted.

hr. The number of particles varies inversely with the particle diameter since the total volume of Si remains constant. Up to about 100 min of solution treatment, there is a rapid reduction in the aspect ratio. Subsequently, there is relatively small decrease in the aspect ratio. As can be expected, unmodified alloys exhibit a higher aspect ratio than modified alloys. Also, aspect ratio is greater in sand cast specimens than in permenent mold samples.

The segregation of Si and Mg in Al–Si–Mg alloys is not severe and, consequently, homogenization and dissolution of Mg_2Si occur in a relatively short period [2]. Electron microprobe analysis was conducted on as-cast and heat treated samples in order to investigate the kinetics of the homogenization process. The Si and Mg concentrations were determined across the dendrites. The results are shown in Figure 3. In the as-cast samples, the highest concentration of Si is found at locations close to the center of the dendrite. Relatively large fluctuations are observed in the Mg concentration. In both sand cast and permanent mold castings, Si and Mg concentration becomes almost uniform after 50 min of solution treatment indicating that homogenization is essentially complete within this short period. No significant differences were detected between modified and unmodified alloys (Fig. 3). Similar results have been reported by Closset et al. [12]. At solution temperatures commonly employed in commercial castings (540° C), about 0.6% Mg can be placed in solid solution. This value is lower than the magnesium concentrations in most castings and hence, all of the magnesium is in solid solution after the solution heat treatment.

The electrical conductivity of the test bars is plotted as a function of solution time in Figure 4. In the as-cast condition, sand cast samples exhibit a lower conductivity than permanent mold specimens. Note also that higher conductivities are obtained in modified than in unmodified specimens because of the differences in eutectic Si morphology [13]. As the solution time increases, conductivity initially decreases, attains a minimum value, and then begins to increase. The initial decrease is due primarily to the dissolution of solutes in the matrix. Subsequent improvements in conductivity result from changes in Si particle morphology. A minimum in conductivity is observed after 50 min of solution treatment in sand cast specimens and after 25 min in permanent mold specimens. These results also confirm that homogenization of the casting and dissolution of Mg_2Si are essentially complete within 50 min of solution treatment.

The average yield strength, ultimate tensile strength, and percent elongation are shown in Tables 1 and 2 as a function of time at 540° C. Because of a refinement of the dendritic structure, the as-cast strength properties in permanent mold bars are greater than in sand cast bars. It has been reported that doubling the dendrite arm spacing from 25 µm to 50 µm reduces YS and UTS by about 20% and 25%, respectively

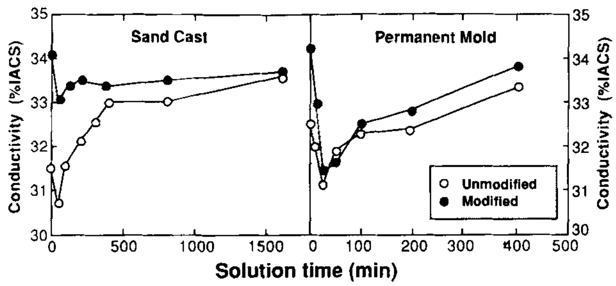


Fig. 4. Variation of electrical conductivity immediately after quenching (T4) as a function of solution treatment time.

[14]. Both YS and UTS generally improve with solution time and attain a maximum after about 200 to 400 min in sand cast alloys and about 100 min in permanent mold samples. Subsequently, strength properties register a slight decrease and then remain essentially constant. Modified alloys exhibit higher YS and UTS than unmodified alloys. The hardness of the test bars does not show any significant dependence on solution treatment time [9]. The property that is most affected by modification and by solution treatment is percent elongation. As can be expected, permanent mold test bars exhibit a higher elongation than sand cast bars. In addition, modified bars possess a higher elongation than unmodified samples. In sand cast bars, percent elongation gradually increases with solution time. After about 400 min of solution treatment, modified alloys possess an elongation which is equivalent to that observed after 1600 min in unmodified alloys.

