

Chapter 3

ALUMINIUM ALLOYS IN MARINE APPLICATIONS

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3. ALUMINIUM ALLOYS

THE WROUGHT aluminium alloys (rolled and extruded) that are used in marine applications belong for the most part to two series:

- the 5000 series comprising aluminium-magnesium alloys, and
- the 6000 series which consists of aluminium-magnesium-silicon alloys.

In view of their specific aptitudes for being 'worked', most rolled semis are made from 5000 series (*Sealium*[®], 5083, 5086, 5754 etc.), while extrusions are made from 5000 series (*Sealium*[®], 5083) and 6000 series (6082, 6005A, 6061 etc.) (1).

They have been chosen for their level of mechanical properties, their ease of assembly by welding and their excellent corrosion resistance in marine environments.

The composition of wrought alloys used in marine applications is shown in table 9.

The properties of semis made from wrought alloys, including:

- their mechanical properties,
- their aptitude to cold working,
- their corrosion resistance,

depend on:

- the chemical composition of the alloy,
- the process of fabrication,
- thermal treatments which they receive during fabrication.

These properties can be significantly modified in the course of:

- cold (or hot) working,
- welding, which heats up the metal either side of the weld bead (2).

It is therefore essential to be fully aware of the influence of these operations on mechanical and other properties so as to gauge their effects and allow for them in stress calculations, for example.

This knowledge is based on fundamental notions of the metallurgy of aluminium alloys of which some of the main aspects are reviewed in the sections below (3).

(1) *Sealium*[®] is 5383 in the H116 temper.

(2) Cf. Chapter 6.

(3) For further information, refer to the brochure entitled "Aluminium semi-finished products" published Pechiney Rhenalu, 160 pages, 1997.

SEAHAWK



IN MARINE APPLICATIONS

**COMPOSITION OF THE MAIN WROUGHT ALLOYS
FOR MARINE APPLICATIONS (*)**

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Remarks (**)
5454	0,25	0,40	0,10	0,50 1,0	2,4 3,0	0,05 0,20	0,25	0,20	
5754	0,40	0,40	0,10	0,50	2,6 3,6	0,30	0,20	0,15	Mn + Cr : 0,1 - 0,6
5086	0,40	0,50	0,10	0,20 0,7	3,5 4,5	0,05 0,25	0,25	0,15	
5083	0,40	0,40	0,10	0,40 1,0	4,3 5,2	0,05 0,25	0,25	0,15	
5383 (1)	0,25	0,25	0,10	0,7 1,0	4,0 5,2	0,25	0,40	0,15	Zr ≤ 0,20
6060	0,30 0,6	0,10 0,30	0,10	0,10	0,35 0,6	0,05	0,15	0,10	
6005A	0,50 0,9	0,35	0,30	0,50	0,40 0,7	0,30	0,20	0,10	Mn + Cr : 0,12 - 0,50
6106	0,30 0,6	0,35	0,25	0,05 0,20	0,40 0,8	0,20	0,10		
6063	0,20 0,6	0,35	0,10	0,10	0,45 0,9	0,10	0,10	0,10	
6082	0,7 1,3	0,50	0,40 0,10	1,0	0,6 1,2	0,25	0,20	0,10	
6061	0,40 0,8	0,7	0,15 0,40	0,15	0,8 1,2	0,04 0,35	0,25	0,15	

(*) Taken from standard EN 573-3.

Table 9

(**) Where a single value is given, it corresponds to a permitted maximum.

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1. THE SERIES OF WROUGHT ALLOYS

There are 8 series of industrial wrought alloys, and their properties are shown in table 10.

They are divided into two categories:

- the strain hardening alloys, whose mechanical properties are determined by rolling (or extrusion) operations and by intermediate annealing (or final annealing, if any). They belong to the 1000, 3000, 5000 and 8000 series.
- the age hardening alloys whose mechanical properties are the result of the thermal processes of solution heat treatment, quenching and artificial ageing. These alloys belong to the 2000, 6000 and 7000 series.

Despite having high mechanical properties, alloys in the 2000 series with copper and 7000 series with zinc (with or without copper) cannot be used in marine applications without any special protection because of their inadequate corrosion resistance.

The 7000 series alloys without copper can be arc welded. However the high sensitivity of the heat affected zone to exfoliating corrosion demands very strict precautions for marine applications such as shipbuilding (4).

2. DESIGNATION OF WROUGHT ALUMINIUM ALLOYS

The 4-digit numerical designation of wrought aluminium alloys has acquired universal usage since 1970. New designations for these alloys were standardised by the CEN (5) in 1994.

According to standard EN 573-1 (6)(7), the first digit of the designation denotes the series of the alloy, as shown in table 10. The last 3 digits have no particular significance.

In fact the designation of a semi-finished product made from an aluminium alloy is in two parts :

- the first part – 4 consecutive digits – denotes the series to which it belongs, hence the dominant alloying element,
- the second – 1 letter (H or T) followed by one or more digits – indicates its temper (tables 12 to 15 pp. 38-39 & table 18 p. 41). Each temper represents a level of mechanical properties that are guaranteed by the standards (Appendix 1).

(4) Cf. Chapter 10, section 5.

(5) CEN: European Committee for Standardisation.

(6) EN 573-1. Aluminium and aluminium alloys. Part 1: System of numerical designation.

(7) Strictly speaking, standard EN 573-1 provides for an "alphanumerical" designation in two parts, each preceded by EN AW (aluminium wrought): the first numerical part with 4 digits, and the second part based on chemical symbols (as in the ISO designation), given in []. With this system therefore 3003 alloy would be written as "EN AW-3003 [EN AW-Al Mn1 Cu]."

SERIES OF ALUMINIUM ALLOYS

Method of Hardening	Series	Alloying Element	Content (% by weight)	Possible Additives	Ultimate Tensile Strength UTS (in MPa)
Strain hardening	1000	None		Cu	50 - 150
	3000	Manganese	0,5 to 1,5	Mg, Cu	100 - 260
	5000	Magnesium	0,5 to 5	Mn, Cr	100 - 400
	8000	Iron and Silicon	Si : 0,30 to 1 Fe : 0,6 to 2		130 - 190
Age hardening	6000	Magnesium and Silicon	Mg : 0,5 to 1,5 Si : 0,5 to 1,5	Cu, Cr	150 - 310
	2000	Copper	2 à 6	Si, Mg	300 - 450
	7000	Zinc and Magnesium	Zn : 5 à 7 Mg : 1 à 2	Cu	Without copper : 320 - 350 With copper : 430 - 600
	4000	Silicon	0,8 to 1,7		150 - 400

Table 10

3. STRAIN HARDENING ALLOYS

These alloys belong to the 1000, 3000, 5000 and 8000 series (8). They are manufactured by a sequence of hot, then cold, forming operations (rolling for sheets) combined with intermediate and/or final annealing.

