Thermo-fluid dynamics model of two-phase system alloy-air inside the shot sleeve in HPDC process

In HPDC manufacturing process, the final quality of castings is related to the injection phase: the dynamics of formation of melt waves and their reflection on the walls of the sleeve can cause defects due to air entrapment during filling. The development of numerical and mathematical models are described in the present article. The numerical model consists in the implementation of thermal equation into the open-source CFD code openFOAM™. The mathematical model consists in a Design Of Experiment (DOE) generation and execution using the previously created model. They have permit to study the correlations obtained by Response Surface Methodology (RSM) between the percentage of trapped air in function of the relevant variable parameters of the process.

Introduction

In HPDC process, the final quality of castings is related to the first stage of injection. During this phase, the wave system in the melt due to plunger acceleration causes air entrapment, inducing air porosity into the component. This could have a detrimental effect on mechanical properties and produces internal and surface defects. To prevent these phenomena, it is important predict how the relevant process parameters are correlated to air porosity and then keep them under strictly control. In the present work, this objective has been achieved through the development of a numerical model that describes the thermo fluid dynamics behavior inside the shot sleeve. The developed solver has been used to simulate several designs with different combinations of input parameters: the designs have been generated using a mathematical model through DOE techniques.

The models allow to determine the response surface that has been used to analyze the percentage of entrapped air.

Numerical Model

The aim of this phase of the project has been the development of the solver that permits to calculate the dynamics of the two-phase system alloy-air inside the shot sleeve.

The solver has been implemented in the CFD framework OpenFOAM™: it is based on the existing "interDyMFoam", solver for two incompressible, isothermal immiscible fluids using a Volume Of Fluid (VOF) phase-fraction based interface capturing approach, with optional mesh motion. This solver takes into account most of the physical phenomena that govern the fluid motion inside the shot sleeve, its main features are (Fig. 1):

- Multiphase flow, which enable the description of the two phase system alloy-air;
- Incompressible fluids, reliable also for the air phase because the stream velocity is relative slow;
- Dynamic mesh, which allow considering the movement of the plunger.

A preliminary study on the fluid-dynamics equations and discretization methods has pointed out the necessity to customize the existing solver because of one of its main features: the isothermal assumption.

The solver has been modified and expanded by adding features:

- The energy equation (Figure 2) has been added to the existing Navier-Stokes transport equations. Also, it has been necessary to implement the temperature field.
- Variable thermo physical properties as a function of the temperature field. In this way the fluid properties become fields itself because they depend on temperature, time and spatial coordinates. These properties are: density (ρ), thermal conductivity (λ), specific heat (c_p) and kinematic viscosity (ν). The user can manage different type of aluminium alloy by implement the curves that describes properties variability as a function of temperature.

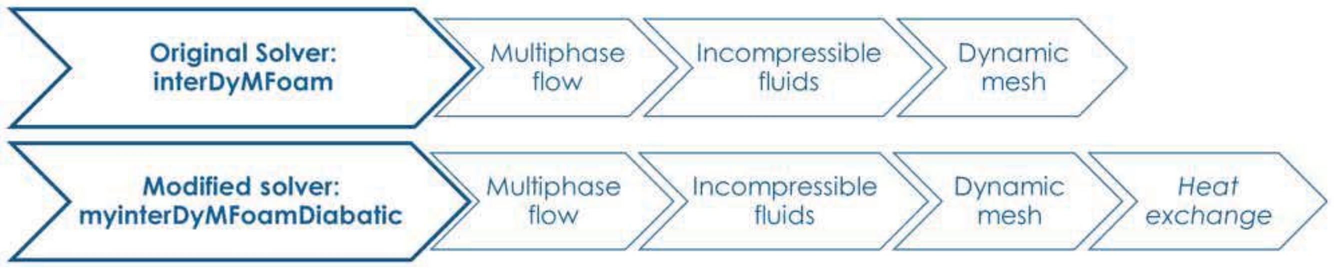


Fig. 1 - Physical phenomena taken into account for the original solver and modified ones.

$$\frac{\partial(\rho i)}{\partial t} + \nabla \cdot (\rho i \boldsymbol{u}) = -p \nabla \cdot \boldsymbol{u} + \nabla \cdot (\lambda\, \nabla \mathrm{T}) + S_i$$

Fig. 2 - Transport equation for internal energy i

Fig. 3 shows the algorithm of the modified solver. The thermal equation is solved at the end of the internal and temporal loops. The first one updates all the fields for each time step and the second one increments the temporal variable and then repeats all the steps.

