The Multidisciplinary Virtual Product Development Integrates the Influence of Die Casting Defects in the Mechanical Response

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The multidisciplinary virtual product development integrates the influence of die casting defects in the mechanical response

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Abstract. The performance of an Al alloy component when tested under dynamic conditions is defined on the basis of the amount of the absorbed energy during impact and the dampening rate of the striker. These tests can be complex and costly, and sometimes difficult to be realized for some specific components. An useful and "ideal" approach could be the use of numerical simulation tools for virtually testing, but this objective actually remains an ambitious approach, since it requires a deep research of the factors that determine the elasto-plastic material behavior up to fracture. Even more difficult is the characterization of the material in the case of Al alloy diecastings, where the mechanical properties strongly depend on casting defects.
By linking mechanical results with numerical simulation data of filling and solidification, a through-process model is developed to predict the defects' location and amount, thus the structural behavior of die cast components. Furthermore, with particular reference to one demonstrator component, an high pressure die cast steering housing, the innovative correlation between defects (e.g. air inclusion, shrinkage porosity etc.) and mechanical properties has been implemented in MAGMASOFT® simulation tool in order to transfer the realistic local ultimate tensile strength to LS-Dyna FEM code. The multi-objective optimization strategy has been applied to minimize the air entrapment and maximize the local mechanical properties of Al alloy. The final full integrated, and more realistic, approach permits to estimate the single effect of proper Al diecasting design, remaining defects and residual stress on the absorbed energy under impact condition.

Keywords. Numerical simulation, HPDC, casting defects, mechanical properties, integrated approach, process optimization

1 Introduction

In the automotive sector, high-pressure die-casting (HPDC) is the preferred foundry process; it is versatile and appropriate for highly engineered components. Unfortunately, a limit to large diffusion of HPDC remains the final integrity of castings. The high injection rate of the metal causes turbulences, which form internal and surface defects, such as gas entrapment, and the variable thicknesses of the component itself can lead to a reduced effect of the intensification pressure on the solidification shrinkage [1-3]. Although the classification of diecasting defects is clear, an advanced study is required to understand the correlations between the type, dimension and form of defects and the mechanical properties of diecastings. The first model from this study is described elsewhere [1, 2].

In the present paper, the final quality model is described and applied to a Steering Pinion, i.e. a safety component requiring high quality standards in order to guarantee that it stays oil tight under pressure, and to assure proper fatigue resistance and ductile behavior in case of impact.

2 Simulation and optimization of the die casting process

The design and review of the die cast steering pinion followed the work-flow reported below and acting on a virtual level, before the final physical dynamic testing:

1. process simulation of the existing version of the pinion, and optimization of the HPDC process in order to enhance the quality of the component;
2. identification of the local mechanical properties and residual stresses, and transfer of these information to FEA code for impact analysis;
3. impact simulation using the new model, the pre-stress condition due to residual stresses, and the local mechanical properties at the end of the manufacturing process, in order to determine the most realistic amount of absorbed energy.

2.1 Process simulation of the original version of the casting

The first virtual analysis was performed by using the actual manufacturing parameters and the operating thermal regime of the die. This evidenced the possible causes of filling and solidification defects, with the resulting localized reduction of the mechanical properties. The CAD models, the materials, the lubrication and the movement of the die parts in the production cycle were imported in the software to simulate the thermal behavior of the die. The virtual results were compared with thermal maps acquired by IR camera.

In particular, the analysis showed that the most evident porosity in the casting is due to air/gas entrapped in the center of the area with the greatest thickness. Cross-sections made of the parts and X-ray NDT investigations identify the defect distribution and morphology. The experimental results were in accordance with numerical simulation ones (Fig. 1).

Despite a noticeable variation of thicknesses in the original casting design, the central area of the component, which undergoes the maximum stresses under impact testing, showed some minor interdendritic porosity, mainly located far from the beneficial compacting action resulting from the applied overpressure. An accurate simulation of the cooling rate and the prediction of positions and dimensions of the aforementioned defects represent the basis for working out the local mechanical properties, as further explained.