The effect of strain hardening is to modify the structure of the material by plastic deformation. It takes place when a semi-product is manufactured, during rolling, drawing or wire drawing, as well as during the processing of semis in the workshop during shape forming or bending, for example.

Strain hardening is accompanied by an increase in mechanical strength and hardness and a loss of ductility, i.e. a decrease in the material's ability to deform. The greater the amount of forming or the higher the rate of strain hardening, the greater will be these effects.

The level of mechanical properties that can be achieved by strain hardening depends on the composition of the alloy. The 5083 alloy for example which contains between 4 and 4.9% of magnesium acquires a greater hardness but a more limited capacity for deformation than the 5754 alloy which only contains between 2.6 and 3.6% of magnesium.

However the gradual rise in strength always reaches a limit beyond which further strain becomes difficult and even impossible. Heat treatment by annealing is therefore needed to "soften" the metal, if working is to be continued.

3.1 Softening by annealing

The ability of the wrought metal to 'work' (deform) can be recovered by a form of thermal treatment known as "annealing".

During this treatment, which is carried out at a temperature above 300°C, the hardness and mechanical properties of the metal start by slowly decreasing - this is recovery annealing according to line A-B in figure 19. They then fall more rapidly, a process known as recrystallisation (curve B-C), and finally reach a minimum value corresponding to the mechanical properties of the annealed metal (line C-D).

These processes of recovery annealing and recrystallisation are accompanied by a modification in the texture and size of the "grains" in the metal. During recrystallisation therefore, reorganisation takes place according to a new grain structure.

It is worth noting that, for the same tensile strength, ductility is greater in the recovery annealed metal (H2X) than in the strain hardened metal (H1X). The recovery

annealed state will therefore be preferred when maximum formability is required.

There are a number of requirements for obtaining an annealed metal with a fine grain:

- The metal must have received a sufficient rate of working, corresponding to a relative reduction in section of at least 15%. If this requirement is not met, then the metal must undergo recovery annealing only (i.e. recrystallisation annealing must be avoided),
- The rate of temperature rise must be rapid, from 20 to 60°C per hour,
- Excessive temperatures, above 350 to 400°C, and excessive temperature holding times, i.e. not more than 2 hours, must be avoided.

(8) Strictly speaking, all metals and alloys strain harden, but in the metallurgy of aluminium the term 'strain hardening' is restricted to the alloys belonging to series that cannot age harden.

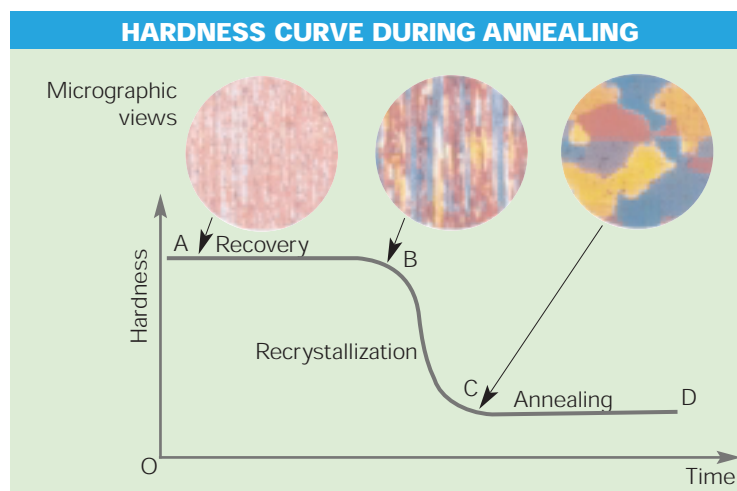


Figure 19

ANNEALING CONDITIONS

Alloy	Recovery Annealing		Recrystallisation Annealing	
	Temperature (°C)	Time in hours	Temperature (°C)	Time in hours
5XXX	240 - 280	1 - 4	330 - 380	0,5 - 2
6060	240 - 280	1 - 4	330 - 380	0,5 - 2
6005A	250 - 280	1 - 4	330 - 380	0,5 - 2
6106	240 - 280	1 - 4	330 - 380	0,5 - 2
6082	250 - 280	1 - 4	330 - 380	0,5 - 2
6061	250 - 280	1 - 4	330 - 380	0,5 - 2

Table 11

3.2 | Tempers

The strain hardening aluminium alloys are available in three basic tempers (table 12) as defined by standard EN 515 (9) :

Most classical H tempers are designated by two digits whose meaning is explained in tables 13 and 14:

- the first denotes the basic temper,
- the second indicates the degree of work hardening.

Some tempers are designated by three digits, e.g. H111 and H116 (table 15):

All of these tempers imply minimum mechanical properties as laid down by EN standards, extracts of which are given in Appendix 1.

Strain hardening alloys and the most common tempers used in marine applications are indicated in table 19.

Notes: Under the new standard ASTM B 928 04 (11) relating to semis intended for marine applications and made from 5059, 5083, 5383 and 5456 alloys in the H116 and H321 tempers and semis in 5086 in the H116 temper, these materials must pass the tests of sensitivity to exfoliating corrosion

according to the ASSET ASTM G66 test (12) and intercrystalline corrosion according to the ASTM G67 test (13).

Sealium[®] therefore undergoes these tests.

STRAIN HARDENING ALLOYS BASIC TEMPERS (ACCORDING TO STANDARD EN 515)

Temper	Définition
F	hot rolled temper, with no guarantee of mechanical properties
O	annealed temper, with maximum forming capacity
H	strain (or work) hardened

Table 12

MEANING OF THE FIRST DIGIT OF HXX TEMPERS

PFirst Digit HXX	Basic Temper
1	Work hardened only
2	Work hardened and recovered
3	Work hardened and stabilised (*)

(*) Temper stabilised by low temperature heat treatment (or by heat applied during working. This temper affects mainly the 5000 series alloys.

