AA 354, C355 & A356 Foundry Ingot

Alcan Prime Alloys

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Product Bulletin

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Introduction

The Aluminum Association (AA) 3XX series of alloys covers a range of aluminum-silicon-magnesium(-copper) alloys that are the backbone of the aluminum investment, sand, semi-permanent mold and permanent mold casting industry. This alloy system has excellent castability, good machinability and weldability, good pressure tightness and resistance to corrosion, freedom from 'hot cracking' susceptibility, is heat treatable and capable of moderate to high mechanical properties. Alcan Inc. produces primary foundry ingot that are well within the Aluminum Association Chemical Composition Limits for these alloys. Moreover, Alcan Ingot can tailor alloys specifically to the customer's requirements. This combined with full technical assistance from a team of experienced researchers, foundry technologists and a knowledgeable sales staff, provides a full service package to foundries.

Aluminum Association AA A356.0 composition castings are found as aircraft parts, fittings, structures, and control components. In the field of automotive castings, these castings are used as differential carriers and water-cooled cylinder blocks and heads. A356-T6 is the common alloy and temper for light alloy automotive wheels and is finding increased usage as lightweight, high integrity automotive suspension parts.

For higher strength than available from A356, the higher magnesium level of the 357 alloys should be considered. There is some loss of elongation, but the alloy retains its good casting and welding characteristics. For more detailed information on the 357-alloy family please ask your Alcan representative for a copy of the "Alcan AA 357 Primary Foundry Alloys" Product Bulletin.

Where higher temperature strengths are required, Cu is added to produce the AA 354 and AA 355 families. This elevated temperature strength capability comes at a sacrifice in corrosion resistance and ductility. The thermal conductivity of the alloy is also reduced by the presence of Cu. Alloys like this are used for things like automotive air condition scrolls, impellers for superchargers, and some high strength automotive suspension and brake components.

A selection of AA registered compositions are shown in Table 1. In the primary 356 family the A356 to C356 variants differ mainly in Fe level, an important determinant of ductility as shown in Figure 2. An exception is F356, which is a low Mg variant designed to give exceptionally high ductility at lower strength. 354 and 355 alloys differ from each other in the amount of Cu as well as Si. 354 is used where higher fluidity is required and is usually referred to as a permanent mould alloy although investment casting and squeeze casting are both use to make parts using this alloy. The 355 is used in either sand or permanent mould. Tables 2 to 5 cover some of the physical properties of these alloys.

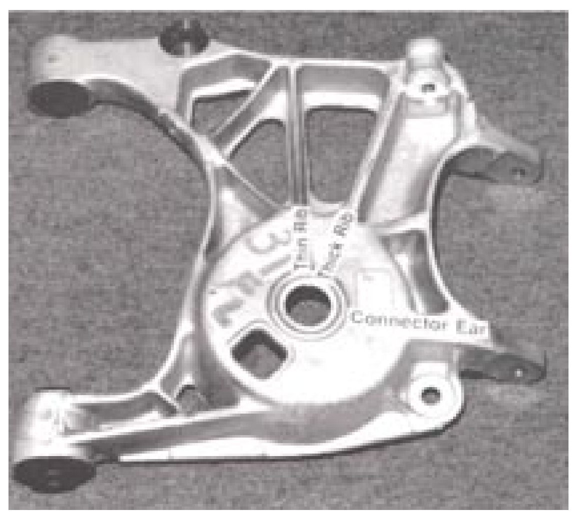

Figure 1. A356-T61 Lincoln Mark VIII Cast Lower Suspension Control Arm

Table 1 - Some Registered AA 3XX Primary Foundry Alloys

Alloy	Si	Fe	Cu	Mn	Mg	Ti	Zn	Others	
								Each	Total
A356.0	6.5-7.5	0.20	0.20	0.10	0.25-0.45	0.20	0.10	0.05	0.15
A356.1	6.5-7.5	0.15	0.20	0.10	0.30-0.45	0.20	0.10	0.05	0.15
A356.2	6.5-7.5	0.12	0.10	0.05	0.30-0.45	0.20	0.05	0.05	0.15
B356.0	6.5-7.5	0.09	0.05	0.05	0.25-0.45	0.04-0.20	0.05	0.05	0.15
B356.2	6.5-7.5	0.06	0.03	0.03	0.30-0.45	0.04-0.20	0.03	0.03	0.10
C356.0	6.5-7.5	0.07	0.05	0.05	0.25-0.45	0.04-0.20	0.05	0.05	0.15
C356.2	6.5-7.5	0.04	0.03	0.03	0.30-0.45	0.04-0.20	0.03	0.03	0.10
F356.0	6.5-7.5	0.20	0.20	0.20	0.17-0.25	0.04-0.20	0.10	0.05	0.15
F356.2	6.5-7.5	0.12	0.10	0.10	0.17-0.25	0.04-0.20	0.05	0.05	0.10
354.0	8.6-9.4	0.20	1.6-2.0	0.10	0.40-0.6	0.20	0.10	0.05	0.15
354.1	8.6-9.4	0.15	1.6-2.0	0.10	0.45-0.6	0.20	0.10	0.05	0.15
354.2	8.6-9.4	0.06	1.6-2.0	0.10	0.45-0.6	0.20	0.10	0.05	0.15
A355.0	4.5-5.5	0.09	1.0-1.5	0.05	0.45-0.6	0.04-0.20	0.05	0.05	0.15
A355.2	4.5-5.5	0.06	1.0-1.5	0.03	0.50-0.6	0.04-0.20	0.03	0.03	0.10
C355.0	4.5-5.5	0.20	1.0-1.5	0.10	0.40-0.6	0.20	0.10	0.05	0.15
C355.1	4.5-5.5	0.15	1.0-1.5	0.10	0.45-0.6	0.20	0.10	0.05	0.15
C355.2	4.5-5.5	0.13	1.0-1.5	0.05	0.50-0.6	0.20	0.05	0.05	0.15