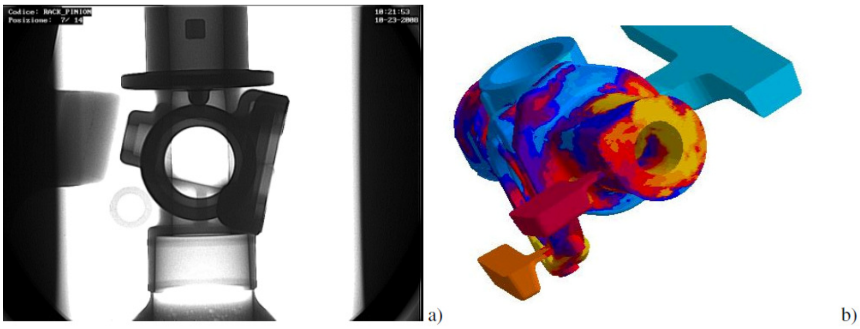

Fig. 1. a) X-ray image in comparison with b) defect prediction by numerical simulation

2.2 Optimization of the die casting

The initial objective of optimizing the mechanical properties of the component can be achieved by modifying the geometry of the component or by varying the diecasting system and the process parameters. Firstly, the thickness of the central cylindrical area was reduced. Furthermore, by using an automatic optimization technique, which allows an advanced research of a multi-objective problem [4, 5], the effect of a single geometric modification to the component was analyzed. The approach adopted is divided into two optimization steps:

- the first step considers the variations of the section of the two gates without any change in the shape of the existing gating and using the original process parameters (solution named ID241);
- the second step analyzes a wide range of all possible modifications and variants in order to search out the highest possible quality of the die-casting component (solution named ID882) while respecting the constraints imposed by the already existing die, i.e. extractors, orientation, cooling channels, etc..

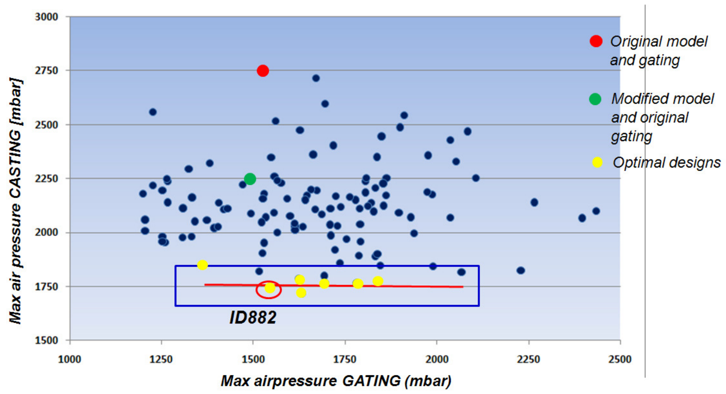

Fig. 2. Possible designs for steering pinion plotted as function of the critical overpressure in the casting and the maximum overpressure in the gating system

The design configurations close to the axis of origin minimize even more the aforementioned objectives, but do not respect the minimum temperature of the molten metal at the gate. Fig. 2 evidences the substantial improvement obtained both in comparison with the original version and with the introduction of the new component with a thickness reduction in the central area (green point in Fig. 2).

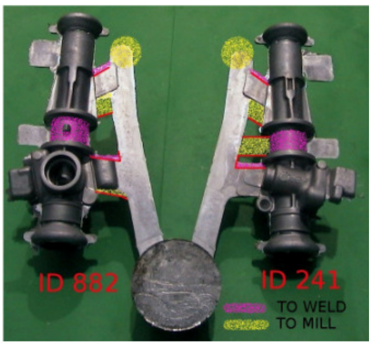

Fig. 3. Integration of the optimized configurations, ID882 and ID241, in the existing die

The two main objectives of the optimization process are the minimum quantity and pressure of gas entrapped in the casting, and the reduction of the gating system volume, with the simultaneous reduction or absence of turbulence in the same gating. Among the possible designs analyzed by numerical simulation, the design identified as ID882 was chosen, being the best compromise between the dimension and concentration of the residual gas bubbles in the component (measured by the critical volume of the overpressure) and the maximum pressure and dimension of these (the air overpressure) (see Fig. 2). The suggested configurations, namely ID882 and ID241, were integrated in the same die as shown in Fig. 3. The experimental investigations carried out on the castings confirmed the results expected from numerical simulation.

3 Determination of the local mechanical properties and residual stresses

The effects of process parameters on material properties were experimentally evaluated by using a multicavity die, which enables to cast specimens for mechanical testing. The multicavity die was used to produce castings with different injection parameters and constant geometry model. Microstructural analysis of cross sections shows the presence of several defects, such as cold shut, segregation bands, oxide films, iron-bearing phases and air/gas bubbles entrapped during mold filling. These defects are typical of the high pressure die casting process, and all specimens contain them, but the amount and distribution vary with the process parameters used [2, 6].