A continuous Si structure which resists crack propagation is produced during solution treatment and hence, fatigue and fracture properties improve with prolonged solution treatment. It has been reported, however, that fatigue strength and fracture toughness begin to improve only after solution times greater than about 500 min [15]. Experiments are currently being conducted at our laboratory to optimize the solution treatment parameters to obtain maximum fatigue and fracture properties.

One of the problems encountered with chemical modification is the susceptibility of the casting to the formation of porosity. This problem is exacerbated at low cooling rates such as those observed in sand castings. Density measurements in sand cast samples indicated that porosity levels in modified samples were higher (~1.5 to 2%) than in unmodified test bars (~1.0%). It should be noted, however, that these porosity values are typically observed in most commercial sand castings. Despite the introduction of poros-

Table 1. Tensile Properties (T6) of Sand Cast Test Bars[a]

Solution Time (min)	Unmodified YS (MPa)	Unmodified UTS (MPa)	Unmodified % Elongation	Modified YS (MPa)	Modified UTS (MPa)	Modified % Elongation
As Cast	100.0 ± 9.3	164.6 ± 4.8	4.25 ± 0.75	9.99 ± 11.1	168.1 ± 3.7	6.12 ± 0.63
50	193.6 ± 4.5	252.1 ± 6.8	3.38 ± 0.67	184.6 ± 12.3	257.5 ± 8.4	5.56 ± 0.83
100	196.0 ± 16.3	264.0 ± 7.5	3.70 ± 0.98	191.0 ± 12.4	267.6 ± 8.3	5.66 ± 0.80
200	212.5 ± 16.4	272.8 ± 8.7	3.87 ± 1.19	201.2 ± 16.2	275.4 ± 11.4	6.20 ± 1.04
400	218.5 ± 11.8	284.9 ± 5.5	4.38 ± 1.04	211.4 ± 7.3	283.5 ± 7.5	6.77 ± 1.26
800	204.3 ± 12.7	271.3 ± 10.7	5.5 ± 0.82	189.4 ± 11.1	270.9 ± 6.0	8.44 ± 1.77
1600	200.9 ± 8.2	280.7 ± 6.6	6.95 ± 1.14	201.5 ± 11.8	274.7 ± 6.4	8.94 ± 0.85

[a] 1 MPa = 0.147 ksi.

Table 2. Tensile Properties (T6) of Permanent Mold Test Bars

Solution Time (min)	Unmodified YS (MPa)	Unmodified UTS (MPa)	Unmodified % Elongation	Modified YS (MPa)	Modified UTS (MPa)	Modified % Elongation
As Cast	100.4 ± 5.8	197.7 ± 4.2	7.42 ± 1.27	95.7 ± 6.6	204.0 ± 3.5	9.45 ± 1.34
25	256.6 ± 5.9	322.6 ± 8.3	6.03 ± 1.42	257.9 ± 8.6	326.7 ± 6.8	7.15 ± 0.89
50	266.9 ± 12.8	326.9 ± 9.3	5.20 ± 1.12	269.2 ± 16.6	335.4 ± 5.1	8.35 ± 1.64
100	269.5 ± 7.0	330.1 ± 10.0	5.61 ± 1.54	273.3 ± 11.9	333.8 ± 5.0	7.32 ± 1.18
200	271.0 ± 14.6	332.8 ± 7.7	6.57 ± 0.84	271.4 ± 12.2	333.8 ± 8.9	7.30 ± 1.21
400	262.3 ± 5.9	334.4 ± 10.6	8.38 ± 2.35	265.6 ± 10.6	340.0 ± 6.2	8.66 ± 1.95
800	280.4 ± 10.8	336.5 ± 7.6	8.60 ± 2.01	281.3 ± 13.3	337.2 ± 5.4	8.53 ± 1.32

ity in the casting, modified samples generally exhibited higher tensile properties than unmodified specimens (Table 1).

