TALAT
Training in Aluminium Application Technologies

TALAT Lecture 1254

Fatigue in Al casting alloys: metallurgical aspects

16 pages, 8 Figures

Advanced level

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Objectives:

To describe the most significant correlation among foundry processes, microstructures and defects of castings and fatigue behaviour of Al casting alloys

Prerequisites:

No prior knowledge is strictly necessary; however, the basic concepts developed in TALAT lectures 2400 and 3200 are very useful for the comprehension of this lecture.

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1254 Fatigue in Al casting alloys: metallurgical aspects

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1254.01 Introduction

The design relevance of fatigue phenomena is certainly well-known, and it has been widely reviewed in the TALAT lecture 2400. The most important and used wrought alloys are presented there, describing their fatigue behaviour as the result of microstructural aspects, heat treatments and manufacturing processes (welding, bolting, and so on).

Due to their increasing relevance in various industrial applications, well documented by market studies, it seems interesting and useful to review the fatigue behaviour of Al casting alloys. Generally speaking, such a behaviour is affected by a lot of variables: the role of some of them (heat treatment, presence of inclusions) is the same as in wrought alloys (and it has been already described in TALAT lecture 2400). There are, however, other variables which are peculiar for cast alloys and decisive in determining the fatigue performance of castings. For studying them, it is necessary to consider that

- the fatigue characteristics of Al casting alloys are strongly related to their microstructural features,
- such features are the result of the processing conditions imposed to the alloys,
- there is a strong development in terms of new casting processes, to improve the quality and the performances of Al cast components.

The process-microstructure-properties path needs to be followed, in order to fully understand the fatigue behaviour of Al casting alloys.

1254.02 From the Process to the Microstructure

The casting processes industrially available for Al alloys are several, and their number is continuously increasing. TALAT lecture 3200 gives an overview of the most common as well as of the newer casting processes. The more useful way for classifying such processes is based on the characteristics of thermal field they impose on the alloy. This means that parameters such as cooling rate [K/s] and thermal gradient [K/mm] are good indexes of the evolution of the process. Table 1 lists the typical thermal parameters induced by different conventional processes.

Process	Cooling rate [K/s]	Thermal gradient [K/mm]
Gravity - dry sand	0.05-0.20	0.05
Gravity - green sand	0.1-0.5	0.05
Gravity - permanent mold	0.3-1.0	n.a.
Die Casting	1.0-3.0	n.a.
DC casting	0.5-2.0	0.3
Chill casting	10-15	0.3-5.0
Directional solidification	0.2-4.0	10

Table 1: Typical values of thermal parameters for various casting processes

New processes are finding industrial success. Some of them can be recalled:

- squeeze casting (direct or indirect), which can be considered, in a simplified way, as "forging of a liquid alloy",
- semi-solid casting, which allows the injection of a partially solidified alloy (due to its particular rheological properties) into a metallic die,
- vacuum die casting, in which an industrial vacuum is produced during filling of the die cavity,
- lost foam, in which the molten alloys causes the replication of a polymeric pattern, embedded in unbound sand.

The driving force for "refining" conventional processes and for developing new ones has been basically the same: improve the metallurgical quality of the castings and, consequently, reach better performances.

What do we mean for metallurgical quality in an Al alloy casting?