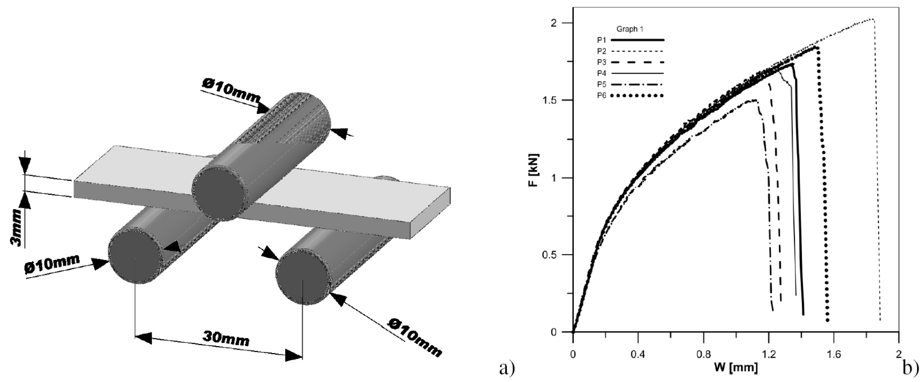

Fig. 4. a) Sketch of three point bend test adopted in this work; b) experimental measurements of force (F) versus displacement (W) obtained in bending tests

The bending tests were performed on specimens drawn from a plate produced by the above-described multi-cavity die and the mechanical results were directly correlated with numerical simulations without performing any determination of defect amount. The configuration for the three point bending test is schematized in Fig. 4a., according to ASTM E290-09. As observed in Fig. 4b, the process condition named P5 produced the worst mechanical properties. This is due to the highest metal velocity produced, which causes a turbulent flow and greater gas entrapment. The same variation of process parameters has been applied at virtual level by using the MAGMAhpdc module in order to simulate the filling and solidification behavior of multicavity die. Fig. 5 shows air-pressure and air-entrapment images of a region of the plate diecast with P5 process parameters. The X-ray image, acquired from the same location, evidences a good agreement between numerical simulations and experimental data.

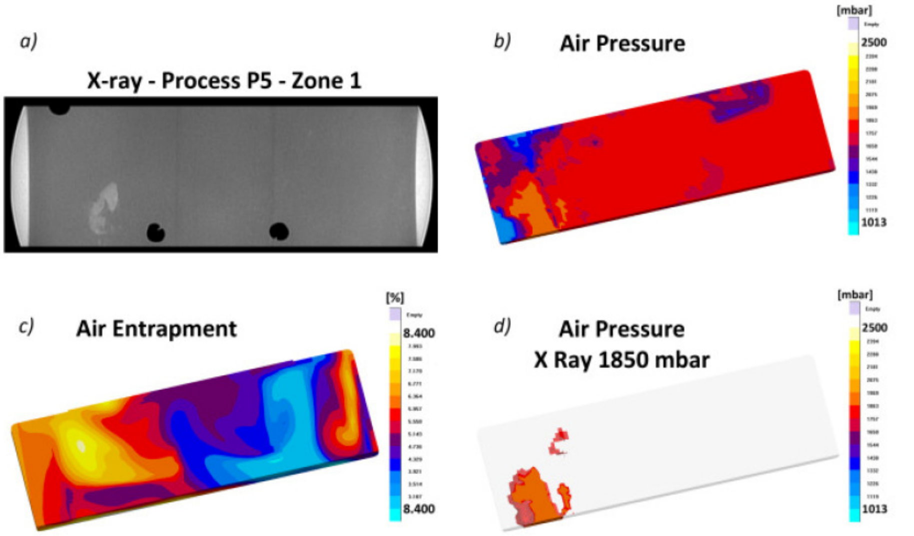

Fig. 5. Coherence verification of the numerical simulations of process P5 : a) X-ray images of diecast plate; b) air-pressure criteria; c) air-entrapment criteria; d) air-pressure representation with a value greater than 1850 mbar

For each specimen the simulations results were correlated each other. The aim was to find an empirical relationship between them and the mechanical properties (particularly UTS). The final suggested model, with normalized coefficients, is:

$$\mathrm{UTS} = \mathrm{A} - \mathrm{B}\times \textit{meanairp} - \mathrm{C}\times \textit{meanflowlen} - \mathrm{D}\times \textit{meanaircontact} - \mathrm{E}\times \textit{diffcoolrate} \quad (1)$$

where UTS is Ultimate Tensile Strength [MPa]; *meanairp* is the mean value of air pressure [mbar] and it identifies the position, severity and dimension of gas entrapment; *meanflowlen* is the path length of the melt [mm] and it shows the possible cooling of the alloy and the impurities due to a less homogeneous fluid-dynamic behavior; *meanaircontact* is the time of metal front in contact with air [sec] and it indicates the degree of risk of oxide formation; *diffcoolrate* is difference between maximum and minimum value of cooling rate in the thickness [°C/s] and it identifies the possible regions of shrinkage porosity.

