Innovative and integrated technologies
for the development of aeronautic components

Nicola Gramegna, Emilia Della Corte[1]
Marco Cocco[2]
Franco Bonollo, Fabio Grosselle[3]

[1]EnginSoft S.p.A;
Via Giambellino 7; 35129 Padova - Italy
[2]AVIO S.p.A;
Via I Maggio, 99; 10040 Rivalta di Torino (Torino) - Italy
[3]Università di Padova, DTG;
Stradella S. Nicola, 3 - 36100 *Vicenza - Italy*

Abstract

The "design innovation program" lies in the development and integration, since the very first steps, of all those aspects related with component life cycle, from manufacturing till end_of_life, in order to meet the requirements of a greater product quality, of a more and more comprehensive knowledge about the component potential, of a cost and TTM (Time To Market) reduction.

In particular, the knowledge about the mechanical properties, coming from the manufacturing process, contributes to the improvement of the component performance and reliability, to exploit the synergies of the departments involved in the project and to maximize the suppliers collaboration.

In such perspective, light alloy components for aeronautic sector play an important role. Propulsive systems consist of complex and diversified parts that require a structural design in the non-linear and fatigue fields, to be also integrated in the main manufacturing aspects: the casting process and the subsequent heat treatment.

Introduction

Generally speaking, the components can present, during their use, static instability, unwelcome deformation or early fracture. Such behavior is due to the interaction between the component itself and the stresses and strains it undergoes. It's important to underline that these stresses do not only consider those acting on the in-service component, but also the residual ones generated during the manufacturing process. The residual stresses are caused by the casting reaction, as it undergoes an uneven contraction due to different local thermal gradients and to a variable resistance to temperature and therefore to the cooling time. The residual tensile stresses reduce the material mechanical performance, the stress corrosion resistance properties; they favor the fatigue susceptibility, the onset of fractures due to wear phenomena. The compressive stresses on the contrary have a positive effect, since they delay starting and crack propagation. In the elastic field, residual stresses are added to those caused by the applied load: surface compression

residual stresses therefore reduce the stress level in the layers where the load is higher, whereas tensile stresses reduce the stress interval the component can undergo [1-5].

All components obtained through a foundry process are characterized by an internal tensile stress, which is balanced but locally different from zero, as a consequence of the thermal gradients characterizing the cooling phase till ambient temperature. The residual tensile stress generally varies within the components, depending on the area.

The component resistance capacity depends on the stress entity, on its geometry, on the residual stress and on the material.

In particular, as far as the material is concerned, the microstructure [6-7], as well as the presence of micro- and macro-defects can contribute to an early failure of the in-service component.

In the specific case of Al-Si alloys, the mechanical properties are determined by the α-Al phase properties, by the grain size, by the eutectic silicon features [12-16], as well as by the presence of secondary and intermetallic phases [17]. Generally speaking, a component, characterized by a fine microstructure, with no embrittlements, presents better mechanical properties than a component with a coarse structure, high SDAS values and acicular eutectic silicon crystals [18-19].

The casting process simulation for the defect prediction resulting from the cavity filling process or to solidification shrinkage, is therefore applied during the design phase and it can be completed taking into account two important and innovative aspects connected to the analysis of the residual stresses and strains and to the mechanical properties prediction, till the end of the heat treatment.

In order to obtain a cast, which meets the technical requirements, it's necessary that during the design phase the component mechanical behavior is determined by means of the process numerical simulation, taking into account all boundary conditions that can affect the component activity for aeronautic applications. The objective is to determine and validate a more efficient simulation procedure for the design phase, able to combine the manufacturing process with the product structural behavior; in particular this work presents the results achieved for the as-cast component and the results coming from the thermal evolution monitoring on the T6-state component during the process.

METHODOLOGICAL APPROACH AND EXPERIMENTAL PROCEDURE

The teamwork has directly involved Foundry and Enginsoft, with regard to the planning and performance of simulation, casting and thermal treatment monitoring, in close collaboration with AVIO and Padova University - DTG, concerning the immediate feedback from real to as-cast and thermally treated product.

The component under investigation is the gearbox Casing Angle V2500, shown in Figure 1.