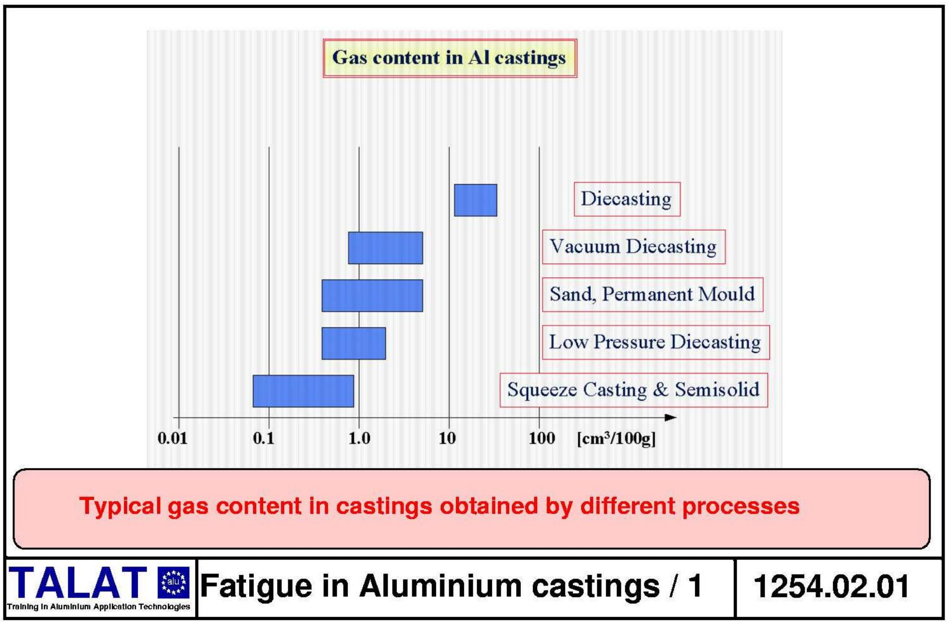
Very generally, two aspects are good indicators of the metallurgical quality of a cast Al alloy:

- the presence, amount, size and shape of porosity and defects,
- the microstructural characteristics of the phases.

As described in Lecture 3200, there are different sources of porosity and defects in Al casting. Such sources are alloy- and process-related. Very roughly, they have to be considered

- the volume reduction associated to the liquid-solid transformation, which may result in macroporosities (due to the presence of hot spots) as well as in microporosities (interdendritic shrinkages);
- the development of Hydrogen, due to the strong decrease on its solubility from the liquid to the solid phase;
- the entrapment of gases (and of the deriving oxides) due to an excessive turbulence in the flow of the molten alloy during the filling stage,
- the establishment of stress states during solidification, causing cracks and hot tears into the cast alloy,
- the presence of inclusions and the development of gases from cores, both due to an incorrect set up of processes and mould materials.

Due to their specific peculiarities, the different casting processes can lead to different amounts of porosity (both in terms shrinkages and gaseous porosities). For what concerns volume shrinkages, the use of pressure gives the molten metal the capability of a better feeding, minimizing this kind of porosity; on the other side the use of pressure in the conventional diecasting process results in turbulence and gas entrapments. For classifying the casting processes of Al alloys in terms of gaseous porosities, a good help is given by **Figure 1254.02.01**.



The ranking among processes is very clear, and two aspects have to be put into evidence:

- the presence of gas (i.e. of gaseous porosity) can not be eliminated in industrial Al castings, and their effect on mechanical properties must be take into account;
- the more recently introduced processes (i.e. semi-solid casting and squeeze casting) allow significant advantages in terms of gaseous porosity reduction; the same is true for vacuum die casting, which lowers the porosity contents of conventional die casting.

The use of pressure directly on the molten alloy (squeeze casting) or in an already partially solidified alloy (semi-solid casting) has also the positive effects of improving the feeding of castings, minimizing the shrinkage porosity phenomena.

The above-mentioned processes can be also described on the basis of their effects on microstructural features. As recalled in Table 1, such processes induce on the casting different thermal field conditions. Table 1 can be extended, to consider the solid-liquid interface velocity and the length scale of the metallurgical grains formed, i.e. the typical size of the system. (Table 2).

Process	Cooling rate [K/s]	Thermal gradient [K/mm]	Interface velocity [mm/s]	Length Scale [mm]
Gravity – dry sand	0.05-0.20	0.05	2.0	0.10-1.00
Gravity – green sand	0.1-0.5	0.05	6.0	0.05-0.10
Gravity – permanent mold	0.3-1.0	n.a.	n.a.	0.03-0.07
Die Casting	1.0-3.0	n.a.	n.a.	0.02-0.07
DC casting	0.5-2.0	0.3	2	0.03-0.07
Chill casting	10-15	0.3-5.0	0.2-2.6	0.01-0.10
Directional solidification	0.2-4.0	10	0.1-0.001	0.03-0.04

Table 2: Typical values of thermal and microstructural parameters for various casting processes

More generally, it has been demonstrated (see also Lecture 3200), that two important quantitative microstructural parameters, the primary dendrite arm spacing (d1) and the secondary dendrite arm spacing (SDAS, d2) can be related to the thermal field derived parameters:

$$d1 = A\, G_L^{a} R^{b} \tag{1}$$

$$d2 = C\, ts^{n} \tag{2}$$

where G_L is the thermal gradient in the liquid in front of dendrites, R is the interface velocity, ts is the solidification time (which can be evaluated as the ratio between the liquidus-solidus temperature interval and the cooling rate during solidification), A, a, b, C and n are constants (related to the alloys).