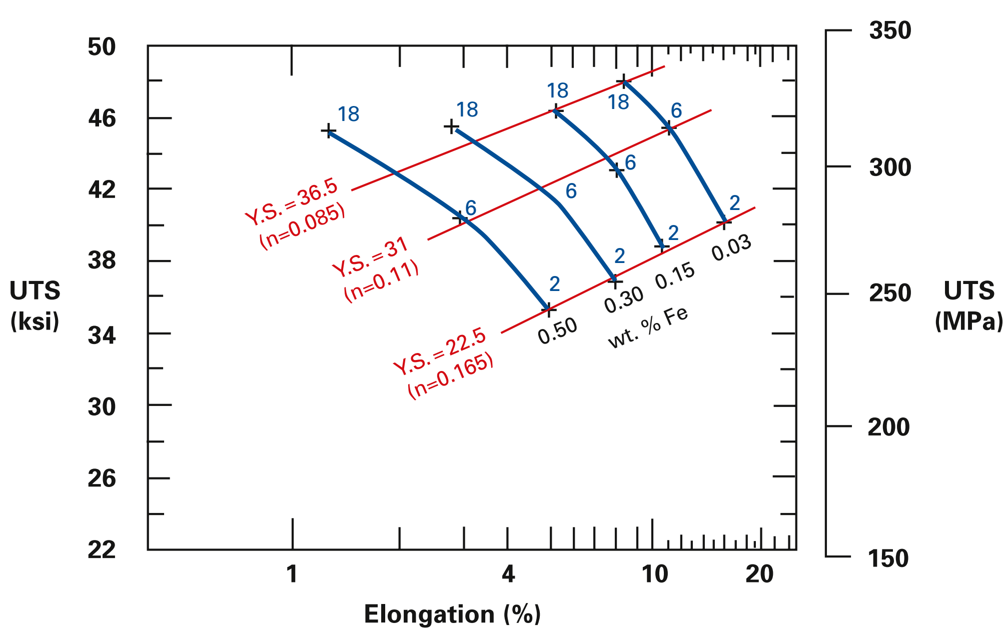

Figure 2. Effect of Fe level on Mechanical Properties of A356. The three different yield stresses referred to correspond to three different aging treatments. In each case the elongation, primarily, is reduced as the Fe level is raised. The tensile strength also suffers. [From Geoff Sigworth, "Quality Issues in Aluminum Net-Shape Castings", AFS Paper No. 04-075(2), Unpublished Work by Ken Whaler, Stahl Specialty]

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Table 2 - Physical Characteristics of AA A356.2 Alloys

Density:	2.685 g/cm³ (0.097 lb/in³) at 20°C [Pure Aluminum 2.699 g/cm³ (0.0975 lb/in³)]
Freezing Range:	Liquidus 615°C (1140°F) Solidus 555°C (1035°F)
Heat Capacity:	963 J/kg•K (0.230 Btu/lb °F) at 100°C (212°F)
Coefficient of Thermal Expansion:	21.5 μm/mK (11.9 μin/in °F) at 20-100°C (68-212°F) 22.5 μm/mK (12.5 μin/in °F) at 20-200°C (68-392°F) 23.5 μm/mK (13.1 μin/in °F) at 20-300°C (68-572°F)
Thermal Conductivity:	T51 Sand 167 W/mK (96 Btu/ft•hr•°F) at 25°C (77°F) T6 Sand 151 W/mK (87 Btu/ft•hr•°F) at 25°C (77°F) T7 Sand 155 W/mK (90 Btu/ft•hr•°F) at 25°C (77°F) T6 PM 159 W/mK (92 Btu/ft•hr•°F) at 25°C (77°F)
Latent Heat of Fusion:	389 kJ/kg (167 Btu/lb)
Electrical Conductivity:	T51 Sand 43% IACS[1] (40.1 nΩ•m) at 20°C (68°F) T6 Sand 39% IACS (44.2 nΩ•m) at 20°C (68°F) T7 Sand 40% IACS (43.1 nΩ•m) at 20°C (68°F) T6 PM 41% IACS (42.1 nΩ•m) at 20°C (68°F)

Electrolytic Solution Potential for A356.0 sand castings in the T6 temper is -0.82 Vs 0.1 N calomel electrode in a solution of 53g NaCl and 3g of hydrogen peroxide in distilled water.

Table 3 - Physical Characteristics of AA 357 Alloys

Density:	2.68 g/cm³ (0.097 lb/in³)
Freezing Range:	Liquidus 615°C (1140°F) Solidus 555°C (1035°F)
Heat Capacity:	963 J/kg•K (0.230 Btu/lb °F) at 100°C (212°F)
Coefficient of Thermal Expansion:	21.6 μm/mK (12.0 μin/in °F) @ 17-100°C (63-212°F)
Thermal Conductivity:	152 W/mK (88 Btu/ft•hr•°F) at 25°C (77°F)
Latent Heat of Fusion:	389 kJ/kg (167 Btu/lb)

Table 4 - Physical Characteristics of AA 354 Alloys

Density:	2.71 g/cm³ (0.098 lb/in³)
Heat Capacity:	963 J/kg•K (0.230 Btu/lb.°F) at 100°C (212°F)
Coefficient of Thermal Expansion:	20.9 μm/mK (11.6 μin/in °F) @ 20-300°C (68-572°F)
Thermal Conductivity:	128 W/mK (74 Btu/ft•hr•°F) at 25°C (77°F)
Latent Heat of Fusion:	389 kJ/kg (167 Btu/lb)

Table 5 - Physical Characteristics of AA 355 Alloys

Density:	2.71 g/cm³ (0.098 lb/in³)			
Freezing Range:	Liquidus 620°C (1150°F) Solidus 545°C (1013°F)			
Heat Capacity:	963 J/kg(K (0.230 Btu/lb °F) at 100°C (212°F)			
Coefficient of Thermal Expansion:	22.4 μ/mK (12.4(μin/in °F) at 20-100°C (68-212°F) 23 μ/mK (12.8(μin/in °F) at 20-200°C (68-392°F) 24 μ/mK (13.3(μin/in °F) at 20-300°C (68-572°F)			
Thermal Conductivity:	T51 Sand	167 W/mK (96 Btu/ft•hr•°F)		at 25°C (77°F)
	T6 Sand	152 W/mK (88 Btu/ft•hr•°F)		at 20°C (68°F)
	T7 Sand	163 W/mK (94 Btu/ft•hr•°F)		at 20°C (68°F)
	T6 PM	151 W/mK (87 Btu/ft•hr•°F)		at 20°C (68°F)
Electrical Conductivity:	T51 Sand	43% IACS²	(40.1 nΩ•m)	at 20°C (68°F)
	T6 Sand	36% IACS²	(47.9 nΩ•m)	at 20°C (68°F)
	T61 Sand	39% IACS²	(44.2 nΩ•m)	at 20°C (68°F)
	T7 Sand	40% IACS²	(41.0 nΩ•m)	at 20°C (68°F)
	T6 PM	41% IACS²	(44.2 nΩ•m)	at 20°C (68°F)
Latent Heat of Fusion:	389 kJ/kg (167 Btu/lb)			