Table 13

(9) EN 515 Aluminium and aluminium alloys – Wrought products – Designation of tempers.

(10) Cf. Chapter 10, page 162.

(11) B 928 - 04: Standard Specification for High Magnesium Aluminum Alloy Sheet and Plate for Marine Service, February 2004

(12) and with a rating better than "Pb",

(13) Cf. Chapter 10

HXXX TEMPERS (ACCORDING TO STANDARD EN 515)

Temper	Characteristics
H111	This temper differs from the O temper in that semis delivered in this temper are roller levelled after annealing to improve their dimensional characteristics such as flatness.
H112	This temper relates to semis whose level of mechanical properties is acquired by hot working or a limited amount of cold working.
H116	This temper denotes semi-finished products in the 5000 series containing 4 % or more of magnesium (5083, 5086 etc.). In this temper, the semis must present a defined resistance to exfoliating corrosion in the ASTM G66 test (ASSET test) (10).
HXX4	This temper is used for "tread plate" engraved from the appropriate HXX temper.

Table 15

4. AGE HARDENING ALLOYS

These alloys belong to the 2000, 6000 and 7000 series.

4.1 Principle of age hardening

The maximum mechanical properties of these alloys are obtained by heat treatment in 3 stages (figure 20):

■ Solution heat treatment is carried out at high temperature, in the region of 530°C for 6000 series alloys. While the metal is held at temperature, the alloy's constituents which are in the form of dispersed intermetallics are dissolved to form a homogeneous solid solution;

■ Quenching is a process of rapid cooling normally obtained by rapidly plunging the metal in cold water when it leaves the furnace. Shapes can be "press quenched" by passing from the exit of the die into a tunnel where they are sprayed with fine droplets of water (14);

■ Natural ageing or artificial ageing. The quenched metal is in a

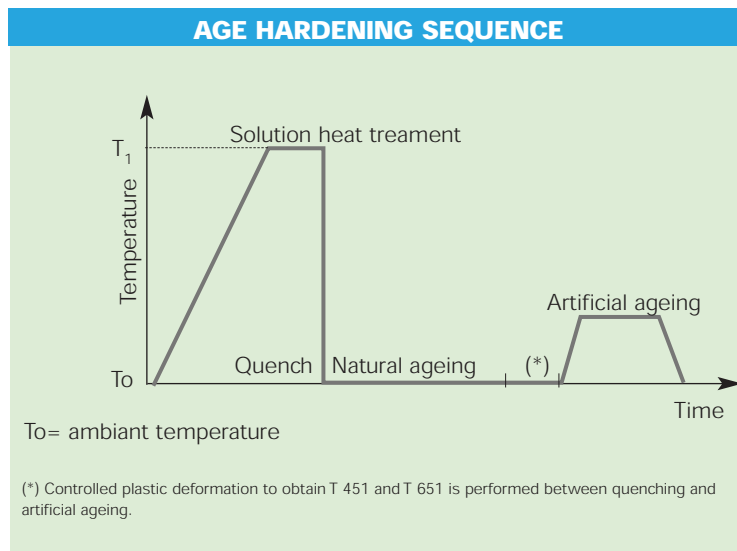


Figure 20

MEANING OF THE SECOND DIGIT OF HXX TEMPERS

Second Digit HXX	Meaning	Degree of Work Hardening (%)
2	Quarter hard	≈ 12
4	Half hard	≈ 25
6	Three-quarter hard	≈ 50
8	Fully hard	≈ 75

Table 14

metastable state, which means that its structure evolves (15) over time culminating in a stable reorganisation in which the alloying elements are rejected from the solid solution in the form of very fine, dispersed precipitates. This precipitation increases the hardness of the metal.

(14) This is common practice with a number of extrusion alloys in the 6000 series (6060, 6005A, 6106) which are "press quenched" by cooling in forced air or water spray. They are designated by tempers T1 (press quenched and naturally aged) and T5 (press quenched and artificially aged).

(15) Quite rapidly, in a few hours for certain alloys.

RECOMMENDED ALLOYS FOR MARINE APPLICATIONS (ACCORDING TO EN 13195-1)

Alloy	Sheet and Strip	Extrusions		
		Bar	Tube	Shapes
5754	O/H111 H112 H32, H34, H36	O/H111	O/H111	H112
5454	O/H111 H112 H32, H34	O/H111 H112	O/ H111 H112	H112
5086	O/H111 H112, H116 (a) H32 (a), H34 (a)	O/ H111 H112	O/ H111 H112	H112
5083 and 5383 (17)	O/H111 H112, H116 (a) H32 (a), H34 (a)	O/H111 H112	O/H111 H112	H112
6082	O (b) T4, T451 T6, T651	O/H111 (b) T4 (c) T6 (c)	O/H111 (b) T4 (c), T5 T6 (c)	O/H111 (b) T4 (c) T6 (c)
6106			T6 (c)	
6005A	T6 (c)	T6 (c)	T4 (c) T6 (c)	

Table 19

(a) The 5083, 5383 and 5086 alloys made in the H116 temper as sheet, strip and plate must be tested evaluate their resistance to intergranular and exfoliating corrosion (cf. Chapter 10).

(b) This temper is not intended for any final use. The thermal treatment is applied after forming.

(c) The mechanical properties can be obtained by press quenching.

MECHANICAL PROPERTIES FOR SHEET AND STRIP (*)

Alloy	Thickness (mm)	Temper	Rm (MPa)		Rp _{0,2} (MPa)	A % (**)	
			min	max	min	A ₅₀	A
5754	3 ≤ t ≤ 50	O/H111	190	240	80	18	17
		H24	240		165	10	8
5086	3 ≤ t ≤ 50	O/H111	240	310	100	17	16
	3 ≤ t ≤ 12,5	H112	250		125	8	
	12,5 ≤ t ≤ 50	H112	240		105		
	3 ≤ t ≤ 50	H116	275		195	10	9
	3 ≤ t ≤ 50	H32 and H321	275	335	185	10	9
	3 ≤ t ≤ 50	H34	300		235	9	8
5083	3 ≤ t ≤ 50	H32 and H321	305	380	215	10	9
	3 ≤ t ≤ 50	O and H111	275	350	125	16	15
	3 ≤ t ≤ 50	H112	275		125	12	10
	3 ≤ t ≤ 50	H116	305		215	12	10
5383 (19)	3 ≤ t ≤ 50	O/H111	290		145		17
	3 ≤ t ≤ 50	H116 or H321	305		220		10

Table 20

(*) Taken from Table 4 of standard EN 13195-1.