Using the implemented solver it has been possible to simulate the first phase of HPDC process: the details of this step will be described next. Fig. 4 contains a representative frame of a simulation that shows a half of the shot sleeve, the separation surface and temperature field.

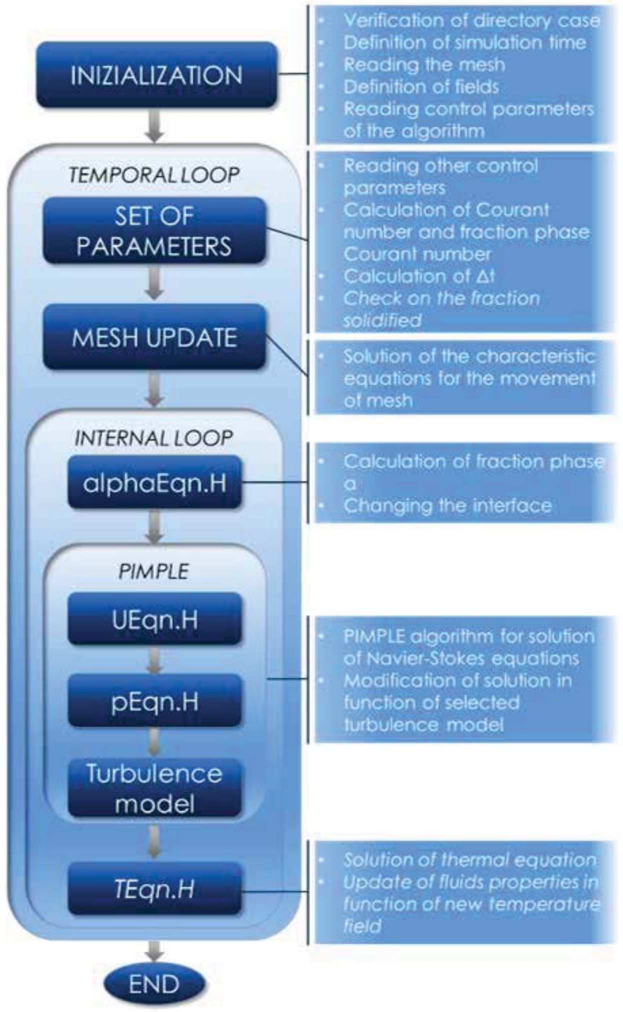


Fig. 3 - Algorithm for the numerical model implemented into a CFD code. Parts in italic font represent changes to the original solver

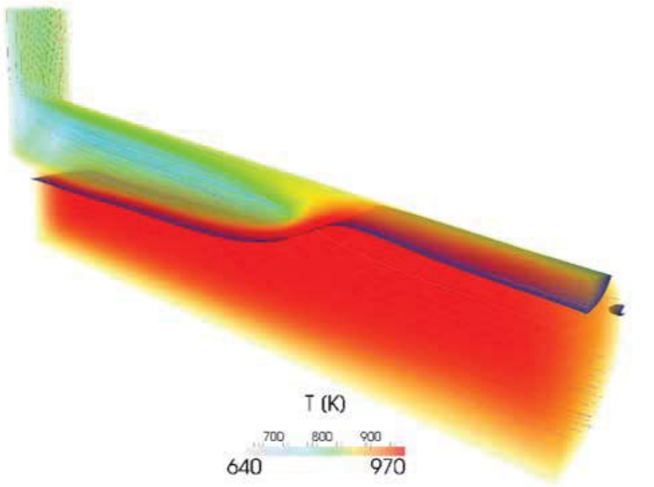


Fig. 4 - 3D view of computational domain used to describe the system inside the shot sleeve. As can be seen, only a half of cylinder has been implemented. This frame shows temperature field and separation surface between air and melt alloy