Although it doesn't have a strategic and innovative impact, its simple geometry and well-known productive cycle offer an ideal reference point for further analysis.
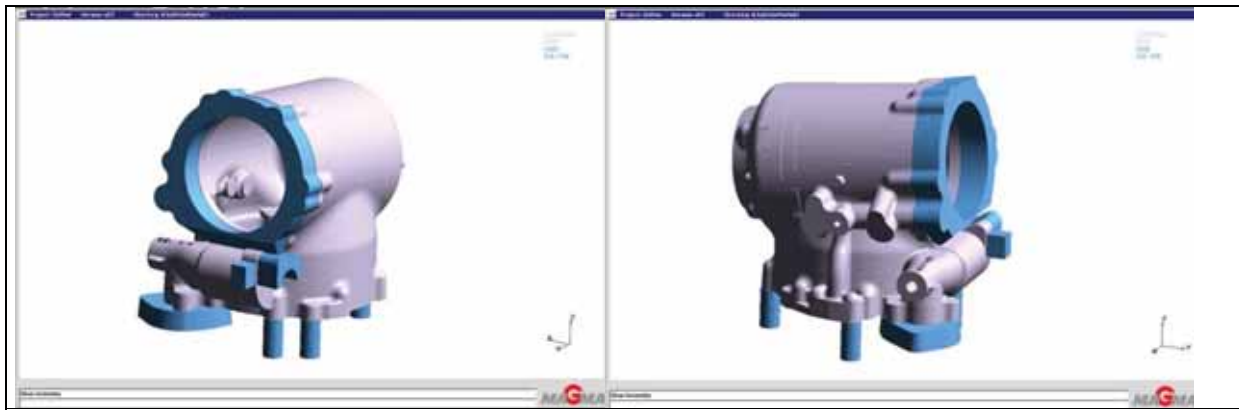
Figure 1 - Geometrical views of the Casing Angle V2500

The component has been cast in sand in two specimens using the A357 alloy. The first casting has been examined as cast, while the latter has undergone a artificial aging heat treatment, in accordance with AVIO regulations. Three thermocouples, included in the cast, have surveyed the temperature evolution during the whole heat treatment. (Particular attention has been paid to the quenching phase, thus highly increasing the data acquisition frequency).

In order to predict any defect generated in the filling phase or during the solidification process, the casting process simulation has been combined with the residual stress and strain simulation together with the mechanical properties prediction [21-25].

The results provided by the numerical simulation have been therefore compared with those achieved by experimental analysis.

The experimental analysis considered a radioscopic control first, in order to identify the presence of possible shrinkage or gas cavity inside the cat, then a micrographic verification of interesting areas in terms of thickness, location, distance from the pouring system and defect probability. In particular, the micro-structural analysis has been addressed to the determination of the dendritic size (SDAS) as well as to the dimensional and morphologic features of the eutectic silicon.

Finally, the use of strain-gauges, in four different areas, has allowed to evaluate the presence of residual stresses, due to both the solidification and heat treatment process.

In order to simplify this presentation and to focus on the method instead of on the numerical detail, Table 1 summarizes what already stated.

Table 1. *Overview of the performed experimental activities and simulations*

- **ANALYSIS OF THE AS-CAST COMPONENT**
  - Mould Filling
  - Casting Solidification
  - Measurements and defect prediction
  - Measurements and microstructure prediction
  - Measurements and mechanical properties prediction
  - Measurements and residual stress and strain prediction
- **ANALYSIS OF THE T6-STATE COMPONENT**
  - Monitoring of the product thermal history
  - Furnace solution heat treatment
  - Water quenching
  - Furnace tempering
  - Air cooling
  - Measurements and prediction of the cast thermal evolution
  - Measurements and microstructure prediction
  - Measurements and mechanical properties prediction (UTS, YS, A%)
  - Measurements and residual stress and strain prediction

RESULTS
Analysis of the as-cast component

From a technologic point of view, the casting process in sand is very common in the industrial context, as it permits to obtain large and complex components; although it can easily generate defects in the cast, such as gas porosity, shrinkage cavity, cold laps in addition to oxide films what negatively affect the cast fatigue resistance properties. In particular, they favor the fracture onset, reducing the overall life of the component.

In order to avoid such defects, apart from the metal quality, it's extremely important to pay attention to the pouring system construction [20].

Aluminum alloys are in fact extremely sensitive to oxide and foam formation, when the liquid metal locally undergoes an abrupt acceleration and deviation, which can alter the die laminar filling. Furthermore the presence of cooling systems can cause cold laps, if they are not accurately dimensioned and characterized by a slow filling. Such systems are anyway necessary to minimize the interdentritic space and the solidification shrinkage in the cast massive areas (specially flanges and bosses) and to favor the solidification process towards the lateral and top risers.

