

SYNTHESIS REPORT

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TITLE : **Advanced Aluminium Precision Casting For Integrally Stiffened Net-Shape Components (ADVACAST)**

PROJECT
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Advanced Aluminium Precision Casting For Integrally Stiffened Net-Shape Components (ADVACAST)

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Abstract

Nineteen different aluminium alloys have been developed and investigated. These alloys have been cast with two investment casting processes, the standard process and a proprietary technique (SOPHIA process) allowing higher cooling rates and a controlled solidification. To achieve optimum properties and short processing times, optimized heat treatments were developed for the alloys under investigation.

A modification of the commercial alloy AlSi7Mg could be developed with very balanced properties showing a small improvement in room temperature tensile properties. However this alloy has much improved tensile and creep properties at elevated temperatures up to 200°C. This alloy has a high potential for commercial introduction.

Attempts to cast modified alloys on the base of Al-Zn, A201 and A224 have finally not been successful. Some progress was made, but the inherent problems of segregation and hot tearing could not be solved sufficiently, so that a broader technical application is presently not visible.

Introduction

The main purpose of this project was to develop new aluminium cast alloys with improved mechanical properties for ambient and elevated temperature applications. The alloy development was done in direct conjunction with two investment casting technologies, the conventional method and a special proprietary technique (SOPHIA process), allowing higher cooling rates and controlled solidification. This concept was used, because casting is a near net-shape process allowing the manufacture of complex, highly integrated components. This correlates directly with environmental benefits as saving of resources in terms of raw material and energy consumption during casting, machining and recycling. Another very important aspect is cost saving which is introduced by the net-shape process and by the high degree of possible design complexity. Improved mechanical properties help castings to find a broader application in light weight structures.

The improvement of casting technology and a better understanding of the casting process was also an objective, because most of our investigated alloys are more difficult to cast than today's commercial casting alloys. Another concern for the introduction of new alloys to industrial application was to grant the reproducibility of properties.

Technical Description

The project began with some metallurgical pre-tests for alloy development and with the production of wax models and ceramic shells for both casting processes. Conventional investment casting as state of the art technology for high quality castings was used as a baseline or reference in respect to the SOPHIA process.

Nineteen different alloys were investigated. Most of them were cast to different parts and some of them were even produced in different batches to prove the reproducibility. To assure the quality of the castings, each part was thoroughly investigated by the means of non destructive testing (x-ray and dye penetrant testing). The development of the alloys and of the corresponding heat treatments were done by a complex interaction of literature research, calculation of phase diagrams, parameter studies on unidirectionally solidification experiments, detailed metallographical investigations, empirical, semi-empirical and experience driven alloy verification and variation of casting parameters.

The nineteen alloys investigated were grouped in three categories:

- a) metallurgical modifications of the alloy AlSi7Mg (A357), ‘basic alloys’,
- b) reproduction of the most promising candidate alloys of the A357 family,
- c) different alloy modifications from the type Al-Zn, A201 and A224, ‘advanced alloys’.

We focused to optimize the heat treatments for the new alloys investigated, especially those under point a) and b) mainly under two aspects:

- + to achieve high but balanced properties, and
- + to assure economical heat treatment conditions in terms of short processing times and workshop safety margins required.

The heat treatment of castings generally consist of three major steps:

- + solutionizing,
- + quenching, and
- + thermal aging.

The main purpose of the solutionizing step is to dissolve and to homogenize possible segregations and inequilibrium phases which can occur during the solidification process of castings and to bring the alloying elements into a homogeneous solid solution. To minimize the time required for this procedure very sound metallurgical and microstructural investigations have been performed to avoid erroneous local onset of melting during heating up due to inequilibrium phase compositions. We determined the start temperatures of local melting when heating up the parts. From this critical temperature we keep a security margin of a few degrees

away and keep the temperature constant for a time required to make a sufficient smoothening of the local inequilibrium compositions. Then we heated up for some degrees and keep the temperature constant again. This procedure was repeated several times until sufficient diffusion could finally take place to dissolve the inequilibrium phases and segregations. The this procedure was supported by estimations of diffusion paths, calculation of existing and expected phases using the software package THERMOCALC, DTA-analysis, scanning electron microscopy and metallography.

Quenching took part in two different media: In icewater, with a temperature of less than five degrees Celsius or in water at ambient temperature with a content of glycol. Icewater is the quenching medium allowing highest practical cooling rates. This procedure leads to higher internal stresses in castings and to an increased straightening effort of the parts cast. Therefore icewater quenching is only used when we require these high cooling rates (e.g. for alloys with Cu additions). Otherwise we prefer quenching in a water/glycol mixture. The storage of some alloys after quenching (e.g. alloys containing copper) was done in a fridge to avoid the onset of precipitation reactions between the following treatment steps. This is necessary before thermal aging is performed.

Some microstructural features are basically determined by the alloy composition and the local cooling rate achievable in castings during the solidification range. The most important features influencing the mechanical properties in addition to the microstructure produced by the heat treatment are secondary dendrite arm spacing and to some degree the 'shape' of the eutectic. For a given alloy these parameters are strongly influenced by the achievable cooling rate, resulting from the casting process and from the wall thickness of castings. The follow-on procedure after quenching is thermal aging. This allows the formation and growth of precipitations from the supersaturation of alloying elements generated by solutionizing and quenching. The kind (composition), number, size, and shape of these precipitations determine together with the secondary dendrite arm spacing and the shape of the eutectic the static and dynamic properties and the corrosion behavior of the alloys. The parameters for thermal aging have been chosen in respect to short (economic) aging times and to achieve a good compromise between highest but balanced mechanical properties and good corrosion resistance in combination with general technical requirements.