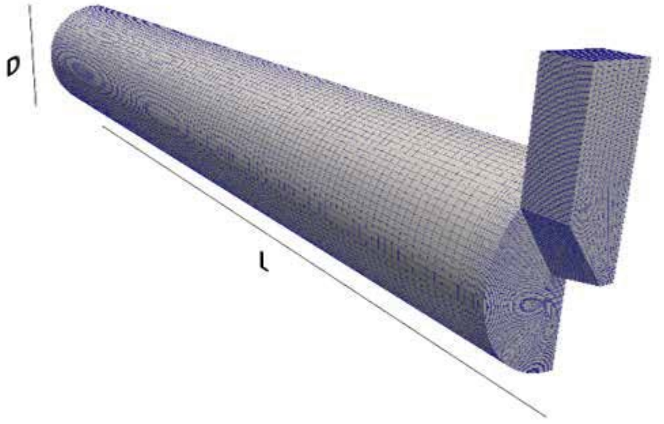


Fig. 5 - View of the computational domain discretized using a finite volume the mesh

MATHEMATICAL MODEL

Design model

HPDC process are controlled by a very high number of process parameters that influence the quality of the cast parts. Among all the influencing variables two geometrical (diameter and length of the shot sleeve) and two process parameters (initial filling of the shot sleeve and first phase velocity) have been defined as relevant, based on the HPDC process knowledge: they are the inputs for the DOE.

Internal diameter (D) and length (L) have been chosen to describe the geometry of the shot sleeve. All other dimensions have been parameterized as a function of these two variables. A finite volume mesh has been employed for properly describing fluid flow phenomena. Finally, only a half of the shot sleeve has been modelled and simulated (using symmetry boundary conditions on the middle plane) to save computational time (Fig. 5).

The third parameter is initial filling (F): it represents the initial volume of the melt into the shot sleeve (percentage value of the entire volume) and it is strictly correlated with its initial height (Fig. 6) once the diameter and length have been defined for each single

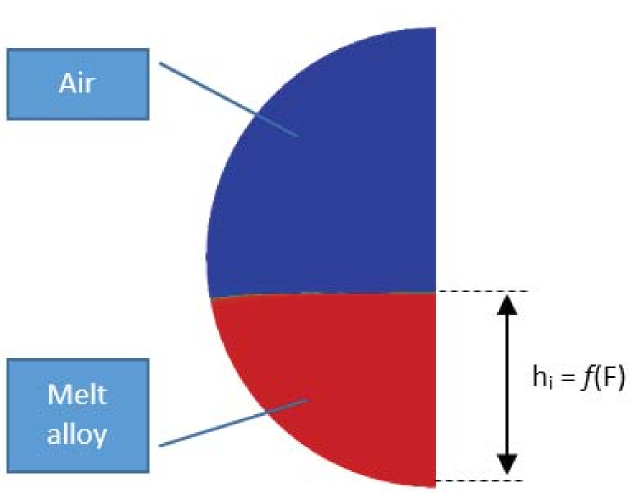


Fig. 6 - Initial filling of the shot sleeve

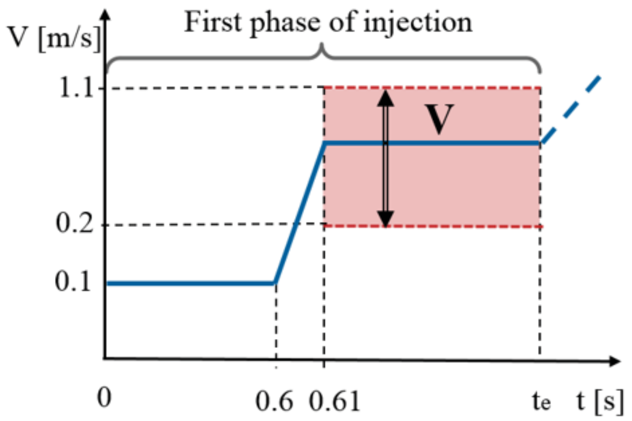


Fig. 7 - Shot profile implemented for the first phase of injection

design.
The fourth parameter is the first phase velocity (V). The shot profile of the first phase of injection presents a first section with reduced (and constant for all designs) speed to avoid leakage and a second section at a constant velocity V (Fig. 7): the velocity profile has been implemented in the solver trough a boundary displacement condition on the plunger wall. This in turn causes the cells to stretch to adapt the whole mesh to the updated dimensions (dynamic mesh motion without topology changes).
All the remaining variables have been set as a function of the four previous input parameters. It has been necessary to define a reliable and consistent condition for the end time of each simulation with the aim to properly compare the results of entrapped air volume percentage belonging to different designs (different geometries, initial filling conditions and velocities imply different simulation times). The simulations end when the total volume of the cylinder is equal to the initial volume occupied by melt alloy (condition of full chamber).