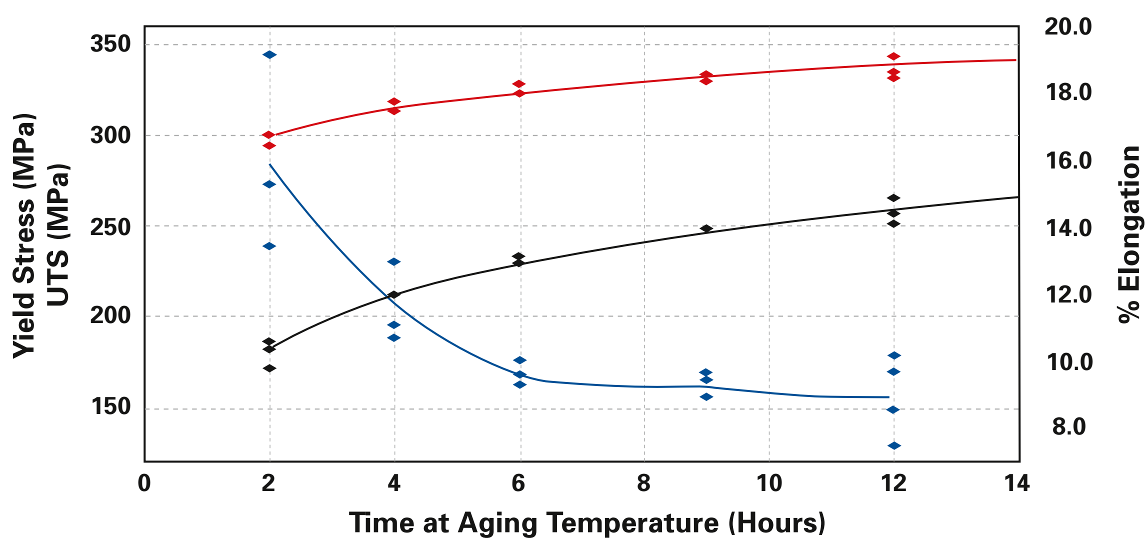


Figure 3. Typical Aging curves for A356-T61 separately cast tensile bars. Aging temperature was 155°C. Note that 170°C is sometimes used for faster aging when accurate time controls are in place.

Table 6 - Example Mean Mechanical Properties A356.0-T6 Cast Suspension Components[3]

Mechanical Property	Example Casting 1	Example Casting 2
Yield Strength (MPa / ksi)	234 / 33.9	251 / 36.5
Tensile Strength (MPa / ksi)	309 / 44.8	328 / 47.6
% Elongation on 5D (Lowest / Mean / Highest)	7.2 / 9.3 / 11.2	4.8 / 9.6 / 12.8
Cyclic 0.2% Yield (MPa / ksi)	314 / 45.5	302 / 43.8
Cyclic Strain Hardening Exponent	0.044	0.071
Cyclic Strength Coefficient (MPa / ksi)	422 / 61.2	468 / 67.9
Fatigue Strength Coefficient (MPa / ksi)	831 / 120.6	573 / 83
Fatigue Strength Exponent	-0.131	-0.097
Fatigue Ductility Coefficient	1.637	0.124
Fatigue Ductility Exponent	-1.008	-0.656
Fracture Toughness K_q (MPa√m / ksi√in)	25.6 / 23.3	21.8 / 19.9
Compressive Yield Strength (MPa / ksi)	244 / 35.4	255 / 37.0
Precision Modulus (GPa / msi)	76.4 / 11.1	74.2 / 10.8
ΔK Threshold, R=0.1(MPa√m / ksi√in)	3.75 / 3.41	4.22 / 3.84
ΔK Threshold, R=0.5 (MPa√m / ksi√in)	2.58 / 2.35	2.52 / 2.29

Mechanical Properties

A356.0-T6 has, probably, the most extensive list of recorded mechanical properties of any aluminum foundry alloy. Further, there is flexibility in the alloy system as aging times during heat treatment can be varied in order to attain different tradeoffs between strength and ductility. Figure 3 shows examples of aging curves for A356-T61 in which a wide range of properties can be obtained for a given composition simply by choosing the correct aging time. Table 6 shows a couple of examples of the capability of A356-T6 castings in the form of high integrity automotive suspension parts. Basic tensile data, cyclical properties (fatigue), compressive, and crack growth properties are also shown.

Like any other aluminum foundry alloy A356 shows sensitivity of properties to freezing rate of the casting. The normal way that this is accounted for is by means of the well-known relationship between the time to solidify, the resultant secondary dendrite arm spacing (DAS), and the ductility and tensile strength. Figure 4 shows a rather classic plot from the literature together with some example production data for the A356-T61 cast part shown in Figure 1. The percent elongation shows a very strong dependency on the DAS in this plot.

Table 7 shows mechanical properties typical of 355 alloys. Figure 5 shows the properties of alloy 354.0-T6 as a function of temperature. Note that this alloy, like all age hardened aluminum casting alloys, is sensitive to prolonged exposures to temperatures at or above the aging temperature. Hence caution is advised when designing for such temperatures as the long-term properties may be different from those quoted for short-term tests.

Table 7 - Typical Mechanical Properties of 355 Alloys

Alloy Designation and Temper	Mould	Ultimate Tensile Strength		0.2% Yield Strength		% Elongation
		MPa	ksi	MPa	ksi	% on 4D
355-T51	Sand	195	28	160	23	1.5
355-T6	Sand	240	35	170	25	3.0
355-T6	P.M.	290	42	185	27	4.0
355-T7	Sand	260	38	250	36	0.5
C355-T6	Sand	297	43	207	30	5.5
C355-T6	P.M.	356	52	228	33	14
C355-T61	P.M.	379	55	255	37	13

Heat Treatment

Heat treatments for these alloys are covered in many references, two examples of which are ASTM B917/B917M[4] and the Metals Handbook[5]. Tables exist in these works which give suggested heat treatment cycles for a wide range of alloys. The commonly used heat treatments fall into four categories: F, T4, T5, T6, and T7. The simplest of these is the foundry, or F-Temper, in which no thermal treatment is given to the part. While the simplest and cheapest, this is also the least stable and most variable condition for a casting. Never the less, many components are perfectly serviceable this way. A summary of the other main tempers follows; detailed descriptions of each are available in many handbooks and publications[6].

T4 heat treatments involve a solutionizing treatment carried out at a high temperature followed by a rapid quench to below 100° C, the purpose of which may be twofold. The first and main purpose is to take all of the hardening elements Mg and/or Cu into solution and keep them there as a super-saturated solid solution upon quenching. The second purpose is to help round off the Si phase in the microstructure. The later effect is of less import when alloys have been Sr or Na modified, as the fine fibers tend to break up and spheroidize almost immediately. Under such conditions the solutionizing times can be quite short. Unmodified alloys on the other hand may take considerable time to accomplish this effect depending, again, on the DAS, since finer structures formed at high freezing rates will change more quickly than coarse structures. As a result a wide range of solutionizing times may be called out. Thin modified permanent mould castings can frequently be fully solutionized in as little as three or four hours while very thick unmodified sand castings may take anywhere from twelve to twenty-four hours. Example micrographs showing these effects may be seen in our 357-alloy product bulletin[7]. Most modern foundries will try to minimize the length of this stage in heat treatment since it is the most expensive in terms of capital equipment and energy consumption. Much work has been done along these lines in recent years[8].