(**) When they are available, values of A_{50mm} must be applied up to (and including) 12.5 mm thick and values of A above 12.5 mm thick.

CONDITIONS FOR SOLUTION HEAT TREATMENT, QUENCHING AND ARTIFICIAL AGEING

Alloy	Temper	Solution Heat Treatment Temperature (°C) (1)	Quench Medium	Artificial Ageing		Natural ageing minimum (days)
				Temperature (°C)	Time (hours)	
6060	T4	530 ± 5	Forced air (3) or water			8
	T6	530 ± 5	Forced air or water	175 ± 5 or 185 ± 5	8 6	
6005A	T4	530 ± 5	Water ≤ 40 °C (3)		8	
	T6	530 ± 5	Water ≤ 40 °C	175 ± 5 (2) or 185 ± 5	8 6	
6082	T4	530 ± 5	Water ≤ 40 °C (3)			8
	T6	530 ± 5	Water ≤ 40 °C (3)	165 ± 5 (2) or 175 ± 5	16 8	
6061	T4	530 ± 5	Water ≤ 40 °C			8
	T6	530 ± 5	Water ≤ 40 °C	175 ± 5 (2) or 185 ± 5	8	6

(1) The holding time is shown in table 17.

Table 16

(2) This treatment produces the optimum mechanical properties associated with the highest values of A %.

(3) because these alloys have a very low critical rate of quench, thin semis can be quenched in forced air.

This phenomenon is known as age hardening. It can take place at ambient temperature, in which case it is referred to as natural ageing. With some alloys, like those of the 6000 series, the process can be accelerated by holding the metal at higher temperatures (150 to 190°C), increasing its hardness as a result. This thermal treatment is performed in a furnace and is known as artificial ageing.

These thermal treatments must be carried out under rigorous conditions of temperature, time and quench rate, otherwise the final mechanical properties of the metal and its corrosion resistance may be affected.

Table 16 and Table 17 list the heat treatment conditions and the solution treatment times respectively for the main alloys of the 6000 series used in marine applications

SOLUTION TREATMENT TIMES

Thickness or Diameter (mm)	Minimum holding time at temperature in air furnace (minutes) (*)
≤ 0,5	20
0,5 - 0,8	25
0,8 - 1,6	30
1,6 - 2,3	35
2,3 - 3,0	40
3,0 - 6,25	50
6,25 - 12,0	60
12,0 - 25,0	90
25,0 - 37,5	120
37,5 - 50	150

(*) This is the minimum holding time at temperature (according to standard AMS STD-2772).

Table 17

4.2 Softening by annealing

When forming semis made from 6000 series alloys, it may be necessary to perform intermediate annealing to restore their plastic-

ity. The temperatures and holding times depend on the alloy, and are given in table 11, p.38.

After annealing, the rate of cooling must be controlled to prevent a quenching effect.

5. THE PRINCIPAL ALLOYS FOR MARINE APPLICATIONS

Most yards that build ships and equipment for coastal and off-shore installations use the alloy semis as recommended by standard EN 13195-1 (16) from which table 19 is taken.

5.1 Guaranteed mechanical properties at ambient temperature

In Appendix 1 the reader will find the mechanical properties guaranteed by standards EN 485-2 and EN 1386 for tread plate (18).

Where semis are controlled by a classification society, standard EN 13195-1 specifies the minimum mechanical properties shown in table 20 and table 21 for rolled and extruded semis respectively.

5.2 Mechanical properties at low temperatures

Aluminium alloys, particularly those that belong to the 5000 and 6000 series, can be exposed to low temperatures without suffering any structural alteration (20).

This property accounts for the growth in the cryogenic uses of aluminium, e.g. tanks in methane carriers (20), exchangers in natural gas liquefaction and regasification plants, etc.

Aluminium has also been used in the construction of a number of polar and circumpolar exploration vessels.

The change in the mechanical properties of 5083 O between -196°C and $+200^{\circ}\text{C}$ are listed in table 22 by way of example. It will be noted that the capacity for elastic deformation does not diminish at cryogenic temperatures (figure 21).

Prolonged holding at low temperatures does not modify the mechanical properties following the return to ambient temperature.

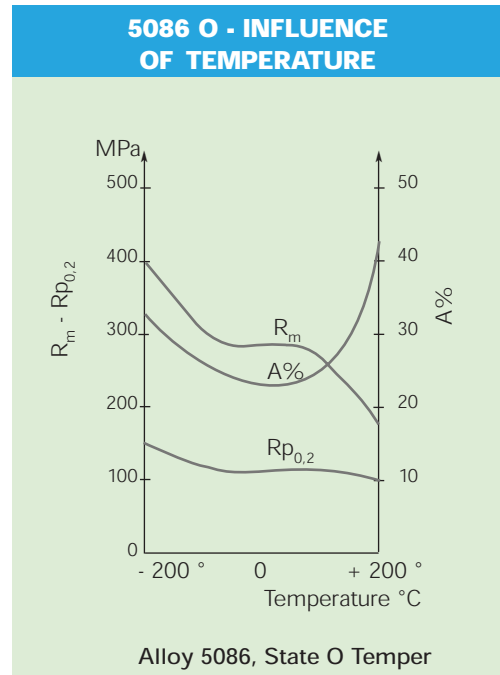


Figure 21

ALUMINIUM WATERJET LJ114E



(16) EN 13195-1: Aluminium and aluminium alloys: Wrought products and castings for marine applications (shipbuilding, maritime and offshore), December 2002, table 1.

(17) Sealium® is always 5383 temper H116 for rolled and temper H112 (capable H116) for extruded.

(18) EN 1386. Aluminium and aluminium alloys – Tread plate – Specifications.

(19) Sealium® is always temper H116.

(20) Unlike steels, aluminium alloys have no "transition point," a temperature below which they may sustain a fragile rupture.

4.3 Designation of tempers

The tempers of age hardening alloys are all designated by the letter T followed by 1 to 5 digits, a full description of which will be found in standard EN 515 (table 18).

Age hardening alloys and the most common tempers used in marine applications are indicated in table 19.