Definition and execution of the DOE

Each design that has been simulated require a reliable value for the input parameters to simulate conditions that are consistent with the real process. To avoid unfeasible designs some constraints have been imposed on combinations between input variables. These consist in:

- Geometric constraints: to avoid "squat" or "slim" shot sleeves, diameter and length combination must respect this empiric relation: -10<D-0.1L<30 [mm]
- An upper limit for the initial filling value has been imposed to 70%;
- In addition, an upper limit of the simulation time has been imposed to remove possibilities for long shot sleeve associated with slow velocity and long filling times. This limit is equal to 2.5 s.

In this way, only the relevant cases in foundry practice have been simulated. As a basis of the planning of the DOE it has been used modeFRONTIER, an integration platform for multi-objective and multi-disciplinary optimization. SOBOL algorithm has been adopted to uniformly distribute a given number of experiments in the design space (standard practice when the final target is the creation of a predictive model), with respect to the upper and lower limits for each input variable and the four described constraints (Fig. 8).
The algorithm returns a table that reports, for each row, the values of the four input variables (D, L, F and V, Fig. 9). Some bash scripts have been developed for the creation of the execution of all designs for automate purpose of the entire procedure. The scripts read each row of the DOE table, write all necessary files in the directories structure to initialize every simulations and add them in a queue on the cluster system. The simulations require a lot of computational power: for this project, it has been allocated 64 processors divided in groups of eight (8 simulations with 8 processors for each have been executed simultaneously). The whole DOE simulation has required about of 5 months.

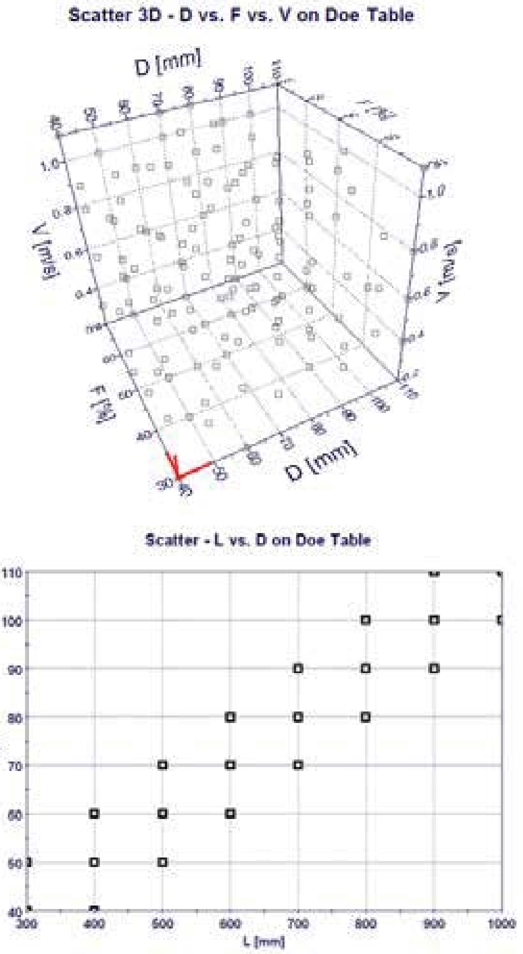
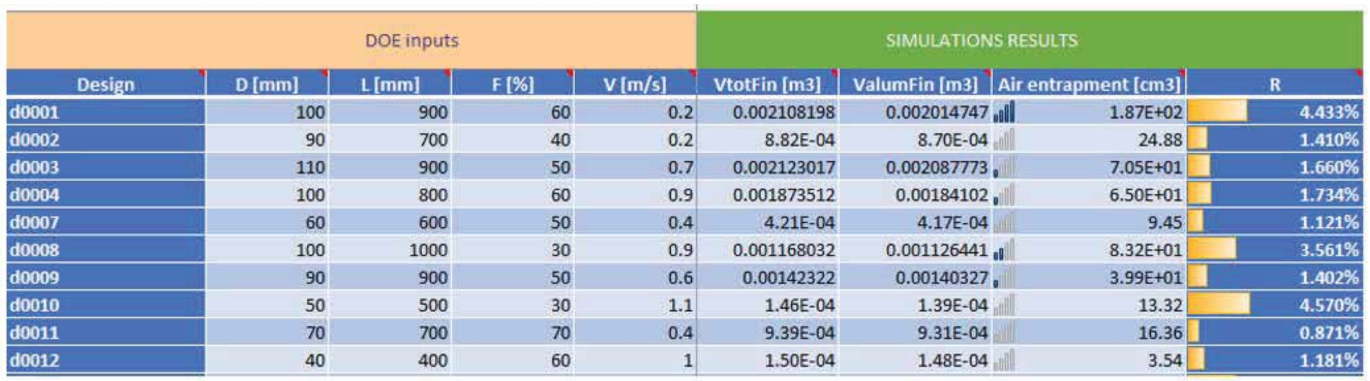