The SDAS parameter is certainly the most commonly used: it increases as the cooling rate decreases: processes having a high heat removal capability give place to finer microstructures.

Finally, another microstructural aspect have to be considered: as the cooling rate induced by a process on an Al alloy increases, the “distance” from the equilibrium conditions described by phase diagrams increases, due to segregation phenomena (see Lecture 3200, with the different hypotheses on which the lever rule and the Scheil equation are based), leading to inhomogeneous composition profiles on primary dendrites and to the amounts of eutectic phases different from thermodynamics prediction. The following Table 3 gives an interesting example (obtained by means of directional solidification processes) of this behaviour.

Al-4.9%Cu alloy	Cooling rate [K/s]	Thermal gradient [K/mm]	Interface velocity [mm/s]	wt% Eutectic
	0.1	10	0.01	7.12
	1.05	10.5	0.10	8.34
	11.25	7.5	1.5	8.75
	65	13	5.0	9.14
	187	19	10	9.57

Table 3: Effect of cooling rate and thermal gradient on microstructural features for an Al-4.9% alloy

1254.03 From the Microstructure to the Fatigue Behaviour

The path from processes to microstructure and defects of casting has been described in the previous paragraph. Generally, microstructure and defects affect the mechanical behaviour of Al casting alloys.

The section reduction effect of porosity, as well as the stress intensification effect of porosity and/or inclusions is obvious when the static behaviour is considered. It is also well-known that a fine grain size usually improves mechanical properties. For Al casting alloys this is expressed by means of correlations between SDAS and UTS, YS and elongation, of the kind:

$$y = a' \, d2^{n'} \qquad (3)$$

where y is UTS, YS or elongation and a', n' are alloy-related constants. Strictly speaking, these correlations are true under the assumption of constant porosity level into the alloy. In other words, attention must be devoted to the overimposing effects of porosity and grain size/SDAS. Let's consider the following Table 4, achieved from end chill casting experiments on an Al-6Si-4Cu-0.5Fe alloy (the Hydrogen level was less than 0.1 cm^3/100g Al, due to an Ar degassing operation). Even in this case, where finer grain size are associated to more reduced porosity amounts, there are contradictory results among UTS and YS.

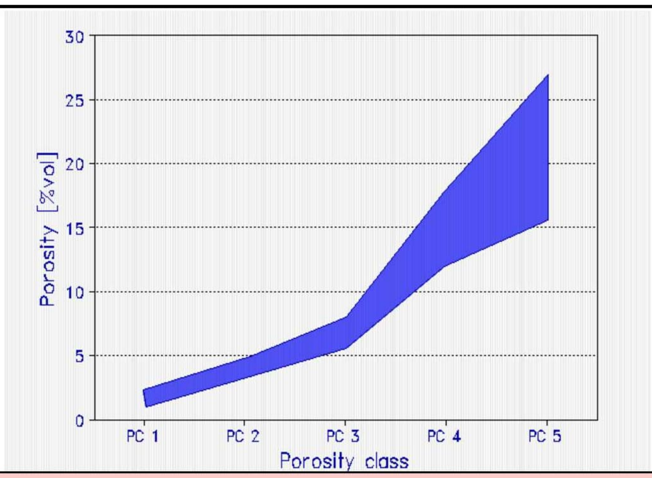
Distance from chill end [mm]	Average SDAS [µm]	Grain size [µm]	Porosity [%vol]	UTS [MPa]	YS [MPa]	e [%]
5	17	650	0.014	234	131	4.5
20	48	950	0.024	214	141	1.7
40	70	1100	0.212	192	141	1.1
100	93	1200	0.505	162	142	0.4

Table 4: Changes in microstructural parameters and in mechanical properties as functions of the distance from chill end

Going to the topic of this lecture, the SDAS and the amount and size of porosity are considered as the most important metallurgical parameters affecting the fatigue behaviour of Al casting alloys.