In this work, the casting process simulation of the "Casing Angle 2500" component did not aim at designing the pouring system, competently produced and tested by Foundry, but verifying the cast quality, taking into account the causes of possible defects during risky cast conditions. In particular the simulation objective was to examine whether the filling, starting from particular cast temperature and flow, could take place laminar conditions (as wished) or assume, in certain conditions, a turbulent flow. It is also important to verify whether the riser system was adequately designed to balance the alloy volumetric shrinkage during the solidification phase, so to avoid the formation of shrinkage macro-cavities.

Figure 2 shows the liquid alloy temperature values during the filling and it can be noticed how, close to the top cap, the contact of two fronts can generate a gas inclusion with a temperature value at the risk of cold lap; such defect has been detected during the experimental check on some castings, as shown in Figure 3.
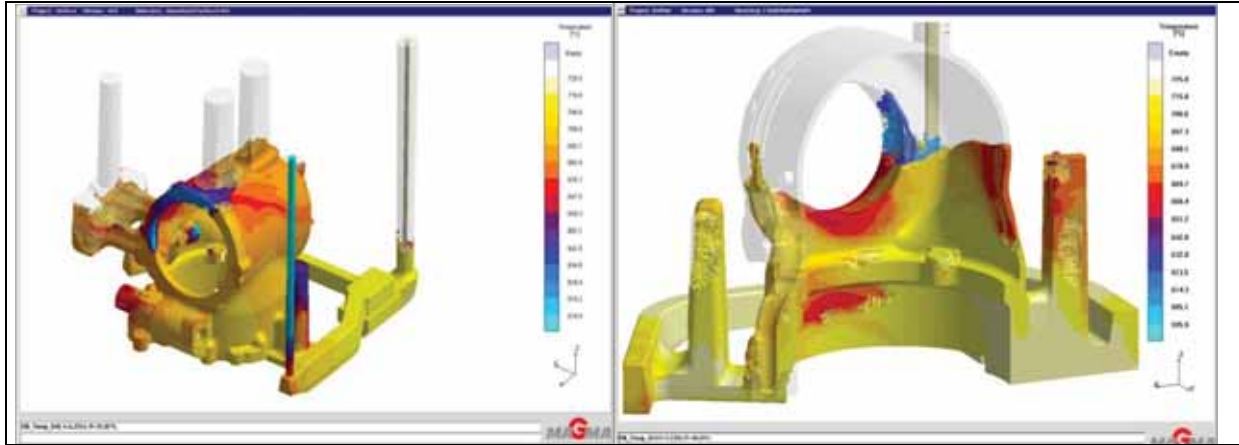

Figure 2 – Sequence of the cavity filling
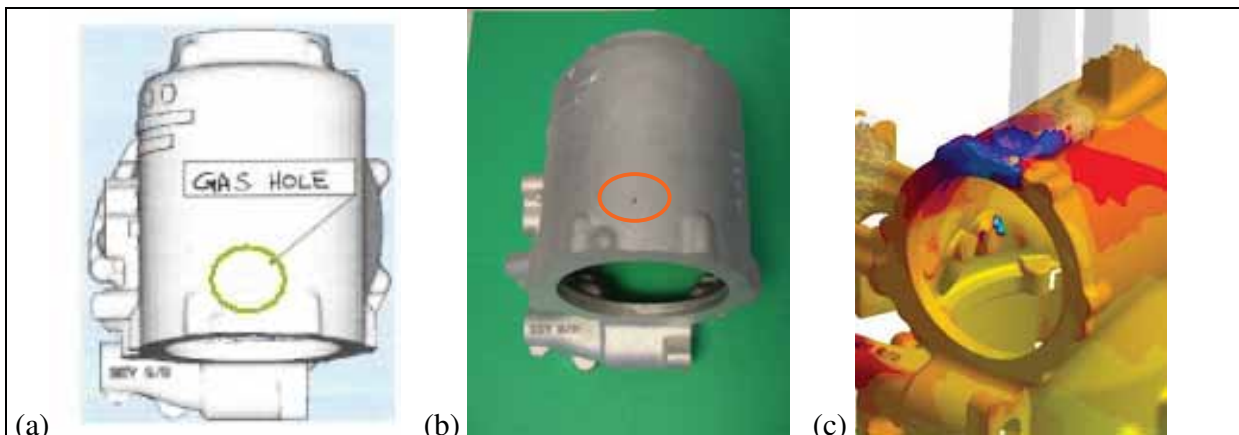

(a) (b) (c)

Figure 3 - (a) Defect location with (b) visual research and (c) correlation with the simulation of the filling defect

Figure 4 illustrates the results of the numerical simulation in terms of "liquid fraction", that is the "solidification sequence": it can be noticed how the feeding system consists of a risers set, providing the cast with the adequate liquid, necessary to balance the solidification macro-shrinkage.