PRINCIPAL TEMPERS OF AGE HARDENING ALLOYS		
Notes	Meaning	Notes
T1	T1 Cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition.	<i>This designation applies to products that undergo no cold working after the cooling process that follows hot working, or in which the effects of cold working associated with flattening or straightening do not alter the limits of mechanical properties.</i>
T3	T3 Solution heat treated, cold worked and naturally aged to a substantially stable condition.	<i>This designation is used for products which, after solution heat treatment, undergo cold working to improve their strength, or in which the effects of cold working associated with flattening or straightening alters the limits of mechanical properties.</i>
T4	Solution heat treated and naturally aged to a substantially stable condition.	<i>This designation applies to products that undergo no cold working after solution heat treatment, or in which the effects of cold working associated with flattening or straightening do not alter the limits of mechanical properties.</i>
T5	T5 Cooled from an elevated temperature shaping process then artificially aged.	<i>This designation applies to products that undergo no cold working after the cooling process that follows hot working, or in which the effects of cold working associated with flattening or straightening do not alter the limits of mechanical properties.</i>
T6	Solution heat treated then artificially aged.	<i>This designation applies to products that undergo no cold working after solution heat treatment, or in which the effects of cold working associated with flattening or straightening do not alter the limits of mechanical properties.</i>
T451 T651	Metal in T4 or T6 temper which, after quenching, undergoes controlled stretching to relieve internal stresses.	<i>This designation is used for sheet, plate, rolled or cold-finished bar, hand or ring forging and rolled ring which, after solution heat treatment or after cooling following hot working, are stretched by the amount indicated:</i> <ul style="list-style-type: none"> ■ plate: 1.5% to 3 % permanent set ■ sheet: 0.5% to 3 % permanent set <i>These products receive no further straightening after stretching.</i>

Table 18

**MECHANICAL PROPERTIES
OF EXTRUDED SEMIS (*)**

Alloy	Form	Thickness (mm)	Temper	R _m	Rp _{0,2} (MPa)	A % (**)	
				min	min	A ₅₀	A
5086	Shapes, bar, tube	3 ≤ t ≤ 50	H112	240	95	10	12
5083	Shapes, bar, tube	3 ≤ t ≤ 50	H111	270	110	10	12
	Shapes, bar, tube	3 ≤ t ≤ 50	O and H112	270	125	10	12
6060	Shapes, bar, tube	3 ≤ t ≤ 25	T5	190	150	12	12
	Shapes, bar, tube	3 ≤ t ≤ 25	T6	190	150	12	12
6061	Shapes, bar, tube	3 ≤ t ≤ 50	T5 or T6	260	240	10	8
	Profilés fermés	3 ≤ t ≤ 50	T5 or T6	245	205		4
6005A	Shapes, bar, tube	3 ≤ t ≤ 25	T5 or T6	260	215	8	6
	Closed shapes	3 ≤ t ≤ 25	T5 or T6	250	215		5
6082	Shapes, bar, tube	3 ≤ t ≤ 25	T5 or T6	310	260	10	8
	Closed shapes	3 ≤ t ≤ 25	T5 or T6	290	240		5
6106	Shapes, bar, tube	3 ≤ t ≤ 25	T6	240	195		

(*) Taken from Table 4 of standard EN 13195-1.

Table 21

(**) When they are available, values of A_{50mm} must be applied up to (and including) 12.5 mm thick and values of A above 12.5 mm thick.

**5083 O CHANGE
IN MECHANICAL PROPERTIES (*)**

Temperature °C (**)	R _m (MPa)	Rp _{0,2} (MPa)	A %
- 196	390	140	34
- 80	280	120	26
- 28	270	120	24
+ 20	270	120	22
+ 100	270	120	26
+ 150	210	110	35
+ 200	155	105	45

(*) After 10,000 hours holding at temperature.

Table 22

(**) Holding and measurement temperature.

**MECHANICAL PROPERTIES AT TEMPERATURE (*)
AFTER HOLDING FOR 10,000 HOURS**

Alloy	Temper	20 °C			100 °C			150 °C			204 °C		
		R _m	Rp _{0,2}	A %	R _m	Rp _{0,2}	A %	R _m	Rp _{0,2}	A %	R _m	Rp _{0,2}	A %
5086	O	262	117	30	262	117	36	200	110	50	152	103	60
5083	O	290	145	25	275	145	36	215	130	50	150	115	60
6082	T6	315	280	12	300	265	14	240	220	17	130	105	28
6061	T6	310	276	17	290	262	18	234	214	20	131	103	28

(*) They are measured at the temperature indicated.

Table 23

5.3 Mechanical properties at temperatures above 100 °C

The mechanical properties of aluminium alloys at temperatures over 100°C depend on the level of the temperature and the holding time as shown in figure 22 for the 6061.

ultimate elongation A% increases. The change in the mechanical properties of alloys 5083, 5086, 6082 and 6061 are given in table 23.

Hot working these alloys therefore leads to a significant drop in mechanical properties, especially among 6000 series alloys in the T5 or T6 temper.

6. A NEW ALLOY: SEALIUM®, "MARINE GRADE"

Because of the presence of the heat affected zone, a welded aluminium alloy structure is designed on the basis of the proof stress s_0 in the annealed condition (O or H111) for strain hardened alloys.

Accordingly, the increase in proof stress in the heat affected zone means that for a welded structure we can either increase unit stresses for the same thickness of parent metal, or reduce the thickness for the same stress.

A welded joint consists of a weld bead and the heat affected zone on either side of it, which is itself connected to the parent metal (figure 23).

The increase in the mechanical properties of the welded joint depend on that of each of the joint's components: the parent metal, the heat affected zone (HAZ) and the weld bead, as well as on their metallurgical structure.

Research has shown that the best results are obtained with a parent metal that has a fibrous structure and a recrystallised weld bead with fine grains [1] (figure 24).