Fig. 8 - Two example graphs that show the distribution of experiments in the design space. The graph a) gives the idea about the constraints imposed on the geometric variables



	DOE inputs				SIMULATIONS RESULTS			
Design	D [mm]	L [mm]	F [%]	V [m/s]	VtotFin [m3]	ValumFin [m3]	Air entrapment [cm3]	R
d0001	100	900	60	0.2	0.002108198	0.002014747	1.87E+02	4.433%
d0002	90	700	40	0.2	8.82E-04	8.70E-04	24.88	1.410%
d0003	110	900	50	0.7	0.002123017	0.002087773	7.05E+01	1.660%
d0004	100	800	60	0.9	0.001873512	0.00184102	6.50E+01	1.734%
d0007	60	600	50	0.4	4.21E-04	4.17E-04	9.45	1.121%
d0008	100	1000	30	0.9	0.001168032	0.001126441	8.32E+01	3.561%
d0009	90	900	50	0.6	0.00142322	0.00140327	3.99E+01	1.402%
d0010	50	500	30	1.1	1.46E-04	1.39E-04	13.32	4.570%
d0011	70	700	70	0.4	9.39E-04	9.31E-04	16.36	0.871%
d0012	40	400	60	1	1.50E-04	1.48E-04	3.54	1.181%

Fig. 9 - Excel spreadsheet that reports inputs and outputs for each design. Inputs derive from SOBOL algorithm of modeFRONTIER and the results originate from an OpenFOAM function and transcribed in this table with a script

Application of a RSM

The aim of this work is the determination of a predictive model that enable the correlation between "entrapped air" and some relevant process parameters during the first phase of HPDC process. The "entrapped air" is the volume of air inside the fluid domain at the end of the first phase of injection. To compare results for different geometries it is not possible to adopt the absolute value of air volume (to bigger shot sleeves correspond also greater air volumes). For this reason, the "rate of trapped air" R has been introduced. It is calculated by dividing the final volume of air (Vair) respect the final total volume of the fluid domain (Vtot).

$$R = \left(\frac{V_{air}}{V_{tot}}\right)_{end\ simulation}$$

The R values are now comparable between designs. The predictive mathematical model consists in the definition of the response surface achieved through Response Surface Methodology (RSM). The next validation procedure has been adopted to find the algorithm with the best fit: the entire DOE table has been split into two distinct tables, named "training table" and "validation table". The "validation table" contains 10% of the total number of designs. Some functions (response surfaces) have been generated, based on the "training table", using different types of algorithms (Gaussian Processes, Kriging, Radial Basis Function, Neural Networks and Multivariate Polynomial Interpolation). The absolute, relative and normalized errors have been evaluated for each functions, based on the "validation table". The errors are defined as the difference between the values of R derived from the simulations and the values of R obtained from the predictive models (Fig. 10). The validation procedure has highlighted that Radial Basis Function algorithm interpolated in the best way the experimental data and minimize the errors. Therefore the RBF algorithm has been adopted to re-calculate the predictive model function using the entire DOE table.