The effect of porosity (which, as shown, is an unavoidable component of castings) on fatigue is certainly complex.

Some simplified approaches tend to consider only the amount of porosity, identifying some classes in terms volume percent of voids. For an Al-9Si-3Cu alloy, 5 porosity classes have been individuated (**Figure 1254.03.01**). The data of axial fatigue tests are given in **Figure 1254.03.02**, showing the detrimental role of relevant porosity amounts.



Porosity classes in Al-9Si-3Cu alloy castings

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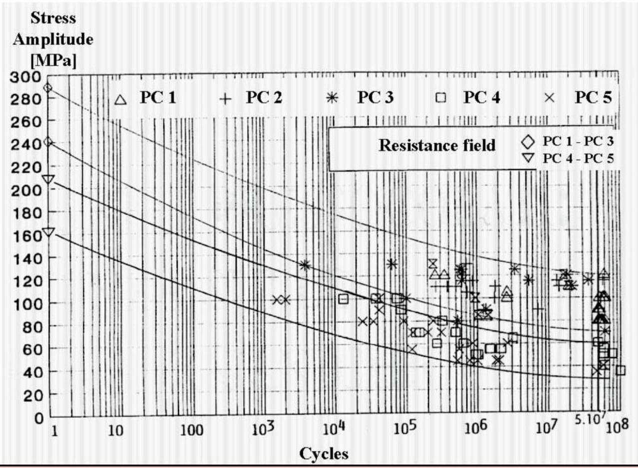
The consequence is clear: porosity has to be minimised; this is the goal of innovative foundry processes for Al alloys. If a comparison is carried out among semisolid casting and more conventional processes, the fatigue behaviour of the semisolid cast alloys is significantly better, due to the strong reduction of porosity which is assured.

The porosity data shown in **Figure 1254.02.01** find an immediate correlation with the Woehler curves reported in **Figure 1254.03.03** (even if the non-dendritic microstructure of semisolid casting should be considered too).



Fatigue behaviour of Al-9Si-3Cu alloy castings of different porosity classes (axial fatigue testing, tensile-compression stress)

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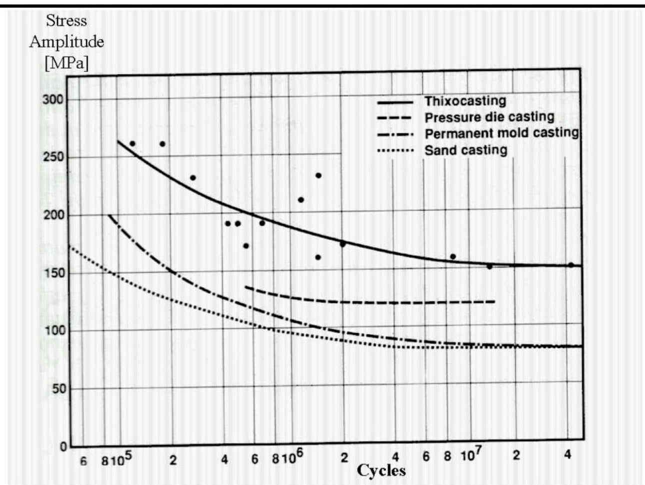

Stress-cycle curves for thixocastings, in comparison with sand, permanent mould and die casting (alloy : Al-7Si-0.3Mg)