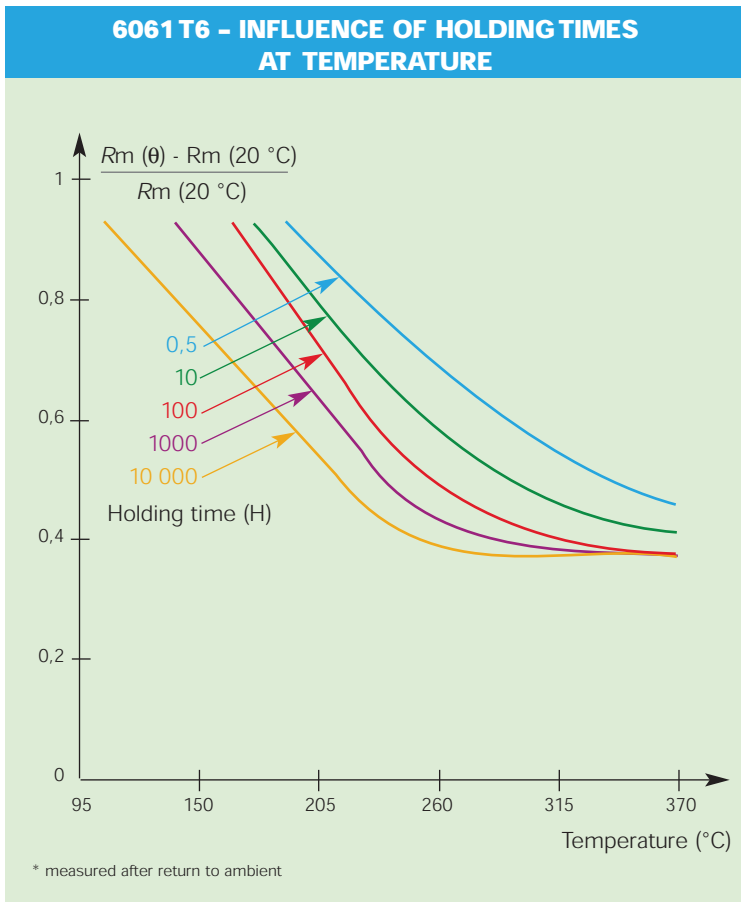


Figure 22

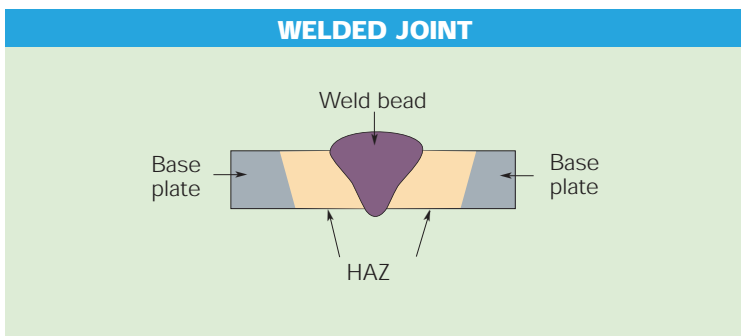


Figure 23



OPUS 45

To achieve this, it is necessary to control a number of more or less interdependent factors that produce a more homogeneous bond between the parent metal, the HAZ and the weld bead:

- the composition of the alloy: the principal effect of a controlled increase in the content of magnesium, zinc and manganese is to raise the level of mechanical properties of the parent metal,

- the metallurgical structure of each of the constituents: the addition of zirconium promotes the grain flow of the parent metal, and a fine grain in the weld bead helps to improve the level of mechanical properties,

- the working conditions, optimised to obtain the H116 temper.

Research by the Alcan Research Center (CRV) has led to the development of *Sealium*[®] (Marine Grade) which is 5383 still in the H116 temper. It meets the demands of constructors looking for high-performance alloys.

This new alloy, which is registered by the Aluminium Association under the designation AA5383, has been approved by most of the classification societies:

- American Bureau of Shipping ABS,
- Bureau Veritas BV,
- Det Norske Veritas DNV,
- Germanischer Lloyd GL,
- Lloyd's Register of Shipping LR,
- Nippon Kaiji Kyokai NKK
- Registro Italiano Navale RINA.

6.1 Mechanical properties

Publications about these new alloys report the following results:

- on parent metal as sheet (table 24),
- on welded metal (table 25).
- on extruded shape (table 26)

Comparative tests have been carried out on 6 mm thick sheet in 5083 and in *Sealium*[®], butt welded with 5183 filler [2].

The mean mechanical properties (five measurements) according to the DNV report (figure 25) are given in table 25.

These results show that on the welded *Sealium*[®], and in the direction square to the weld, the gain in ultimate tensile is 12 MPa and in proof stress 15 MPa compared with the 5083, or 4 % UTS and 11 % proof stress. In the heat affected zone the gains are 20.5 and 11.6 % respectively.

STRUCTURE OF WELDED JOINT ON SEALIUM[®]

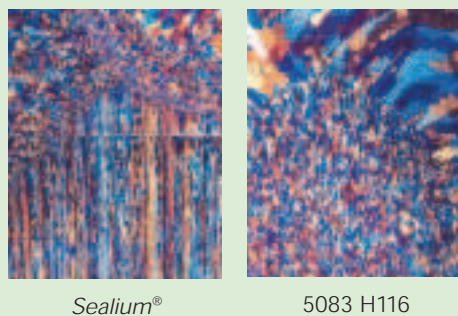


Figure 24

MECHANICAL CHARACTERISTICS ON WELD

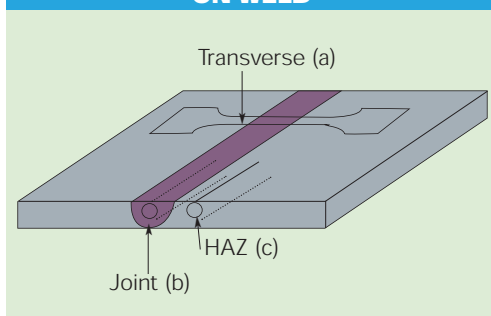


Figure 25

MINIMUM MECHANICAL PROPERTIES OF THE PARENT METAL (*) SHEETS

Alloy	Temper	Rm (MPa)	Rp _{0.2} (MPa)	A %
<i>Sealium</i> [®]	(**)	305	220	10
5083	O	275	125	10
	H116	305	215	10

(*) Thickness < 20 mm. (**) *Sealium*[®] is always temper H116.

Table 24

MEAN MECHANICAL PROPERTIES ON WELDED METAL [1] SHEETS

Parent Metal	Square to the weld (a)			In the weld seam (b)			In the heat affected zone (c)		
	Rp _{0.2} (MPa)	Rm (MPa)	A %	Rp _{0.2} (MPa)	Rm (MPa)	A %	Rp _{0.2} (MPa)	Rm (MPa)	A %
5083 H116	134	287	12,8	128	271	22,0	141	301	25,2
<i>Sealium</i> [®]	149	299	10,2	141	279	21,8	170	336	21,3
Gain in % (*)	11,2	4,2					20,5	11,6	

(*) compared with 5083.