Nevertheless, the simulation presented in detail in Figure 5(a) highlights the risk of micro-porosity (however below the acceptability limits for location and size) in certain complex points of the casting, as the experimental analysis and the quality control confirmed (Figure 5(b)).
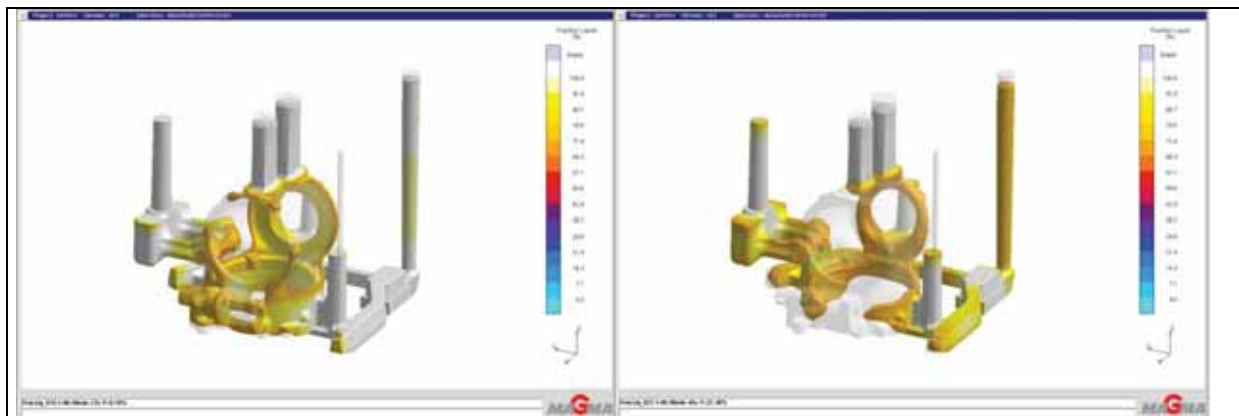
Figure 4 – Solidification sequence of the Casing Angle component

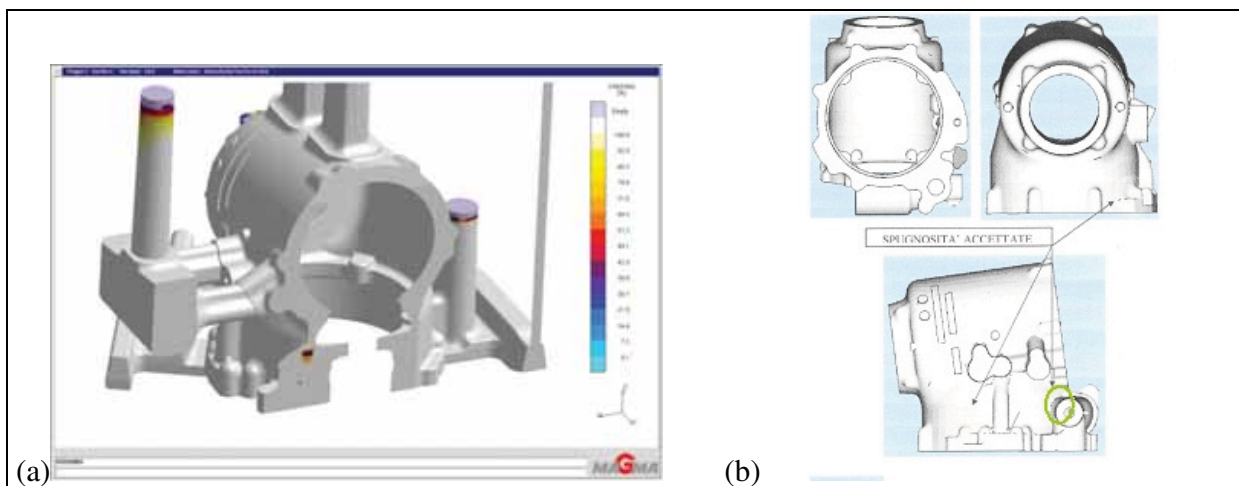(a)   (b)

Figure 5 - In (a) Shrinkage rate value provided by the simulation, whereas in (b) the Quality control report

This procedure doesn't illustrate any innovative element, since the design of the die-casting system is commonly faced with the support of simulation tools.

In order to integrate into the simulation process all the component features that contribute to the determination of its in-service behavior, the solidification parameters have been elaborated to predict the alloy microstructure and mechanical properties, so to evaluate, starting from the as-cast state, their evolution at the end of the heat treatment.