The T6 heat treatment involves artificially aging the castings from the T4 temper at temperatures sufficient to allow precipitation hardening to take place. In the case of A356, this may be done immediately (T6) or after a set period at room temperature (T61).

Elongation with Dendrite Arm Spacing (µm)

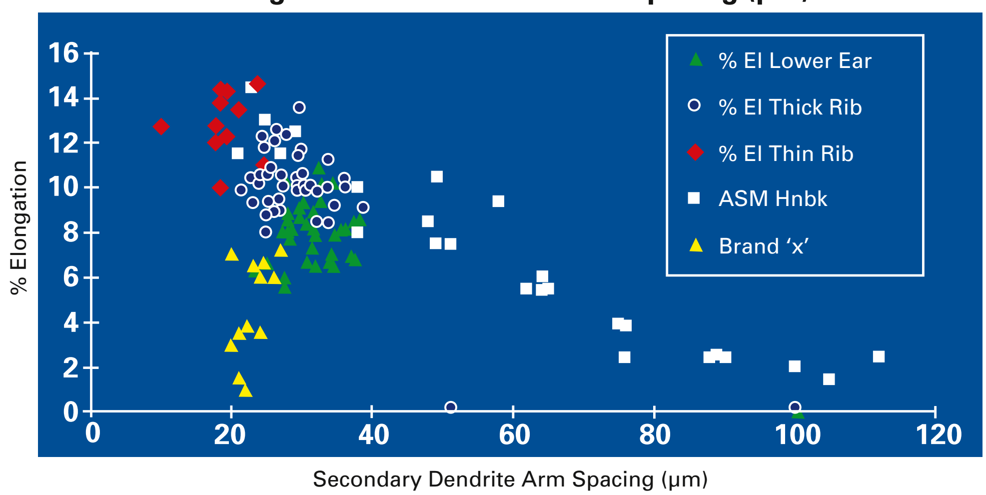


Figure 4. A plot of DAS versus percent elongation to fracture. Note that 'brand "X"' refers to a part that contained significant porosity. One of the more utilitarian uses of this plot is as a measure of alloy capability. If the percent elongation in your part at a measured DAS falls far below this curve, you know that some defect is preventing you from realizing the full potential of the alloy. The plot also graphically represents the reason that low freezing rate processes, like sand casting, frequently under perform high freezing rate processes, like permanent mould or premium sand casting with chills.

The two options will give slightly different balances between strength and ductility depending on the exact conditions. The natural aging step also allows for intermediate steps such as straightening of the castings if needed. It also tends to give the narrowest spread in properties compared to the T6, in which the castings are put into the aging oven immediately, since the castings change over the first 8 hours or so at room temperature fairly quickly but are largely stable for the next 16 or so thereafter. This effect is particularly important when trying to show tight process capability in a system where castings are manually loaded into the ovens, as variability in the room temperature aging time between quenching and aging will be reflected in variation in the properties in the case of T6. This is less serious in the case of an automated line using T6 or manually operated lines using T61. In the case of AlSiCuMg alloys, such as 354 and 355, the resistance to Stress Corrosion Cracking is strongly affected by the heat treatment parameters: underaging leads to a high sensitivity to SCC, while peak aging and overaging (T7) strongly reduce this sensitivity.

T5 heat treatments are also called stabilization heat treatments since their main purpose is to prevent the growth of the castings in service due to ongoing precipitation at warm temperatures. These consist of an artificial aging treatment on the as-cast (F-temper) part with no prior solutionizing step. As the properties achieved this way are very dependent on the initial state of the casting they can be quite variable. The factors, which can influence properties in A356-T5 or 357-T5 castings, are covered in a recent Alcan publication[9]. Use of quenching techniques upon demolding of parts in lieu of a formal solutionizing step is another way of reducing costs while obtaining properties close to that of T6. This is becoming common practice in semi-solid metal casting processes.

T7 heat treatments are also used as stabilization treatments in which the castings are intentionally over aged at higher than optimum temperatures after a full solutionizing treatment. These are commonly applied to alloys in which a tight range of mechanical properties is desired but with an intentional sacrifice in strength to achieve higher ductility.

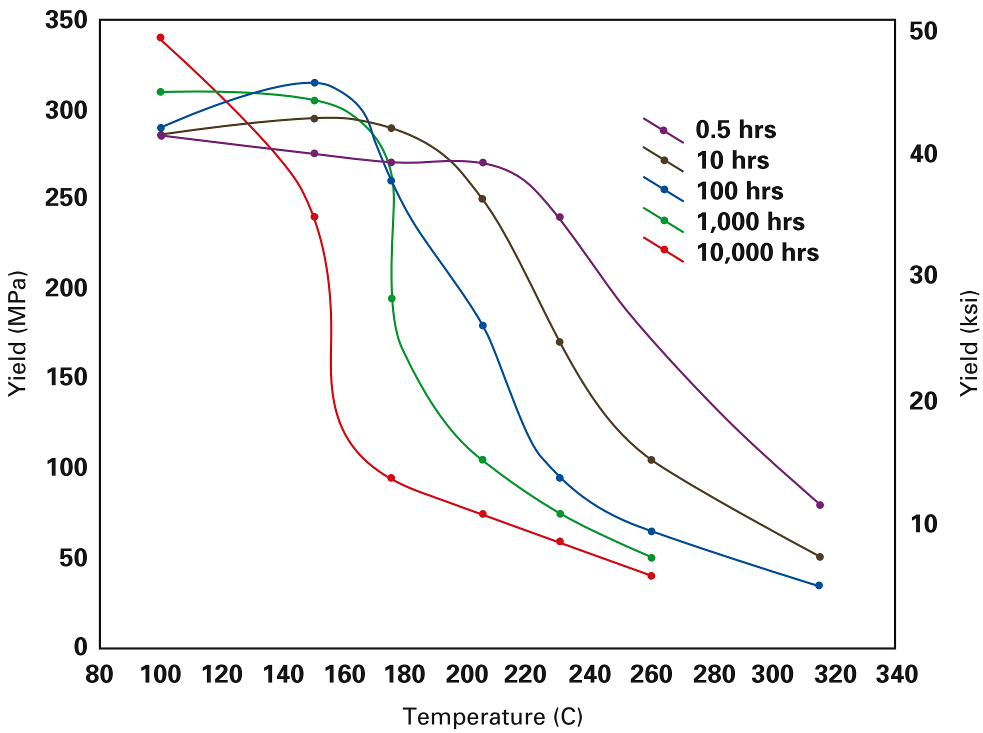


Figure 5. A plot of Yield Strength versus temperature for 354-T6 as a function of exposure time at temperature before testing at temperature.