For the alloys from the group a) and b) we have been very successful to find optimized heat treatments for solutionizing, quenching and thermal aging to fulfill all needs of practical

workshop requirements in terms of process reproducibility, short processing times and high but balanced properties.

To demonstrate and to verify the high properties of our new investigated alloys, a very complex and detailed test program was defined:

- + tensile properties at room temperature and elevated temperatures (ultimate tensile strength, yield strength, elongation and Youngs-Modulus),
- + fatigue behavior (notched and unnotched specimens),
- + crack propagation behavior,
- + fracture toughness,
- + creep behavior,
- + intergranular corrosion behavior,
- + sensitivity to stress corrosion cracking.

To eliminate possible influences on the test results due different test laboratories, reference tests and round robin tests were performed.

To be accepted on a broader commercial market a new cast alloy must fulfill some additional practical requirements. So we focused on repair weldability, because many castings have small surface imperfections which must be cleaned out and repair welded simply for economical reasons. Additional investigations of selected new alloys were performed on the workshop level e.g. to quantify

- + general machining behavior,
- + internal stresses of castings in terms of distortion during machining,
- + the behavior in respect to chemical standard aerospace processes like pickling, chromic acid anodizing, chromate conversion coating and chemical milling.

We feel very encouraged that the new investigated alloys show good repair weldability and behave very similar under workshop conditions in comparison to the commercial standard alloy A357.

Theoretical models to predict the creep behavior and the influence of overloads on the crack propagation properties have been developed for the special microstructural features of castings. These models could be successfully verified by experimental investigations. These developed models give very important assistance for practical applications of weight optimized casting in respect to dynamic loading conditions and for the application at elevated temperatures.

Results

Basic Alloys - modifications of alloy AlSi7Mg (A357):

The alloy A357 was used as a reference alloy for all room temperature properties investigated on the basic alloys. For high temperature properties we referred to alloy A224 and C355.

Starting from the composition of alloy A357 we investigated the influence of many alloying elements like strontium, silver, copper, samarium and lanthanum in different compositions and several element combinations. The most promising alloys have been remanufactured to prove the reproducibility of castings and of heat treatments and to apply the latest know how in melt processing and gating and feeding technique.

The results of the most promising alloy (A357 + copper) is summarized in comparison to the standard composition of A357 (heat treatment T6):

- + Room temperature tensile strength is a bit (about 10MPa) higher as for A357.
- + The elongation is high for castings made by the SOPHIA process, but depends strongly from the cooling rate. For higher wall thicknesses (about 20-30mm) it reduces to about 3%.
- + The Youngs-Modulus remains unchanged.
- + Fracture mechanics behavior (fracture toughness, crack propagation and fatigue) is comparable.
- + Hot tensile and creep properties up to 200°C are superior to any other aluminium cast alloy.
- + Intergranular corrosion attack has increased, but is still acceptable for aerospace and automotive application.
- + The new alloy, as well as A357 is not sensitive to stress corrosion cracking (up to 85% yield strength).

The alloy is easy to cast, can be repair welded without any degradation of properties, and does not show a tendency to hot tearing.

Advanced Alloys - alloy modifications from the type Al-Zn, A201 and A224:

Many different alloy compositions on the basis of these alloys have been investigated. Tensile properties over 500MPa have been measured on single specimens, together with high elongations. Unfortunately the reproducibility of such properties is still very poor and the scatter in data is very high. The alloys investigated are not sensitive to stress corrosion cracking (except those from the base composition of A201). The Al-Zn castings show a high porosity level, because the solution heat treatment procedure could not avoid some localized onset of melting.

The main problems which could finally not be solved are:

+ segregation and

+ hot tearing.

It has been shown very clearly, that the application of higher cooling rates as introduced by the SOPHIA process does not improve the castability of these alloys significantly compared to the standard investment casting process.

No clear concept could be developed during the project giving hints to an improvement of this present situation.

Conclusion

After starting the project, we have set us very high targets for the new alloys to be developed within the project. Not all of this targets could be reached. This reflects mainly to the castability of the advanced alloys where some inherent problems concerning segregation of major alloying elements and hot tearing could not fully be overcome.

For the alloys on the base of A357 we were much more successful: One new cast alloy was developed on the base of the conventional alloy A357 and has small improvements in mechanical properties at room temperature. However, this new alloy has much improved creep and strength properties at elevated temperatures up to about 200°C in comparison to the standard cast alloys for this application C355 and A224. These high temperature properties are very important, because presently Europe starts activities for the development of an successor for the supersonic passenger aircraft „ Concorde” which is exposed to higher temperatures due to aerodynamic friction.

This alloy has a good castability. The high and improved properties can be achieved with high cooling rates which can easily be realized with the SOPHIA process.

The interaction between fundamental investigations of the microstructure of the new alloys, theoretical considerations and calculations has stimulated the development of new alloys and optimized heat treatments and was demonstrated in a very fruitful way within this project. A very interesting attempt was made to calculate phase diagrams of the new and very complex alloys using the software package THERMOCALC. These calculations gave important hints in terms of existing phases, liquidus and solidus temperatures as an input for the development of new alloys and their heat treatments. However, today the accuracy of these predictions is not

high enough to rely only on these information, since the thermodynamic input data require still further improvement.

Theoretical models to predict the creep behavior and the influence of overloads on the crack propagation have been very successfully developed regarding the special microstructural features of castings.

In general, it can be stated that the complexity of alloy development was underestimated in the begin of the project, resulting in very high efforts to spend and in a high time pressure at the end of the project. But anyway, it can be claimed as a great progress to have a new alloy developed with balanced and partly superior properties in respect to existing commercial alloys within such a short time.

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