A “quality mapping” approach [2] was then applied to the steering pinion in order to support advanced design (Fig. 6). By means of a proper tool, this approach can elaborate results from numerical simulation (mold filling, thermal field, defect prediction criteria), with the aim of visualizing the final quality of the casting in terms of defect localization and criticality, local distribution of residual stress and mechanical properties. In comparison to the original cast component which was used as a reference, the last optimization of the shape and process parameters shows that the maximum value of ultimate tensile strength of the material is always in the range of 296-298 MPa.

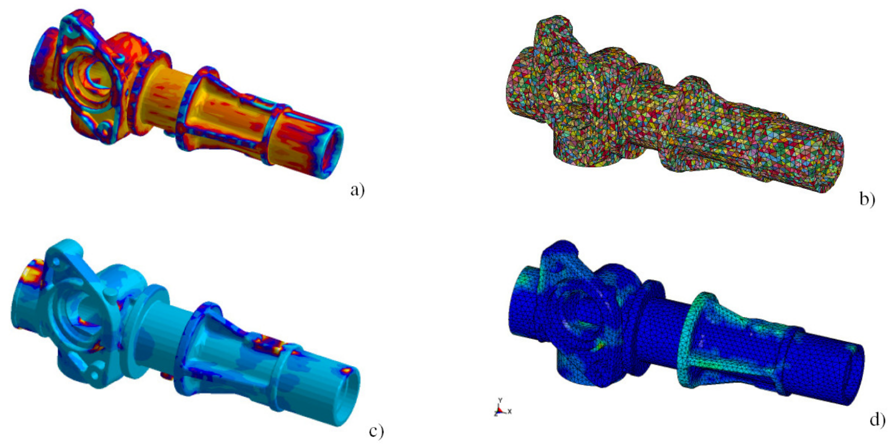

Fig. 6. Mechanical properties (UTS) and residual stresses transferred from a CV to a FEM program: a,b) local UTS properties prediction; c,d) residual stress distribution

4 The innovative integrated approach

In order to appreciate the effect of the methodology of integration of process simulation and impact simulation, the results of the impact simulation, performed using original geometry and process (curve A) and assuming homogeneous mechanical properties and no residual stress, are compared in Fig. 7a with three different design approaches:

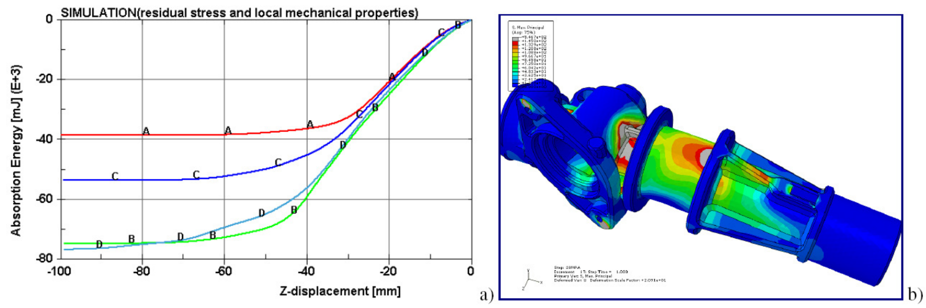

Fig. 7. a) Comparison between the results of different impact simulations; b) result of impact test simulation

- curve B) represents the modified model along with the optimized die casting process, without applying the integrated approach;
- curve C) represents the original model and die casting system, but considering the prediction of the localized mechanical properties and the residual stress state;
- curve D) represents the modified model and optimized die casting system, using the integrated approach.

In other terms, the similarity of curves B and D (+3% energy absorbed) is backed up by the local UTS values which are very close to the values normally used in "sound" material.

5 Conclusions

The present work describes an integrated approach between process simulation and impact test evaluation of a diecast component, in order to perform a virtual, but realiable, verification of the life of the component from the production stage up to the impact test. The methodology illustrated is specifically directed at the die casting field of light alloys, as it was demonstrated in the practical application on the component studied, and addresses particularly the stages of product design and development which take place in engineering and design offices, in die casting foundries and in end-users industrial companies.

The innovative aspect of the proposed method does not consist in the use of simulation software for the process or the mechanical response, both highly adopted in their fields of application. It consists in the prediction of the mechanical properties as a function of the process, in the prediction of the quality distribution in diecastings and finally in the communication between the different software applications. This makes possible to visualize the realistic mechanical behavior of the cast product and consequently allows the validation and prediction of the mechanical response of the diecast component at in-service conditions.

Acknowledgements. This work was developed with the financial support of the European Project NADIA (New Automotive components Designed for and manufactured by Intelligent processing of light Alloys, NMP-2004-SME 3.4.4.5, contract n.026563-2).

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