The Alcan "Cristal" Model for Prediction of Heat Treatment Response Introduction and Scope of the Model

The mechanical properties of A356/357 alloys in the T6 temper depends on numerous factors, including the fineness of the microstructure (DAS and eutectic modification), the general quality (soundness, absence of inclusions), the chemistry of the alloy (especially its Fe and Mg contents) and the heat treatment, itself comprising a solution treatment, a quench and an aging.

The "Cristal" model addresses structural hardening: it has been developed to predict the tensile properties as a function of the Mg content and of the aging parameters (time and temperature) not only in T6 but also in T7, assuming that Mg has been fully solutionized and effectively quenched.

Physically, it is based on the accumulated diffusion distance of magnesium λ, which correlates well to the degree of hardening. When a solutionized and quenched A356/357 casting undergoes aging, Mg diffuses to combine with Si and form G.P. zones, then the β" and β' transient phases. Up to peak aging, the yield and tensile strength increase and the elongation drops as these coherent phases grow. From peak aging on, the stable Mg_2Si phase grows further and progressively becomes incoherent, so that the strength decreases. This process is time and temperature dependent, but it has been observed that both parameters can be effectively integrated into a single one: the diffusion distance of magnesium λ. Peak aging is for example always reached at the same value of λ whatever the set of time and temperature. The maximum strength is, of course, dependent on the aging temperature and this has also been integrated into the model.

Cristal can also take into account double aging, or the effect of an exposure to elevated temperature during service life.

The basis for the model is a database of tensile properties measured in an 18mm diameter permanent mold cast test piece (the French standardized AFNOR) machined to 13.8 mm. Different levels of Mg ranging from 0.20 to 0.60 were used in a base alloy containing Si 7%, Fe 0.13%, Ti 0.14% which was grain refined and Sr modified.

The AFNOR test-piece, when cast at an initial die temperature of 300°C, has a high cooling rate (solidification time about 13 s) leading to a fine DAS (about 23 µm) and the solution treatment applied for this study, 6 hours at 540°C, is sufficient in such conditions to provide both a full solutionizing of Mg up to about 0.60% and a good spheroidization of the eutectic silicon particles in a Sr modified alloy.

Consequently the measured and predicted mechanical properties are high and reflect the maximum potential of the alloy. The absolute values of Elongation and Ultimate Tensile Strength cannot be generalized to industrial castings except for their soundest and most rapidly solidified areas, but their variation is effectively described by the model.

The 0.2% Yield Strength and Brinell Hardness, on the other hand, generally show little dependency on the microstructure, so that the model predictions can be applied to most castings.

The table below indicates the allowable range of input parameters:

It addresses T4, T6, T7 and the effect of service temperatures up to 250°C for long durations.

	Minimum	**Maximum**
Mg %	0.20%	0.60%
Aging Temperature	20°C (T4)	250°C
Aging Time	0.05 hr	1000 hrs

One enters the Mg % and t & T° aging parameters in an Excel table and obtains the tensile properties as well as the Quality Index (Q = UTS+150*logE%) which is constant up to peak aging:

Mg (%)	**T (°C)**	**t (h)**
0.35	**160**	**6**

Forecasted tensile properties:

R_{p02}		**R_m**		**Q**	
221	MPa	**315**	MPa	**504**	MPa

A		**HB**
18	%	**94**

Figure 6. Example Cristal Excel spreadsheet input/output

Example Applications of the Cristal Model

There are many possible uses for a model addressing such general problems as the impact of the Mg content and aging parameters of A356/357 on the balance between strength and ductility. Three examples have been selected:

1 What is the robustness of a given A356 T6 production in terms of hardness?

Assuming nominal values of Mg = 0.35%, aging 160°C-6hrs, and maximum variations of +/-0.05% Mg in the melt, +/- 5°C and +/- 0.5 hr in the oven, the model gives the following range of properties:

	0.2%YS	UTS	E%	**BHN**
nominal	**221**	315	18	**94**
minimum	**172**	304	22	**82**
maximum	**260**	330	15	**103**

The spread in the Yield Strength as well as that of the Elongation, which will be similar in relative terms, i.e. +/- 20% of the mean value whatever it is, is relatively high, and the foundry will almost certainly want to reduce it. Playing with the 3 parameters will give a rapid indication of how the problem can best be solved within the constraints of the existing industrial equipment.

2 What is the impact of a paint baking treatment on an A356 T64 casting.

Let us consider parts in which a high elongation is required and which are consequently underaged at 150°C – 4 hrs but which have to undergo a paint baking treatment at 190°C for 15 minutes. What is the impact of that paint baking? If for some reason a part has to be painted a second time, what happens? The double aging capability of the model can be used here:

	0.2%YS	UTS	E%	BHN
After T6	169	293	23	82
Painted once	213	312	19	92
Painted twice	235	320	17	97

The impact of the paint baking treatment on the elongation is significant and must be considered. Recent paints have been introduced which can be baked at lower temperatures and will have less impact.

3 What properties remain after a long service life at elevated temperature?

Let us consider the A356 T6 part of example 1. What happens if it is exposed to 130°C for 1000 hrs, which might be typical for a suspension part close to the exhaust line?

If a shield decreases the peak temperature to 100°C, what is the effect?

After 1000 hrs at 130°C, the part has become over-aged and the alloy has lost much of its elongation. Although Cristal does not predict fatigue properties, it is well established that fatigue strength decreases in over-aged conditions.

	0.2%YS	UTS	E%	BHN
After T6	221	315	18	94
After 130°C - 1000 hrs	268	324	11	103
After 100°C - 1000 hrs	241	321	16	98

Reducing the maximum temperature even only to 100°C makes the impact on the properties far more acceptable. The casting will remain in an under-aged condition and its fatigue strength will be practically unaffected.

Double aging can also be used to predict properties after higher service temperatures – in cylinder heads for example – but values calculated for service life temperatures above 190°C tend to be conservative.

To summarize, Cristal can predict the degree of structural hardening of A356/357 alloys from T4 through T6 up to T7. The prediction is normally directly applicable to industrial castings as far as the Yield Strength and Hardness are concerned. With regard to UTS and Elongation, the model predicts optimal values based on the separately cast test-bar data used to build the database. The actual values will reflect those to be expected in industrial castings. The effect of multiple aging and exposure to elevated temperatures during service life can also be estimated.

Metallurgy of the Primary Al-Si-Mg(Cu) Alloys

The Ingredients

The major alloying elements in this alloy series are, of course, Si, Mg, and Cu. Additional alloying elements may include Ti, Ti-Borides from grain refiners, and modifying agents such as Na, or more commonly, Sr. Then there are the major impurity elements of Cu (in the case of the non-Cu containing alloys), Fe, Ca, and P. As well there are many minor impurities such as Ni, Mn, Cr, and Sb. Many of these are simple to avoid through the use of primary metal and are controlled by the smelters through proper choice of raw materials and good reduction practice.