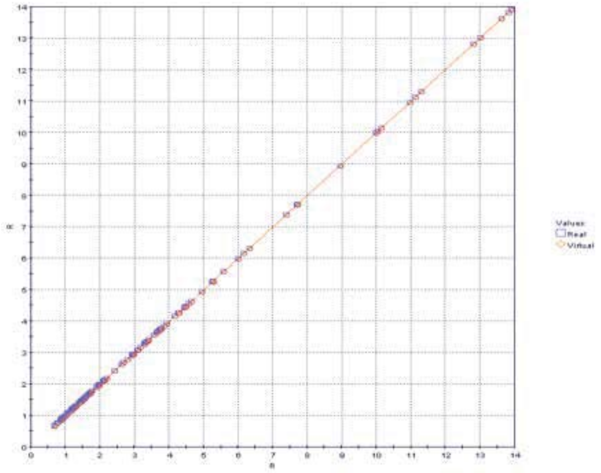


Fig. 10 - Differences between R values derived from DOE simulations (blue line) and the ones obtained from RBF predictive model (orange line)

Obtained results

The predictive model can be utilized to study some different cases of the first phase of HPDC process. With this tool, in fact, it is possible to find the optimal value for one (or more) parameters in function of the other ones. Next, it has been reported two possible way of investigation of the response surface.

Finding of the plunger's optimal velocity with a fixed shot sleeve geometry

One of the main target in HPDC process is the research of the optimal velocity of the plunger to minimize the entrapped air given the geometry of the shot sleeve. With this tool is possible to explore the surface response fixing the geometry variables (D and L) and plotting the R values as a function of V and F into a 3D graph (Fig. 11).
In this way, the process engineer can evaluate the optimal velocity for its initial filling value F (imposed by the volume of the cavity). For example, for F = 50 %, the model reports a minimum value for R at V = 0.6 m/s (Fig. 12).

Ideal shot sleeve choice as a function of the melt volume

If it has to select from two shot sleeve to realize a component, it is possible to interrogate the mathematical model in order to support the choice. The constraint is on the volume of the melt

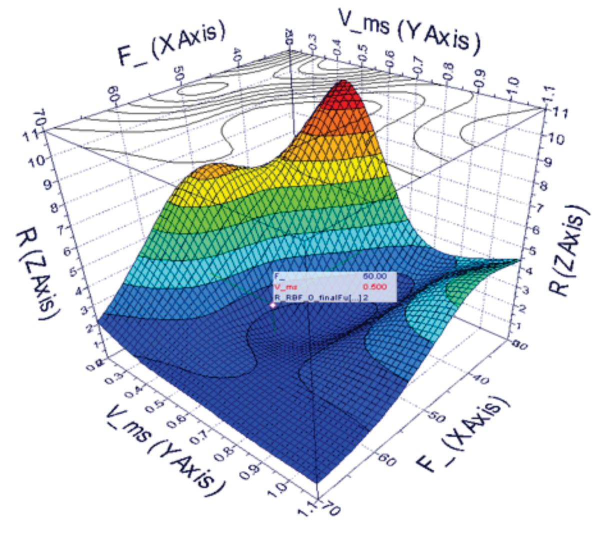


Fig. 11 - Explore 3D graph that reports R as a function of V and F parameters. The geometry variables have been imposed to D = 70 mm and L = 500 mm

alloy that must be equal in all cases. With this value, and knowing geometry (D and L), we can calculate the filling F. It is possible to demonstrate that there is a parabolic relationship between D and F considering L as a constant. Fig. 13 shows this approach to plot the response surface.

Conclusions

The described work has permit to develop a predictive model for air entrapment during the first phase of injection in HPDC process. A new solver has been developed in the open source framework OpenFOAM™. The code is a customization of the solver "interDyMFoam" with adding features such as temperature field, heat exchange, temperature dependent aluminium alloy properties. A DOE has been created using the SOBOL algorithm (133 total designs) considering the inputs parameters (diameter and length of the shot sleeve, initial filling and first phase velocity), their maximum and minimum value and combinations between them that represent relevant cases in foundry practice.

Each design has been simulated using the customized solver. A High Performance Computing (HPC) system has been necessary to run the 133 designs due to the high computational resources required for each simulation (a total of 64 processor have been used for 20 weeks of computational time).

A predictive model has been created based on the simulation results. The function has been created using response surface methodology for which radial basis function algorithm has proved to provide the best interpolation fit to numerical data.