As well-known, macro- and micro- structural characteristics determine the cast mechanical properties: grain size, SDAS, morphology, eutectic silicon size and distribution and the intermetallic phases that not only affect the tensile strength, but also the ductility, toughness, resilience, resistance to changes in temperature and fatigue resistance.

Figure 6 shows the micro-structural analysis results for two of the eight investigated areas. In particular, the picture considers different enlargements, the maximum and minimum values, the average and the standard deviation of SDAS, of the eutectic silicon particles, their roundness, shape ratio and equivalent diameter.

The SDAS values are also indicated, as expected by the simulation software and elaborated according to the cooling rate. As far as the SDAS is concerned, it's clear how experimental data

perfectly match the expected values: for instance, considering the sample nr.22, the expected SDAS value of 30-36µm corresponds to an measured average value of 34µm.
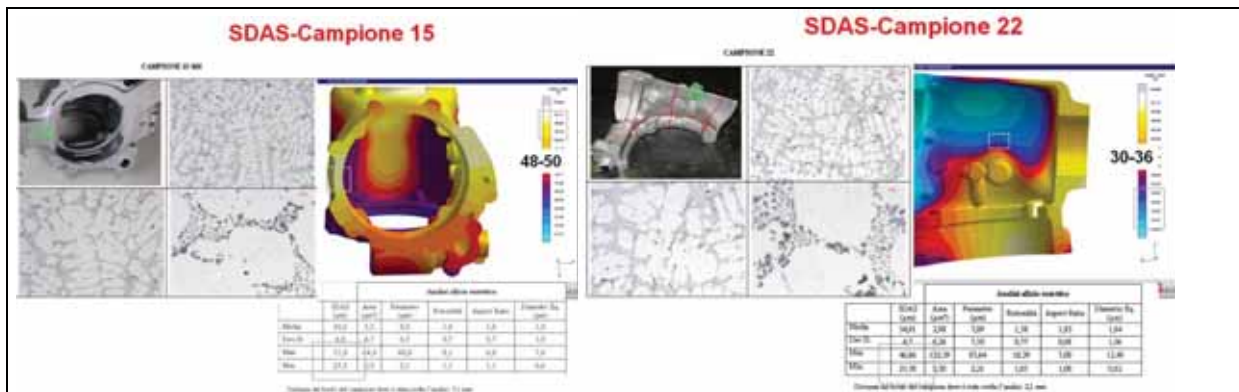

Figure 6 – Results of the micro structural investigation and SDAS values provided by the numerical simulation

The values of mechanical properties are displayed in Table 2. Some cylindrical samples have been taken from four different areas (T1, T2, T3 e T4) in order to perform tensile tests in accordance to AVIO supply specifications.

Simultaneously, the simulation has evaluated the fracture load in any part of the cast, so to compare it in the four investigated points. The mapping of the fracture load values is illustrated in Figure 7. In this case as well, the simulation results and the experimental reached a good match: for the sample T3 the simulation vales is about 130 Mpa whereas the experimental measurement is 140.

Table 2. *Mechanical properties values*

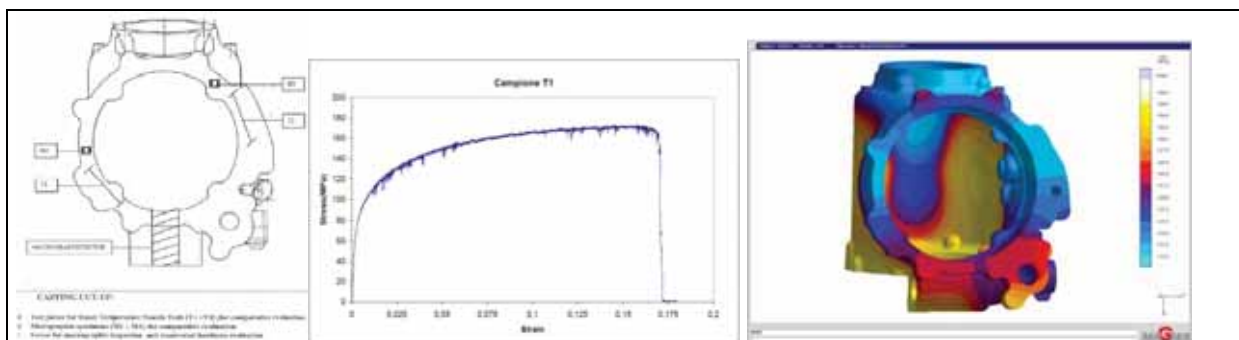|	SDAS (µm)	YS(MPa)	UTS(MPa)	Elongation(%)
Specimen 1 (T1)	22,6	77,0	173,5	16,9
Specimen 2 (T2)	23,8	71,1	156,9	23,6
Specimen 3 (T3)	38,3	65,3	140,6	11,9
Specimen 4 (T4)	38,0	66,3	148,0	17,7

Figure 7 – Sampling areas with related fracture curve and UTS prediction through simulation

As previously mentioned, the integration of the productive process with the structural behavior has to consider the residual stress effects and the subsequent strains due to the casting process.