Silicon

This element imparts high fluidity and low shrinkage, resulting in a 'foundry friendly' alloy with good castability and weldability. Silicon is present as a eutectic phase up to approximately 12.7% (the actual figure depending upon the other elements present). Greater than 12.7% Si in the binary alloy would result in primary silicon particles. The presence of the Si eutectic, with a low melting point of 577°C, provides good feeding and practically eliminates the 'hot-short' cracking common to pure aluminum and the non-Si containing foundry alloys of the 2XX, 5XX, and 7XX series. Silicon is also responsible for the relatively low thermal expansion of the alloys.

Silicon has high hardness, which is advantageous as regards to wear resistance of the alloy although it does reduce machining tool life. It also embrittles the alloys to a greater or lesser extent depending on its size and shape in the microstructure. The easy castability of these alloys hence comes at the price of an engineering compromise in properties.

Magnesium

Magnesium is the strengthening ingredient in many of these alloys. In the presence of silicon, magnesium silicide is formed. This nucleates and grows during the solidification of the casting, and is mostly seen in slowly solidified castings as coarse, black, Chinese script-like constituents. In the eutectic phase, the Al-Mg_2Si-Si melts at 555°C.

The full advantage of the magnesium is obtained when the castings are fully heat treated to the T6 temper. Strength increases with increasing magnesium content, but the ductility, or percentage elongation, decreases.

Because magnesium oxidizes at the surface of the melt, good melting and handling conditions are necessary. In addition, the magnesium content will have to be replenished. These precautions are necessary, because the products of oxidation, magnesium oxide and spinels, could cause problems with soundness, mechanical properties and machining.

Strontium

Strontium is the most commonly used Al-Si eutectic modifier in today's foundry. It is generally added as a master alloy, 10% Sr in aluminum. It is easier to handle and longer lasting than sodium, and only slightly less effective in thick sections that have a lower solidification rate. Well-modified Aluminum-Silicon alloys give castings with enhanced mechanical properties and are more easily machined than unmodified alloys.

The improvement in ductility and machining is caused by the change from the unmodified plate-like eutectic structure to a fine modified fibrous structure. A metallographic section would show the unmodified plates and needle-like structure, versus as-cast fibers or heat-treated rods and small rounded islands of the modified silicon eutectic.

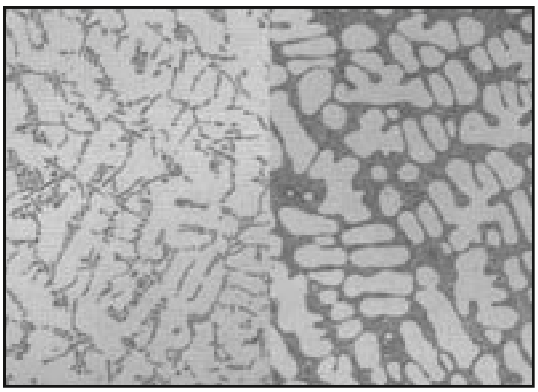


Figure 7. Modified (right) versus unmodified (left) microstructures.

The amount of modifier should be judged by the least amount necessary to provide an acceptable structure in the thickest critical sections of the castings, that is, the areas more slowly solidified. Increasing amounts of modifier have also been shown to increase the amount of micro porosity in the casting. Less is best. Over the past decade or so average levels used in volume A356 casting production have decreased from above 200ppm to levels as low as 40ppm. In addition to the savings in Sr consumption there is also a control issue in so far as Sr does burn off with time and the burn off rate decreases with decreasing Sr content making control limits easier to maintain.

Modification is a visible change in the morphology of the silicon eutectic. It can be measured metallographically or via thermal analysis. Chemistry is typically used to track modifier level by most foundries using SPC controls. This is effective so long as modifier antagonists like P or Sb are not present in significant amounts. If, because of multiple suppliers or the use of secondary (recycled) metal, these are expected to vary then metallographic tracking or thermal analysis may be the only certain way to monitor modification.

With the Alcan Al-Si-Mg/Cu series of alloys, the customer is given the choice of strontium level in premodified ingot, or the alloy can be provided modifier free for the foundry that prefers to do its own modification.

Copper

Intentionally added to the 354 and 355 alloys Cu also functions as a hardener in two ways. It contributes to precipitation hardening via the formation of copper aluminide or copper magnesium aluminide. In addition Cu will solid solution strengthen the alloy. Stable to higher temperatures than magnesium-silicide alone, these combined effects give the alloys better high temperature hardness and strength.

In its role as an impurity in the non-Cu containing alloys, Cu will reduce the corrosion resistance of the alloy somewhat and must be controlled to very low levels for products such as automotive wheels in which both general corrosion resistance and filliform corrosion resistance are important.

Iron

Fe is the major impurity in aluminum-silicon foundry alloys. It combines with the Al and Si to create extremely embrittling $FeSiAl_5$ needles. It enters the primary alloy stream to a limited extent through its presence in the alumina and silicon used to batch the alloys, as well as pickup from ferrous based materials used in the tooling or cell construction materials. A far more serious source is ferrous material entrapped with Al scrap when alloys are made from recycled materials. Alloys made via the secondary or recycled route are less expensive but at the cost of severely impaired mechanical properties, particularly the ductility. *(See again Figure 2)*

Molten aluminum is very aggressive towards ferrous alloys. Because most of the furnace cleaning tools, stirrers, skimmers and pouring ladles are made from iron or steel, there is every likelihood that a reaction will take place, resulting in an increase in iron content of the molten aluminum alloy. To reduce the pick-up, scrap should be well segregated, and all tools, ladles and the like coming in contact with the molten aluminum, should be effectively coated with a refractory wash and well maintained.

Manganese, Chromium, and Nickel

Manganese is sometimes added to high iron secondary alloys to reduce the embrittling effect of the iron needles by converting them to $(Fe,Mn)_3Si_2Al_{15}$ complex-regular script phases. However, this improvement in ductility does not restore the alloy capability to anywhere near the level of primary alloys. It also comes at a further sacrifice in machinability. Chromium is never a deliberate addition to this alloy family, but may occur through secondary ingot or through the use of non-segregated scrap. Chromium in the presence of iron and manganese can form sludge in high pressure diecasting remelt furnaces. This reduces the furnace capacity and causes hard spots in the casting, which will damage machining tools.

Nickel is also mostly a secondary alloy problem as it will return from the scrap cycle in the form of Ni containing high temperature alloys or piston alloys. It can enter primary metal via the carbonaceous materials used to make anodes in the smelters. Generally such levels are only seen in the tens of ppm though in modern smelters.