In this way, a parametric shot sleeve and variable process parameters have been related to the entrapped air percentage value in condition of full chamber. The predictive model allows process engineers to choose the best combination of process parameters to avoid air entrapment during the first phase of injection without requiring high time consuming numerical simulations.

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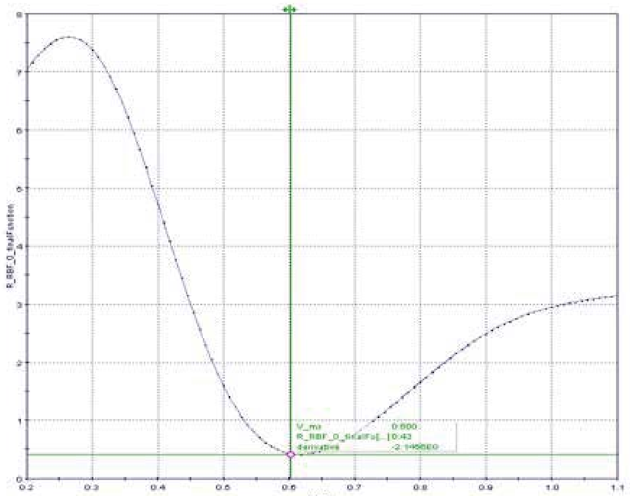


Fig. 12 - Plot of R as a function of the plunger's speed for D = 70 mm, L = 500 mm and F = 50 %. This plot is derived with the 3D graph of Figure 11

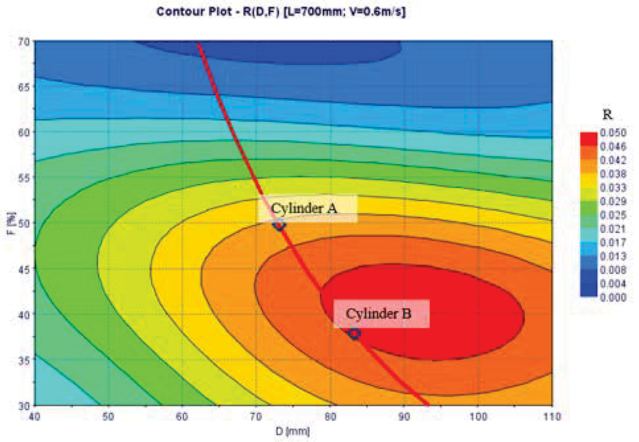
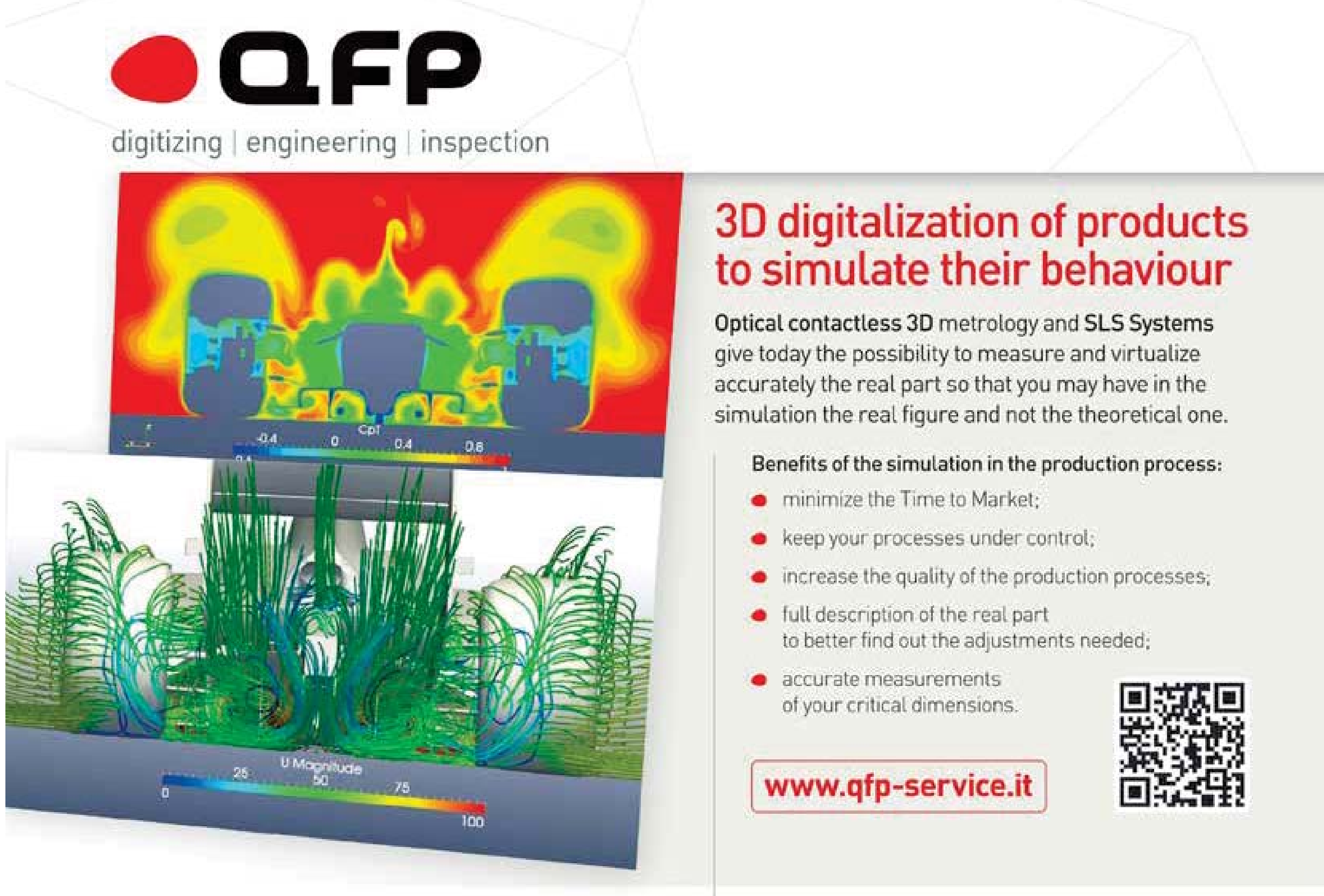