This is therefore required to estimate the tolerance size respect or the presence of cracks and to evaluate the component tensile state before the heat treatment process, although it's likely that the solution heat treatment cancels any residual effect of the solidification and the cooling till ambient temperature.

The experimental measurement of the residual stress has been performed applying some extensometric gauges on the component surface that have been afterwards dissected from the component for further cuts. This action allows the release of the internal tensile stress: the relation strains can therefore be measured using the gauge extensometers.

Simulation techniques are generally much more affordable than experimental ones, as the can couple the cast thermal evolution with the associated contraction and deformation during the whole cooling phase. The results accuracy depends, as for the filling and solidification simulation, on the element size, as well as on the material specific curves, that determine the evolution of the thermal expansion coefficient and of the mechanical properties with relation to temperature.

Figure 8 (a) shows an example of the location of gauge 3, which detected the tensile state inside the cap and allowed to compare such values with the ones provided by the numerical simulation (Figure 8 (b) e (c)).
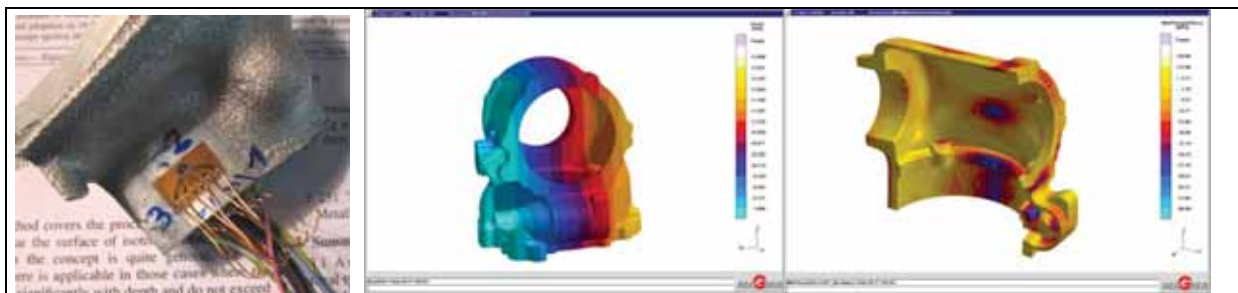

Figure 8 - (a) Example of extensometer (extensometric gauge) location and (b) with (c) residual stress and strain simulation on the as-cast component

Analysis of the T6-state component

In order to obtain high mechanical properties, the productive cycle of the "Casing Angle 2500" gearbox considers a T6 heat treatment, described in the following table.

Table 3. *Phases of the heat treatment cycle, undergone by the investigated component*

1. HEATING up to 540°C
2. SOLUTION HEAT TREATMENT at 540°C for about 18 hours
3. WATER QUENCHING at 40°C for 10 minutes
4. AIR COOLING at 30°C for about 3,5 hours
5. FURNACE HEATING up to 200°C
6. AGING at 200°C for about 6 hours
7. AIR COOLING for at least 3 hours

As it happens in reality, the simulation searches for a more suitable method to analyze the overall thermal evolution of a component in order to deduct its effects on the microstructure and local mechanical properties.

The thermal analysis of a T6 treatment requires the accurate determination of the heat-transfer coefficient (HTC) between the cast and the quenching medium. In spite of several studies and experiments, the cooling process is influenced by the part geometry, the immersion method and sometimes by the quenching tank size that make it difficult to determine a general HTC value.

By monitoring the cast temperature during the whole heat treatment process, the quenching heat-transfer coefficient has been determined with a reverse engineering approach.

Five thermocouples, engaged inside the cast in different thickness areas, have surveyed the cast temperature during the process: Table 4 summarizes the thermocouple location, whereas Figure 9 displays the temperature-time diagram.