Table 25

MINIMUM MECHANICAL PROPERTIES ON EXTRUSIONS				
Alloy	Temper	R _m (MPa)	R _{p0,2} (MPa)	A %
Sealium®	H112	310	190	12
5083	O	270	110	14
	H112	270	125	12

Table 26

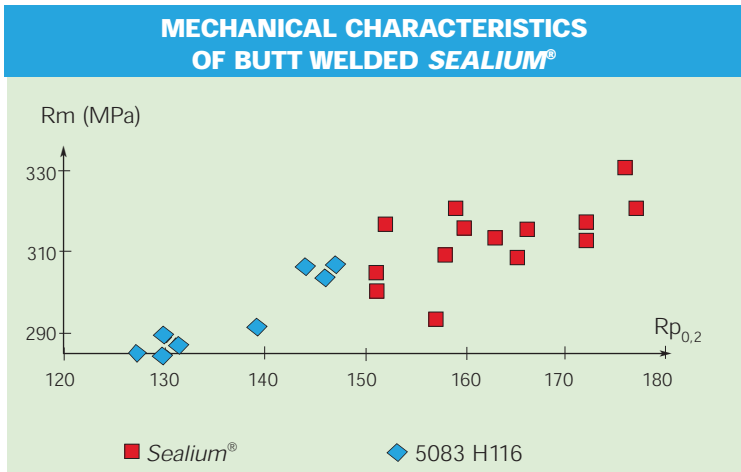


Figure 26

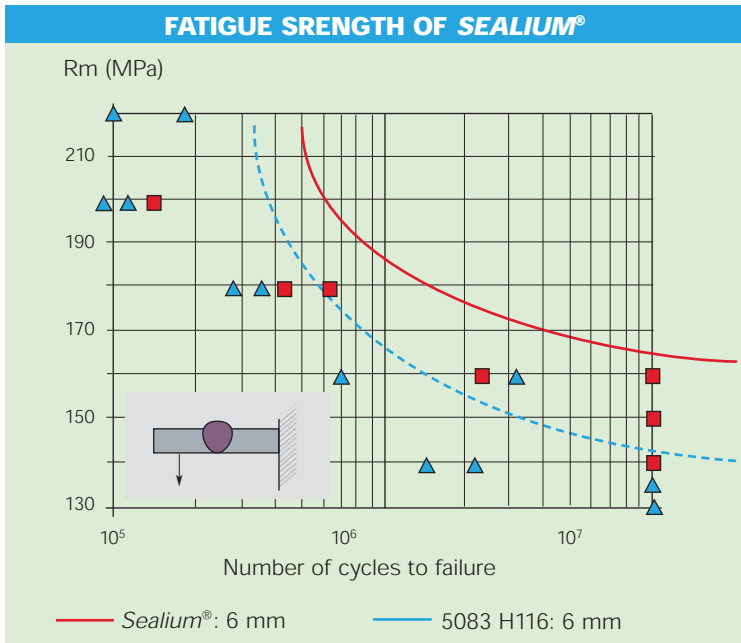


Figure 27

	RESISTANCE TO CORROSION OF SEALIUM®			
	Exfoliating Corrosion ASSET ASTM G66 Test		Intercrystalline Corrosion Test ASTM G67 NAMLT	
	Sealium®	5083	Sealium®	5083
Parent metal	N/PA	PA/PB	4,3 mg.cm ⁻²	3,8 mg.cm ⁻²
Heat affected zone	PA	PB		

Table 27

Generally speaking, tests across the weld seam, according to the DNV recommendations, show that the yield strength R_{p0,2} of Sealium® (see note (17) page 43) is always higher than that of 5083 H116 (figure 26).

These results have been corroborated by measurements carried out on welded sheet (using 5183 as filler) by a number of shipyards.

6.2 | Fatigue strength

Tests have shown that the fatigue limit of butt welded Sealium® is approximately 20 MPa higher than that of 5083, all other things being equal (figure 27).

6.3 | Corrosion resistance

Corrosion tests performed according to the specifications of standard ASTM B928 on over 50 lots of Sealium® manufactured by Alcan's Isoire plant have shown that its corrosion resistance is at least equivalent to if not better than that of 5083 (table 27).

To pass, a lot must be classified N, PA and PB in the ASSET test and the loss of weight in the NAMLT must be less than 15 mg.cm⁻² (21).

(21) Cf. Section 11 of Chapter 10.

7. THE SERIES OF CASTING ALLOYS

There are 5 series of industrial casting alloys (table 28). Like the wrought alloys, casting alloys have a 5 digit numerical designation according to standard EN 1706 (22). Their tempers are shown in table 29.

The potential offered by casting processes - especially for the creation of relatively complex shapes - makes it possible to use aluminium casting alloys in numerous marine applications. These include:

- ships' superstructures,
- structural components,
- assembly nodes,
- components for assemblies with mechanical functions,
- interior fitments,
- various supports.

The alloys used for these marine applications are first melt alloys, and belong almost exclusively to two series:

- the 40000 series comprising aluminium-silicon alloys, and
- the 50000 series comprising aluminium-magnesium alloys.

Aluminium-copper alloys must be avoided for marine applications unless they are well protected.

7.1 The silicon alloys of the 40000 series

These alloys have:

- excellent potential for casting, making it possible to easily design sound components with complex shapes,
- very good weldability (23),
- very good mechanical properties after thermal treatment for the age hardened alloys that contain magnesium (24),
- very good behaviour in marine environments.

Four alloys in particular are recommended:

- 41000 for components required to present a good appearance after mechanical polishing and anodising,
- 42100 and 42200 for complex components required to have high mechanical properties. These two alloys must be age hardened in order to present good mechanical properties,
- 44100 for slender chill-cast components.

7.2 The magnesium alloys of the 50000 series

The aluminium-magnesium alloys are particularly notable for their:

- excellent aspect after mechanical polishing,
- eminent suitability for anodising for protection and decorative purposes,
- good weldability: they can be joined to other cast, rolled or extruded products of similar composition,
- excellent resistance to corrosion in marine environments. They are all ideally suited to marine applications, but two alloys in particular are recommended:
- 51100, with 3 % magnesium,
- 51300, with 6 % magnesium.