Calcium

Calcium may be associated with the alloy through pick-up from the metallic silicon (calcite stringers occur naturally therein) or from furnace cleaning salts or furnace brick. It should be controlled in the remelt ingot to a maximum of 0.002%. Though calcium is a weak silicon eutectic modifier, it has a pronounced effect on the freezing skin. High calcium melts are difficult to modify with sodium or strontium due to chemical reaction. Calcium is considered the main cause of 'orange peel' skin on castings. Levels of Ca in the tens of ppm are known to exaggerate porosity in castings. Some materials used to patch refractories, such as bone ash, are a known source of Ca contamination.

Phosphorous

Phosphorous is the main modification antagonist. The amount of Sr or Na needed to modify the Al-Si eutectic is a function of the level of this impurity. Phosphorus is present in bauxite and the salts used in the smelting process. It is also present as a contaminant in the silicon metal used for alloying. Phosphorus is part of a compound used in refractory bricks, mortars, and crucible glazes. It is very difficult to remove. In fact, doing so is uneconomical. Stress must be placed on the purity of the raw material. There is, of course, a tradeoff for this in terms of cost. A maximum of 0.001% is usually sufficient to prevent most problems. Lower levels can be obtained in which case agreement must be reached between the customer and Alcan.

Antimony

Antimony has been termed a "permanent modifier". Actually this is a misnomer since Antimony (Sb) does not modify the Al-Si eutectic in the same way that Na and Sr do. Rather than conversion to fine fibers, Sb simply refines the platelets to a much finer size reminiscent of type 2 eutectic according to the AFS rating system. It will not refine thick, slowly cooled sections however. This can result in worse properties than unmodified alloy under those conditions. It also takes >0.05% Sb to achieve this and hence is not a minor addition.

It is very seldom used in North America but is used in Europe and Japan. There are no natural sources in the primary metal system for this element. It can appear in the secondary alloy system via remelt of Sb refined scrap parts originating abroad.

Antimony reacts with the modifiers Na and Sr as well as Mg to form an intermetallic that settles out. It is thus a modification antagonist. Optical spectroscopy of this element is very difficult because its main lines overlap those of Fe; hence fictitious ghost readings are very common and foundries should be aware that just having an Sb line added to their instrument doesn't mean that you can necessarily believe the results. Alcan will not report an analysis on this element for that reason although our metal will always contain <0.01% Sb.

Titanium and Boron

These elements are associated with grain refinement of the hypoeutectic Al-Si alloys. Over the years, the understanding of the mechanisms and effects of grain refiners has gradually advanced. Unlike non-Al-Si alloys, in which grain refining helps tremendously in the control of hot tearing, the reasons for grain refining the 3XX series alloys are subtler. Grain refining helps with mass feeding, where that is a problem, by delaying the dendrite coherency point. It also helps improve the surface appearance of the parts. It has side effects as well in so far as particulates in some of the grain refiners can nucleate gas bubbles and make the metal appear gassier by lowering the threshold hydrogen content.

Elemental Ti was one of the first grain refiners used. By itself it is a weak grain refiner in alloys like A356. The active species is $TiAl_3$. This compound forms during solidification of the alloys and acts as a nucleant onto which Al subsequently forms. Unfortunately, as the Ti begins as completely dissolved in the liquid Al, the number of nuclei is low and the grain size, while improved quite a bit, is still rather large. Grain refining curves for Ti, as well as more complex grain refiners, are shown in Figure 6. The one advantage of Ti is its lack of susceptibility to settling out except when the melt gets cold enough to form large Ti-Al-Si lathes; an event generally seen only when the Ti level exceeds the peretectic point at 0.15% Ti. For A356 alloy 0.08-0.12% is recommended as a background Ti level for use with or without the addition of borides.

Alcan Prime Alloys

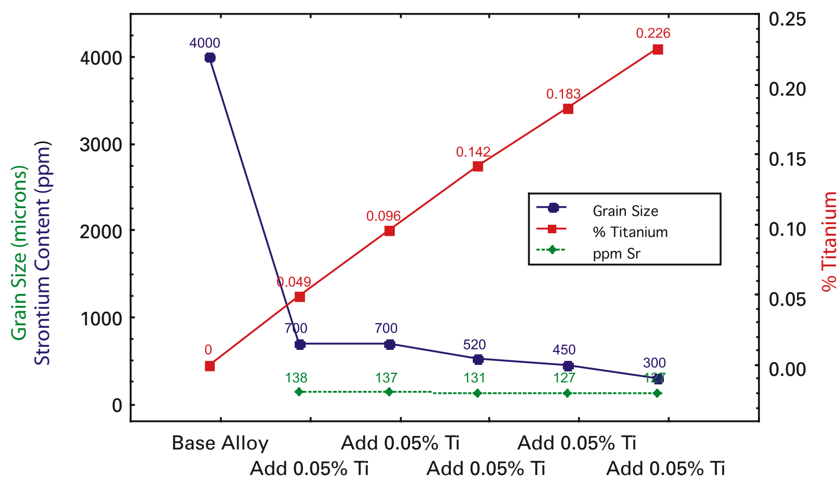
AA 354, C355 & A356 Foundry Ingot

Alcan Ingot

Product Bulletin

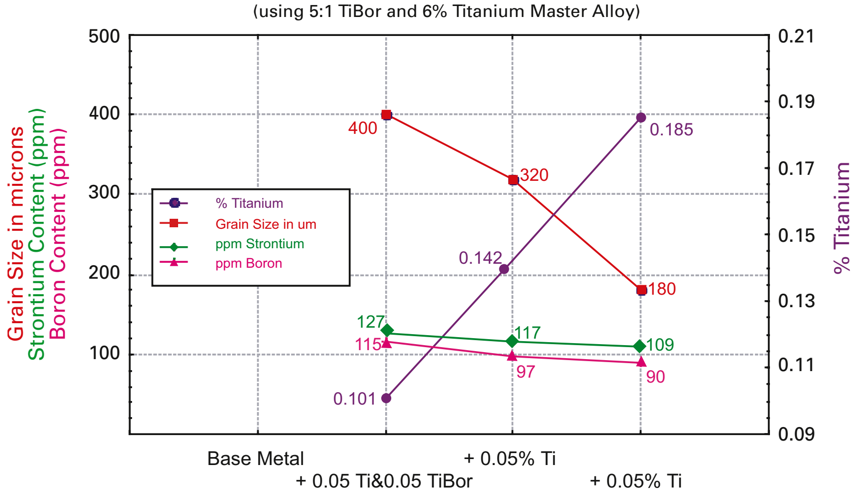
Sequential Titanium Addition from Base

(using 6% Titanium Master Alloy)



0.05% Tibor at Various Ti Levels

(using 5:1 TiBor and 6% Titanium Master Alloy)



Initially: 0.05% Ti + 0.05% Ti as 5:1 TiBor
Followed by two sequential additions of 0.05% Ti using a 6% Ti master alloy

In order to improve the grain refining of these alloys even further, particulates have been added to modern grain refiners. TiB_2 and AlB_2 are the most commonly added of these and grain refiners are frequently referred to according to the ratio of Ti to B. A 5:1 grain refiner, for example, will contain 5% Ti, 1% B, and the remainder is Al. The 5:1 and 3:1 formulations have been common for some time. Recently, 1:1 formations have also appeared on the market. These are particularly interesting as they are very effective in Al-Si alloys but not at all effective for wrought alloys. There is also some anecdotal evidence that their settling rate is lower.