Table 4. *Location of the thermocouples to monitor the thermal evolution during the heat treatment process.*

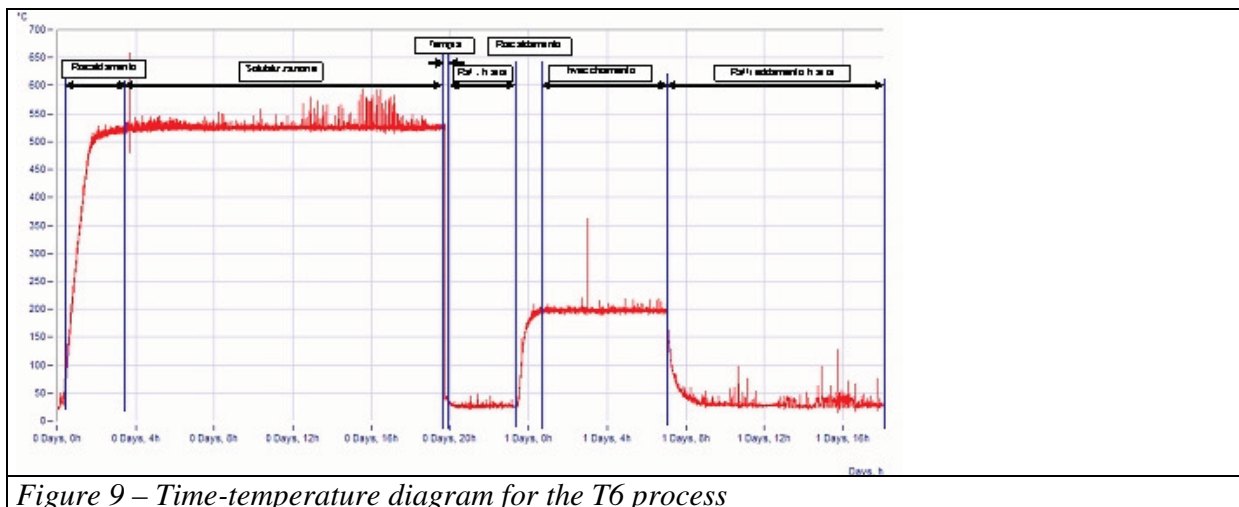| Thermocouple	Surface depth [mm]	Material thickness [mm]
T1	7	14.3
T2	2	14.3
T3	4	5.5
T4	7	15
T5	14	35

Figure 9 – Time-temperature diagram for the T6 process

The temperature-time curves, in particular for the quenching phase, become the objectives of the reverse computation (figure 10), which, using the optimization genetic algorithm (MOGA-II), allows the definition of the heat-transfer coefficient as a function of the temperature and the overlapping of the experimentally measured temperature-time curves with the virtual ones provided by the simulation [21-25].

The automatism is directed towards the error minimization between the different curves of each thermocouple, till the identification of the univocal parameters that define the shape and value variation of the heat-transfer coefficient calculated in W/m^2*K.
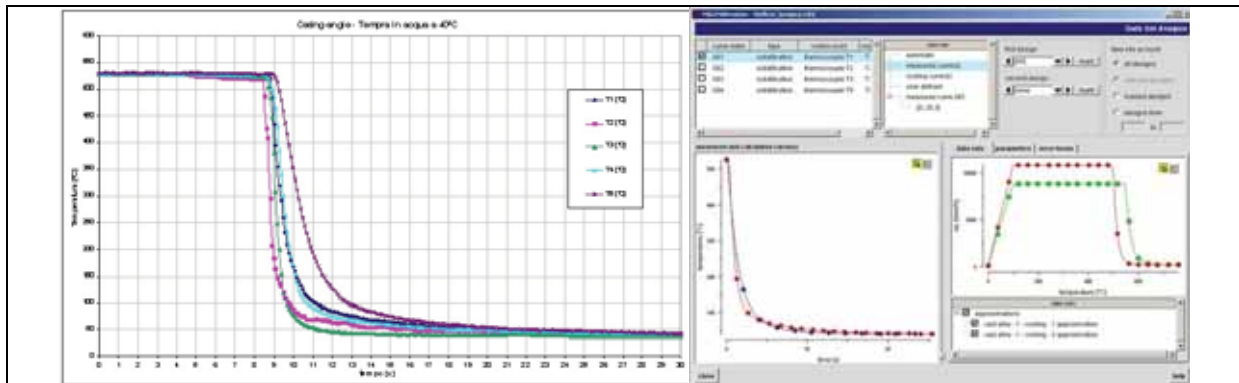
Figure 10 – Results of the reverse engineering process performed for the calibration of the heat-transfer coefficient during the water quenching