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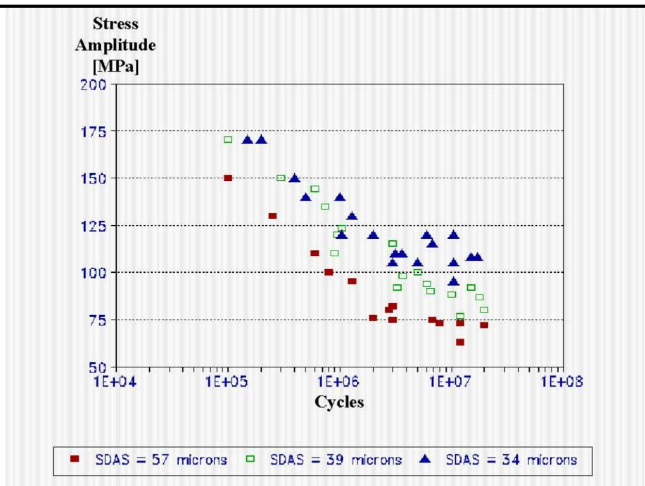
Due to the sensitivity of fatigue properties to defect geometry, the aspects related to size and shape of porosity have to be taken into account, as well as that of the maximum size pore. The failure of the alloy under fatigue depends on these factors: two materials belonging to the same porosity class (i.e. having the same average amount of porosity) but having small sized and round pores the first one and irregular big size porosities the second one are completely different.

The other key-factor affecting the fatigue behaviour is the SDAS. Various collections of data are available in literature between SDAS and fatigue for Al alloys.

As an example, an Al-4.5Si-4Cu-0.2Mg-Ti alloy has been cast controlling the heat removal conditions (selection of mould materials, steel and sand, and temperatures) and the Hydrogen content (always less than 0.15 mL/100g Al): cooling rates of 5.3, 1.8 and 0.25°C/s have been achieved, leading, respectively, to secondary dendrite arm spacing of 35, 39 and 57µm. The results of fatigue rotating bending tests, carried out on defects-free specimens, are collected in **Figure 1254.03.04**. A regression analysis showed very good correlation coefficient using the following formula:

$$\sigma_{10^7} = 550\ d2^{-0.52} \tag{4}$$

which is formally similar to equation (3) and where σ_{10^7} indicates the fatigue strength at 10^7 cycles.



Effect of SDAS on fatigue behaviour of an Al-4.5Si-4Cu-0.2Mg-Ti alloy.

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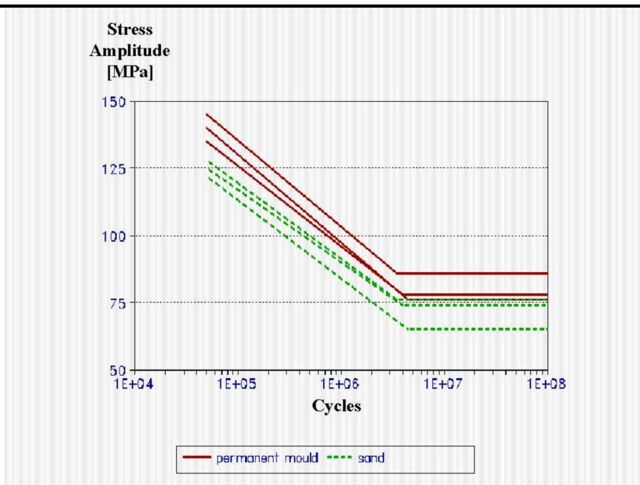
In a similar way, for an Al-7Si-0.6Mg, cast in a sand or in a permanent mould (the higher SDAS values being obviously in the sand cast specimens) the fatigue behaviour is schematically shown in **Figure 1254.03.05**. The fatigue strength at 10^7 cycles and after heat treatments ranges from 76 to 86 MPa for the permanent mould cast specimens and from 65 to 74 for the sand cast ones.

It is difficult, however, to manage porosity (amount, size, shape...) and SDAS as two separate variables. A cast alloy is characterised by the presence of porosity and has proper values of SDAS, coming from the processing conditions. Some attempts have been made to evaluate the behaviour of cast alloys under the combined effects of these variables. It is interesting, for example, to compare the fatigue behaviour of specimens of Al-7Si-0.3Mg taken from

- a cast ingot,
- a separately cast test bar,
- a low pressure die cast wheel.



Fatigue behaviour of an Al-7Si-0.3Mg alloy cast in a sand or permanent mould.