The borides are insoluble in molten Al. Hence they are there even before solidification begins and serve as points for nucleation of $TiAl_3$ and hence Al. These grain refiners give much smaller grains than Ti alone. It must be kept in mind that TiB_2 in particular is denser than Al and will settle with time. The same is true of the mixture of Al and Ti borides present in the 1:1 formulations. They can also be fluxed out during cleaning operations though they are too fine to be stopped by gate filters in general. As few foundries analyze for B, the loss of these borides can be hard to detect chemically.

Accumulation of these phases as sludge in furnaces is also a possibility if they settle out. Stirred up again, some of these phases may stick together (agglomerate) and result in surface defects.

Ti is generally ordered in with the ingot. Particulate grain refiners are generally not recommended as ingot additions as due to the settling/cleaning issues. These are best added just before casting in a batch operation or together with a metal transfer in continuous operations. Should the customer need a boride addition this can be negotiated.

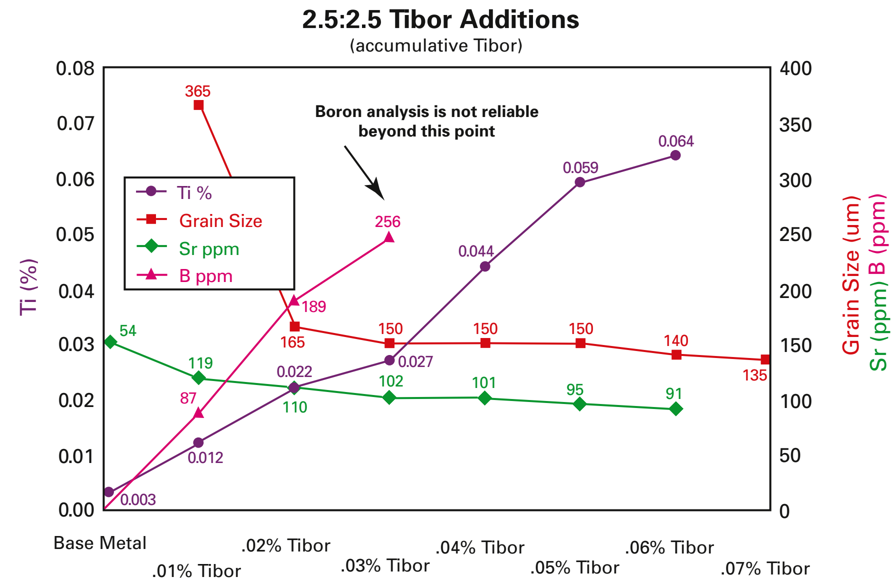


Figure 8. Grain refining action curves based on the Alcan / Aluminum Association TP-1 grain refining test apparatus. The effect of Ti alone on A356 is shown at the top, the middle graph shows the effect of A 0.05% Ti addition as 5:1 TiBor at different total Ti contents and the bottom graph shows the impact of a 1:1 ratio TiBor.

Hydrogen

The most pernicious impurity in Al, hydrogen enters the melt via the reduction of water vapor to dissolved hydrogen in the liquid, and aluminum oxide as a solid film on the surface. Water vapor from furnace combustion gases, humidity in the air, moisture in salt fluxes, incompletely dried tools, all of these sources are available in the average foundry. The pickup is relatively rapid and seldom does the final gas level in the melt have any direct relationship to the gas level in the incoming ingot.

Gas removal is possible via sparging of dry inert gas through the melt. In increasing order of efficiency, lances, porous plugs or T-Sticks, or rotary impeller degassers may be used. The manufacturers of these implements sell these with a full set of operating instructions for their most efficient use. The finer the inert gas bubbles and the more widely they are dispersed through the melt, the quicker the hydrogen level drops as the bubbles equilibrate with the hydrogen content in the melt and carry it out.

Alcan markets the AlSCAN unit; an instrument used to actually measure the amount of dissolved hydrogen. In addition, many suppliers of reduced pressure test (RPT) equipment are available on the open market. The RPT test is a cheap alternative to AlSCAN that measures porosity potential rather than a true gas level. As dirt or particulate grain refiners will nucleate gas bubbles, the RPT test essentially measures both without the ability to discriminate between them for the actual cause. As a porous or non-porous test result is all that is generally desired by foundries, this is frequently sufficient.

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[1] IACS = International Annealed Copper Standard, taken as 100%.

[2] IACS = International Annealed Copper Standard, taken as 100%.

[3] Source Reference: USCAR Report: Design and Product Optimization for Cast Light Metals (with CDROMs). This report is available through the American Foundry Society. http://www.afsinc.org/estore/srch_Detail.asp? OrderNum=RR02CD

Note that this data is for illustrative purposes and was taken from samples excised from cast parts. Alcan, USAMP-AMD/DPO, associate members, and Westmoreland Mechanical Testing and Research assume no responsibility or liability for its use. Process capability data like this is foundry specific and designers should consult with the specific foundry for appropriate design data.

[4] Available via www.astm.org

[5] ASM Metals Handbook Series, Vol. 4, "Heat Treating".

[6] Major, F. & Apelian, D., "A Microstructural Atlas of Common Commercial Al-Si-X Structural Castings", Proceedings from the AFS International Conference on Structural Aluminum Casting, 2-4, November 2003, Orlando, FL, pp. 267-285.

[7] Alcan Product Bulletin: "AA 357 Primary Foundry Alloys", available from your Alcan Ingot sales representative.

[8] Shivkumar, S., Ricci, S., and Apelian, D., "Influence of Solution Parameters and Simplified Supersaturation Treatments on Tensile Properties Of A356 Alloy, AFS Trans., 90-180, 1990, pp. 913-922.

[9] Purdon, L., & Major, J.F., "T5 Aging Response of A356/357 Hypoeutectic Al-Si Foundry Alloys Under Conditions of Varying Quench Rate from the Mould., AFS Transactions, 04-089, 2004, pp. 461-471.

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