Influence of Solution Temperature

The solution treatment temperature also plays a major role in determining the Si particle characteristics (Fig. 5). The spheroidization and coarsening rates are directly proportional to the solution temperature. At temperatures greater than 550° C, extremely large silicon particles are observed in the microstructure. The activation energy for coarsening has been measured to be of the order of 80 kcal/mole indicating that the coarsening process is very sensitive to temperature fluctuations [4]. At a temperature of 570° C, particles exhibit faceting even at short times. The temperature may not be increased indefinitely because of the formation of complex eutectics which melt at temperatures below the equilibrium eutectic temperature (Fig. 5). If the temperature of solution treatment exceeds 560° C, the melting of the tenary eutectic phases occurs at the grain boundaries. These tenary phases are predominantly iron-rich particles.

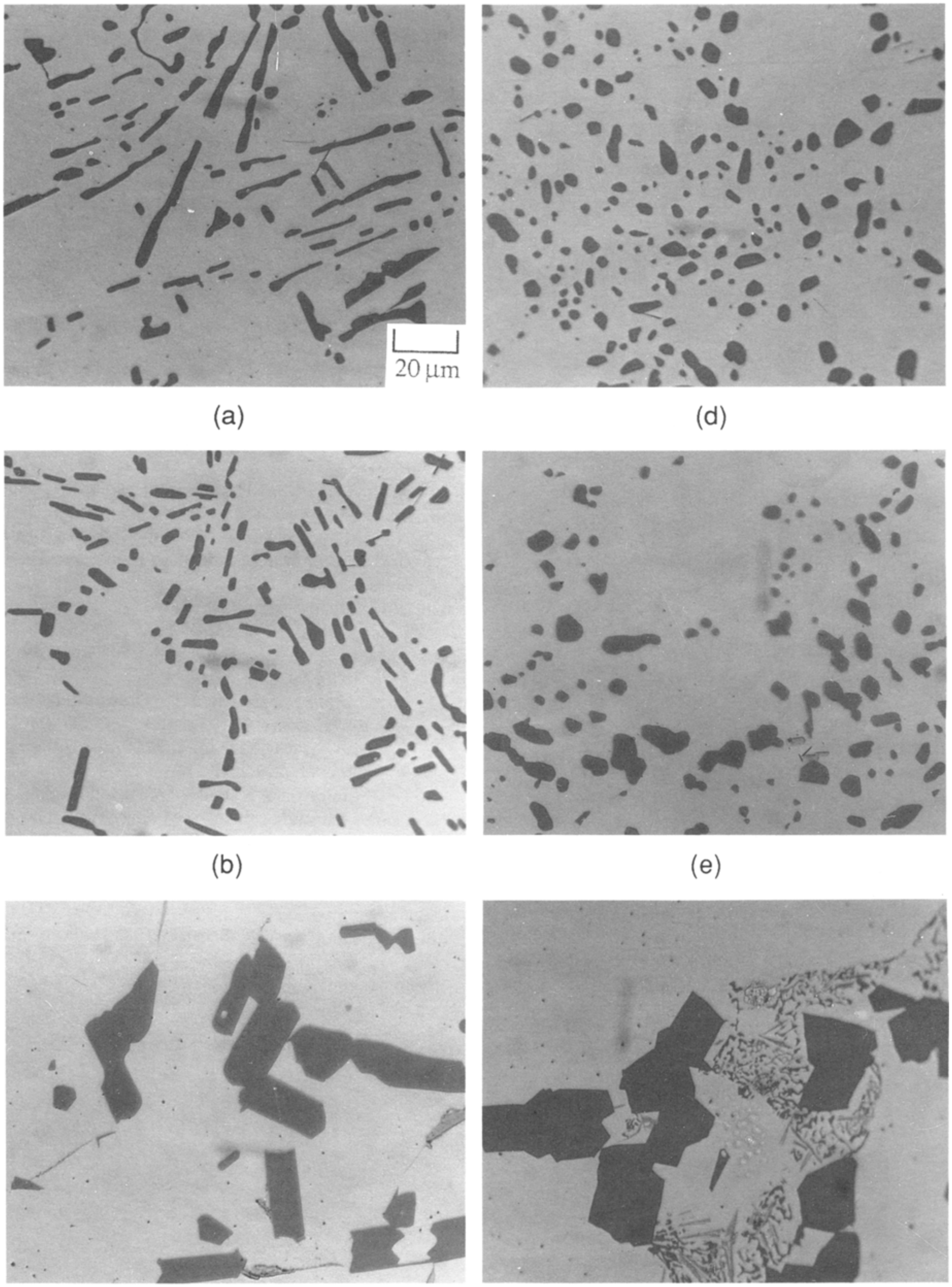
The variation of YS, UTS, and elongation with solution temperature for a solution time of 50 min is shown in Figure 6. Both YS and UTS improve with temperature and maximum properties are attained at 550° C. At this temperature, maximum properties are obtained at times of the order of 50 to 100 min in sand cast alloys and about 25 to 50 min in permanent mold castings. In unmodified sand cast alloys, substantial improvements in elongation can be obtained by increasing temperature from 540 to 550° C. In modified sand cast alloys, however, elongation registers a small decrease when solution temperature is increased from 540 to 550° C. In permanent mold specimens, elongation is essentially unaffected as temperature is increased from 540 to 550° C. Because of grain boundary melting, YS and UTS and elongation are lowered appreciably at 560 and 570° C.