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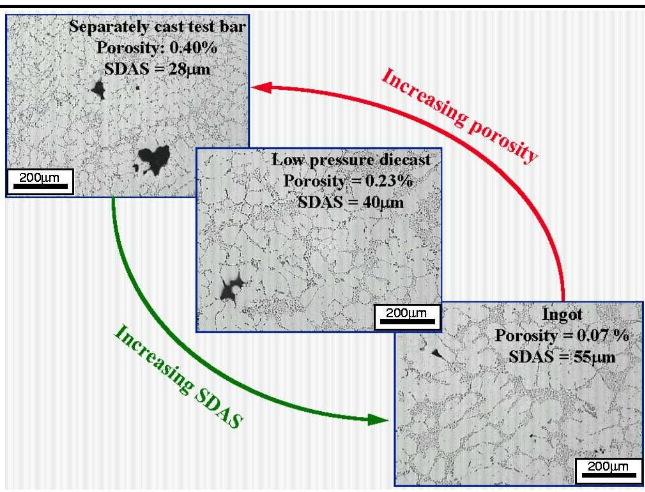
Their main characteristics, in terms of SDAS and porosity are collected in Table 5 and schematically shown in **Figure 1254.03.06**.



SDAS values and porosity characteristics for an Al-7Si-0.3Mg alloy cast by various processes.

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Material	SDAS [µm]	porosity [%vol]	porosity class (PC)	maximum pore size [µm]	pore size class (SC)	maximum pore area [μm^2]
Ingot	55	0.07	0a	57	0	1350
test bar	28	0.40	0b	216	2	15270
l.p. wheel	40	0.23	0b	136	1	2720

Porosity class (PC)	=	0a	Porosity ≤ 0.15%
	=	0b	Porosity ranging from 0.16% to 1.0%
Pore size class (SC)	=	0	Maximum pore size ≤ 100µm
		1	Maximum pore size ranging from 101 to 200 µm
		2	Maximum pore size > 200 µm

Table 5: SDAS values and porosity characteristics (amount, maximum pore size and area) for an Al-7Si-0.3Mg alloy cast by various processes

The higher values of SDAS are, as expected, in the cast ingot, the lower ones are in the separately cast (in a permanent mould) test bar. On the other side, the ingot shows, in terms of both %vol and size, minimum porosity; the separately cast test bar and the specimens from the wheels fall in the same porosity class, while the test bar presents big sized pores.

Such specimens, after a T6 heat treatment, showed the fatigue behaviour summarized in Table 6, adopting the Woehler curve model:

$$\sigma_{50\%} = \sigma_{50\%,\ 2\,000\,000}\ (N/2\,000\,000)^{-1/k} \qquad (5)$$

where $\sigma_{50\%}$ = average fatigue strength, $\sigma_{50\%,\ 2\,000\,000}$ = average fatigue strength at 2 millions of cycles, N = number of cycles, k = exponent of the Woehler curve.

material	$\sigma_{50\%,\ 100\,000}$ [MPa]	k	$\sigma_{50\%,\ 2\,000\,000}$ [MPa]
ingot	192	7.52	130
test bar	200	5.25	113
l.p. wheel	172	8.00	117

Table 6: Fatigue parameters for an Al-7Si-0.3Mg alloy cast by various processes

Some general comments can be drawn from these data. First of all, as discussed above, low values of SDAS and minimum porosity give place to the best fatigue behaviour. In real specimens it is difficult to satisfy both these requirements. In fact, the separately cast test bar has small SDAS, a porosity class similar to specimens from wheels but big sized pores. At high cycle fatigue, mainly within elastic field, the biggest pore acts as an initiated crack and its propagation condition determines the overall behaviour. At a lower number of cycles (in this case close to 100 000 cycles) the elastic-plastic properties of the matrix become meaningful so that the refined SDAS gives a positive contribution. The practical absence of porosity in the ingot overcomes, at high number of cycles, the negative effect of a large SDAS: specimens from ingots show the best $\sigma_{50\%,\ 2\ 000\ 000}$.

The specimens taken from the low pressure diecast wheel represent a good compromise: the relatively small SDAS and the acceptable porosity content (without big sized pores) lead to the highest k value and to an intermediate fatigue limit at 2 millions of cycles. Experimental low cycle data, under axial strain-controlled tests, showed a similar trend.