This quenching heat-transfer coefficient has been used as boundary parameter of the thermal analysis. It's easy to understand how the thermal evolution during the heat treatment represents the background for further simulation concerning the microstructure (with specific regard to the secondary phases that determine the final mechanical properties) and the residual stress (with specific regard to quenching phase that can lead to the component deformation of fracture).
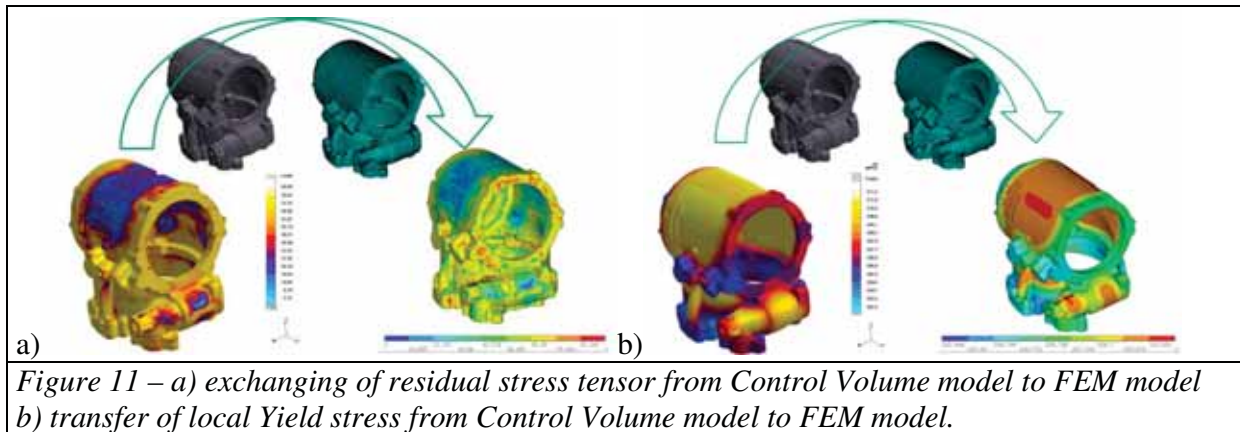
Integrated Design_Chain approach

The virtual prototype development needs an integrated method between the casting process simulation tool and the numerical response (based on FEM code) of the component at in-service conditions.

The connecting link of different tools with non-consistent solid mesh of finite elements (e.g. Control Volumes and Tetraedric Solid Element) calls for an appropriated interpolation method and specific numerical routines to apply the new information as starting point of the mechanical response. In view of this link, the interesting data are the residual stress after heat treatment, the local mechanical properties at the end of the artificial ageing and the local weakness due to the porosity defects as well.

Of course, the predicted residual stress/strain at as-cast status is available to estimate the possible cracks initialization but it is nullified by solution heat treatment and the visco-plasticity phenomena. The advanced CAE tool can simulate the stress evolution during quenching and the successive stress relaxation at ageing heating phase to share this information with FEM structural codes (Fig.11a).

The possibility of performing heat treatment is a key issue to improve mechanical properties in some Aluminium based alloys. In particular, the diffusion process, active during artificial ageing, is strictly dependent on the amount of solute in α-Al matrix at the end of the quenching stage. Such an amount is correlated to the cooling rate induced by the quenching medium adopted. At rising cooling rates the amount of solute at room temperature increases, leading to a more efficient precipitation and improved mechanical properties after ageing.

A more sophisticated numerical routine can import the local mechanical properties (e.g. elastic modulus, yield stress, ultimate tensile stress and corresponding elongation) from the heat treatment simulation tool and export them to the FEM software considering also the possible local defect impact (Fig.11b) .

Figure 11 – a) exchanging of residual stress tensor from Control Volume model to FEM model b) transfer of local Yield stress from Control Volume model to FEM model.

CONCLUSIONS

The CAE approach here described has been supported and confirmed by the experimental tests and therefore constitutes an innovative method for a component virtual prototype, considering the interactions between the productive process and the on-stream performance.

The as-cast component analysis has been completed as scheduled and the prediction and transfer of the local mechanical properties and the tensile state to the FEM computation codes currently in use at AVIO.

This objective clearly requires a multi-scale evolution of the numerical simulation systems including, beyond the traditional macro-scale approach, a suitable micro-modeling for micro-defect prediction and the elaboration of the microstucture characteristics (grain size, SDAS, morphology and size of the eutectic silicon and intermetallic phases) that determine the material mechanical properties.

The detailed knowledge of the manufacturing process, at its different stages (from casting to heat treatment and machining) and scale factors, can be virtually implemented and exploited, considerably benefiting the design phase, to increase the component reliability and the company competitiveness.

Acknowledgement

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