This work demonstrates that solution times can be reduced significantly in modified castings. Optimum solution times at 540° C are of the order of 50 to 100 min in permanent mold castings and about 200 to 400 min in sand castings. The solution times can be reduced further by increasing the solution temperature. For example, at 550° C, optimum solution times are about 25 to 50 min in permanent mold castings and about 50 to 100 in sand castings. When the solution temperature is increased above 540° C, it becomes imperative that temperature in the parts being heat treated be controlled precisely in order to avoid grain boundary melting. Differential thermal analysis experiments indicate that the first liquid begins to form in the temperature range 560 to 563° C. Clearly, this temperature depends on chemical composition of the alloy, primarily copper and iron concentrations. Hence, the temperature of eutectic melting should be determined accurately before elevating the solution temperature. In this respect, several other investigators have reported that with proper control of melt quality and heat treatment conditions, solution treatment times can be reduced appreciably in modified castings [6,8,16]. Researchers in Europe [17,18] have proposed the total elimination of solution treatment in selected castings which are modified. Instead the casting is removed from the mold as soon as possible (when the metal temperature is still close to the eutectic temperature), and quenched. A subsequent aging treatment gives a good combination of strength and ductility. Heat treatment costs are typically of the order of 15 to 25¢/lb. The potential economic savings resulting from a reduced heat treatment cycle are substantial.

CONCLUSIONS

The heat treatment cycles being used in most foundries were developed several decades ago when grain refinement and modification were not a common practice. It is clear from our results that Sr modification has a strong effect on the structural changes occurring during solution treatment. As a result, solution treatment times can be reduced significantly in modified castings. The extent of reduction in the solution time depends on the solution temperature. At 540° C, optimum solution times are of the order of 3 to 6 hr in sand cast alloys and 1 to 2 hr in permanent mold samples. At 550° C, optimum solution times are around 1.5 to 3 hr in sand cast alloys and 0.5 to 1 hr in permanent mold castings. It should be noted that longer times may be necessary to obtain significant improvements in fatigue and fracture properties. Increasing the solution temperature also has a beneficial effect on the mechanical properties attainable after heat treatment. The strength properties in the casting can be enhanced by up to 25% when the temperature is increased from 540 to 550° C. The solution temperature cannot be increased above 560° C since the first liquid begins to form at the grain boundaries in the temperature range 560 to 563° C.

Since the morphology of Si particles can be controlled to a large extent by chemical treatment of the melt, the strength properties are essentially determined by the aging conditions. The kinetics of Mg_2Si precipitation may have a dominant influence on the strength properties attainable in the casting. A combination of natural and artificial aging cycles may be utilized to obtain maximum strength properties in the



(a) (d)

(b) (e)

(c) (f)

Fig. 5. Typical microstructures of sand cast samples as a function of solution temperature (solution time = 200 min) (500X). Unmodified: (a) 550° C (b) 560° C (c) 570° C Modified: (d) 550° C (e) 560° C (f) 570° C.