It is worth mentioning, as a summarising remark, that the effect of porosity and SDAS on fatigue behaviour of Al alloys castings is not "constant". The positive effect of low SDAS values is intensified at low cycles, while porosity (and particularly its size) plays a key-role at high cycles.

The overview carried out suggests that the engineer has to pay particular care in considering the fatigue data collected in general literature and handbooks. If the material history (processing) and conditions (microstructure) are not well specified, those data must be considered only as general, even as useful, guidelines. Examples of these guidance data are collected in Table 7.

Alloy	Process	Fatigue strength [MPa] (R.R. Moore specimen, 5 10^8 cycles)
Al-6Si-3.5Cu	Sand casting	70
	Sand casting + T6	75
	Permanent mold	70
Al-9Si-1.8Cu-0.5Mg	Permanent mold + T61	135
Al-5Si-1.3Cu-0.3Mg	Sand casting + T6	62
	Permanent mould + T6	69
Al-7Si-0.3Mg	Permanent mold + T6	90
Al-9.5Si-0.5Mg	Die casting	120
Al-8.5Si-3.5Cu	Die casting	140
Al-12Si	Die casting	130
Al-8Mg	Die casting	140

Table 7: Collection of fatigue data for some Al casting alloys

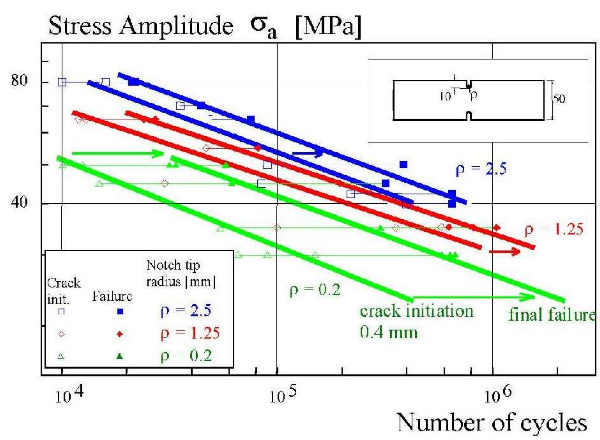
1254.04 From the Cast Alloy to the Component

Finally, as far as real component, instead of base material, are concerned, further considerations shall be made because the fatigue strength is the result of several interactions among parent material, technological processes, component design, environmental and usage conditions.

On mechanical components stress raiser are always present and crack initiation site is mainly fixed by the stress concentrations and not only by the porosity distribution. So the crack initiation time can be less influenced by the overall porosity parameters (as the average porosity percentage or the greatest pore size and shape) and dependent on the strictly local material characteristics at the tip of a notch and on the notch sharpness.

Moreover the total amount of cycles to failure is the sum of crack initiation and crack propagation time and the ratio between the two phases length is dependent on material properties, on component geometry and on loading intensity (see TALAT lectures 2400).

As an example, the experimental results on notched specimens are shown in **Figure 1254.04.01** and it is evident the dependence on the notch acuity, first of all on fatigue strength, but also on the crack propagation contribution to the total life of the structural element.



Crack initiation and crack propagation time in notched plates in AA356T6 (net section 5x 30 mm).

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Since crack growth rates of sufficiently long cracks (in this case longer than 0.4 mm) are sufficiently well described by the ***Paris law*** within linear elastic fracture mechanics, then crack propagation cycles can be estimated by means of the procedures described in TALAT lectures 2400.

Among the different influencing factors, the material characteristics can act in opposite directions, because several experimental works showed how coarser microstructures or a decrease in yield strength could give a marked reduction in the near-threshold fatigue crack growth rates.

As a final result, while the strength to crack initiation of the base material is well conditioned by a reduced porosity and refined microstructure, the fatigue life of notched elements as well as real components (particularly if inner flaws exist) can be lesser affected by those properties.

In conclusion, the main summarizing comment is that casting processes lead Al alloys to a variety not only of shapes, but also of microstructural features (including defects) and of mechanical and fatigue properties. The design engineer will be able to fully exploiting the enormous potential of Al alloys and Al casting processes only developing a personal sensitivity about the process-microstructure-properties path, which will help him in improving the components performance by means of a correct selection of materials and of manufacturing routes.

1254.05 Literature

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