SERIES OF CASTING ALLOYS	
Alloying Element	Designation
None	10000
Copper	20000
Silicon	40000
Magnesium	50000
Zinc	70000

Table 28

(22) EN 1706. Aluminium and aluminium alloys. Chemical composition and mechanical properties.

(23) It is not advisable to weld 40000 series casting alloys to 5000 series wrought alloys (and vice versa). (Cf. Chapter 6).

(24) The age hardening process for the 42100 and 42200 alloys is as follows: solution heat treatment for 10 h at 540 °C, water quenching then artificially ageing for 6 h at 160 °C; the process for the 41000 is the same except: solution heat treatment for 4 h at 540 °C.

TEMPERS OF CASTING ALLOYS

Principal Thermal Treatments	EN 1706		AFNOR NF A 57 702 (*)	
None, as-cast	F		Y 20	Y 30
Solution heat treatment, quenching and natural ageing	T4		Y 24	Y 34
Solution heat treated, quenched and artificially aged to peak strength	T6 (**)		Y 23	Y 33
Solution heat treated, quenched and under-aged	T64		Y 23	Y 33

(*) Y2X denotes sand cast, Y3X denotes chill cast. (**) In practice the artificially aged T6 is never at peak strength but is always just below it to retain a minimum of elongation. T64 denotes an under-aged temper designed to promote elongation.

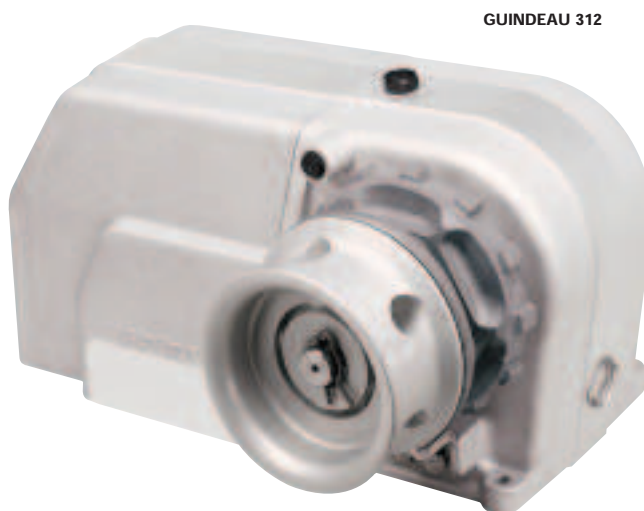
Table 29

8. PROPERTIES OF CASTING ALLOYS

The principal properties of the casting alloys used in marine applications are shown in the tables below.

8.1 Chemical composition

The chemical composition in components according to EN 1706 is given in table 30.



STANDARD COMPOSITION IN COMPONENTS (% BY WEIGHT)

Alloy	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Pb	Sn
41000	1,6			0,30	0,45			0,05		
	2,4	0,60	0,10	0,50	0,65	0,05	0,10	0,20	0,05	0,05
42100	6,5				0,25			0,08		
	7,5	0,19	0,05	0,10	0,45		0,07	0,25		
42200	6,5				0,45			0,08		
	7,5	0,19	0,05	0,10	0,70		0,07	0,25		
44100	10,5									
	13,5	0,65	0,15	0,55	0,10	0,10	0,15	0,20	0,10	0,05
51100					2,5					
	0,55	0,55	0,05	0,45	3,5		0,10	0,20		
51300					4,5					
	0,55	0,55	0,10	0,45	6,5		0,10	0,20		

Note: Where a single value is given, it corresponds to the permitted maximum.

Table 30

8.2 Physical properties

PHYSICAL PROPERTIES OF CASTING ALLOYS

Alloys	Density (kg.m ⁻³)	Thermal Conductivity at 20 °C (W.m ⁻¹ °C ⁻¹)	Coefficient of linear expansion between 20 and 100 °C	Solidification Interval °C	Mean contraction (%)
41000	2700	160	22.10 ⁻⁶	640-555	14
42100	2680	160	21,5.10 ⁻⁶	615-555	12,5
42200	2680	160	21,5.10 ⁻⁶	615-555	12,5
44100	2650	165	20.10 ⁻⁶	580-575	11
51100	2670	145	24.10 ⁻⁶	640-590	14
51300	2640	125	24.10 ⁻⁶	625-540	13

Table 31

8.3 | Engineering suitability

ENGINEERING SUITABILITY OF CASTING ALLOYS										
Alloy	Casting	Cracks Sensibility	Thin Pieces	Dimensional Stability	Machinability	Weldability (TIG and MIG arc)	Polishing	Anodizing for protection	Anodizing for decoration	Resistance to corrosion in marine environment
41000	2	2	2	3	3	3	4	4	4	3
42100	3	3	4	3	2	3	3	4	0	3
42200	3	3	4	2	3	3	3	4	0	3
44100	4	4	4	4	1	4	2	4	0	3
51100	2	1	1	3	4	4	4	4	4	4
51300	2	1	2	3	4	4	4	4	3	4

0 - Unsuitable. 1 - Poor. 2 - Fair. 3 - Good. 4 - Excellent.

Table 32

8.4 | Mechanical properties

MECHANICAL CHARACTERISTICS ON CAST SAMPLES					
Alloy	Temper	Cast Mode	R _m (MPa)	Rp _{0,2} (Mpa)	A %
41000	T6	Y23	240	180	3
		Y33	260	180	5
42100	T6	Y23	230	190	2
		Y33	290	210	4
42200	T6	Y23	250	210	1
		Y33	320	240	3
44100	F	Y20	150	70	4
		Y30	170	80	5
51000	F	Y20	140	70	3
		Y30	150	70	5
51300	F	Y20	160	90	3
		Y30	180	100	4

Table 33

Bibliography

[1] "High Strength Marine Grade Aluminium Alloys: a new generation of 5383 with improved properties," C. HENON, R. DIF, A. DURAN, *18th Fast Ferry Conference and Exhibition*, Nice, France, February 2002.

[2] The potential of 5383 alloy in marine application. G. M. RAYNAUD AND PH GOMIERO, *Pechiney Rhenalu, Conférence Alumitech 97*, pp. 353-366.



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