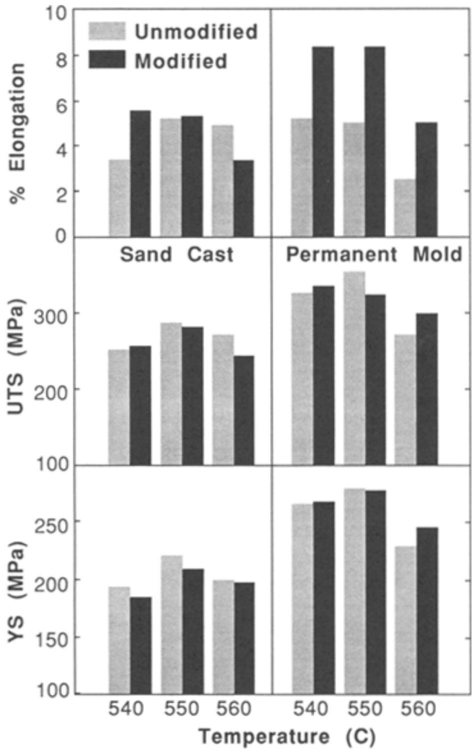


Fig. 6. Variation of tensile properties with solution temperature (solution time = 100 min).

cast component. Experiments are currently underway at our laboratory to optimize the aging conditions for A356 alloys.

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REFERENCES

1. *Metals Handbook,* Volume 15, Ninth edition, American Society for Metals, 1988.
2. D. Apelian, S. Shivkumar, and G. Sigworth, *Trans AFS,* 1989, **97,** pp. 727–742.
3. B.A. Parker, D.S. Saunders, and J.R. Griffiths, *Metals Forum,* 1982, **5**(1), pp. 48–53.
4. F.N. Rhines and M. Aballe, *Met Trans A,* 1986, **17A,** pp. 2139–2152.
5. M.M. Tuttle and D.L. Mclellan, *Trans AFS,* 1982, **90,** pp. 13–23.
6. H.J. Li, S. Shivkumar, X.J. Luo, and D. Apelian, *Cast Metals,* 1989, **1**(4), pp. 227–234.
7. M. Adachi, *Alutopia(Jpn.),* 1984, **14**(12), pp. 16–22.
8. E. Mauveaux and M. Lafargi, *Trait. Therm.,* 1982, **169,** pp. 31–35.
9. S. Shivkumar, S. Ricci, Jr., B. Steenhoff, D. Apelian, and G. Sigworth, *Trans AFS,* 1989, **97,** pp. 791–810.
10. J.W. Martin and R.D. Doherty: *Stability of Microstructures in Metallic Systems,* Cambridge University Press, London, 1980.
11. I.M. Liftshitz and V.V. Sloyozov, *J. Phys. Chem. Solids,* 1961, **19,** pp. 35–47.
12. B. Closset, R.A.L. Drew and J.E. Gruzleski, *Trans AFS,* 1986, **94,** pp. 9–16.
13. M.H. Mulazimoglu, R.A.L. Drew, and J.E. Gruzleski, *Met Trans A,* 1987, **18A,** pp. 941–947.
14. J.A. Eady and D.M. Smith, *Materials Forum,* 1986, **9**(4), pp. 217–223.
15. D.M. Smith and J.A. Eady, "Metals in Mining" [Proc. Conf.], Australian Inst. of Mining, 1981, pp. 78–81.
16. M. Tsukuda, S. Koike, and M. Harada, *J. of Japan Inst. of Light Metals,* 1978, **28**(1), pp. 8–14.
17. M. Kaczorowski and R. Szostak, *Aluminium,* 1983, **59,** pp. 304–306.
18. P. Murza-Mucha, R. Szostak, *J. of Materials Science,* 1972, **17,** pp. 3621–3629.

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