Fig. 13 - Surface response as a function of D and F (with constant value of L and V). The red line represent the conservation of volume law for a given volume of the melt alloy

MUSIC Survey on High Pressure Die Casting Market in Europe

The MUSIC project – MUlti-layers control&cognitive System to drive metal and plastic production line for Injected Components – is about to launch a European survey aimed at collecting useful quantitative information to better understand the quality requirements in particular for the SME companies, widely representative in the High Pressure Die Casting sector.

Collaborate with us and participate in the project survey:
https://music.eucoord.com/Survey/body.pe



The MUSIC Project at the International CAE Conference 2015

At the 2015 edition of the International CAE Conference, the MUSIC Project had the chance to show the Beta version of the MUSIC "Control&Cognitive System" (C&CS) in the Agorà Research, thanks to the support of EnginSoft and the sponsorship of Assomet Servizi srl.

The C&CS, developed by EnginSoft S.p.A., will activate a quality control and cost efficiency loop in the high pressure die casting of light alloys (HDPC) and plastic injection molding (PIM) industry by introducing for the very first time a holistic approach in real time data monitoring, analysis and control of all the phases of the currently fragmented automated production lines.

The two days' event of the CAE Conference provided the ideal context and venue to discuss the increasing relevance of "simulation based engineering and sciences", research and innovation as opportunities to become "smart factories" as required by the current market challenges.

The MUSIC project was also a protagonist in the successful "Foundry session" of the conference with a presentation concerning "Analytical computation of the plunger kinematic parameters affecting quality in HPDC" .

Further information about the project and the abstract of the paper are available at: http://music.eucoord.com/

MUSIC Tour at EUROGUSS 2016

The Consortium of the MUSIC Project invites the visitors of the EUROGUSS International Trade Fair for Die Casting Technology, Processes and Products to visit its partners and get acquainted with their research activities in the High Pressure Die Casting and Plastic Injection Moulding sectors. During the three day exhibition, the MUSIC project will also deliver insights at the International Die Casting Congress, proving once more the relevance and the quality of the results achieved. For further information and to download the flyer of the event go to:
https://music.eucoord.com/Euroguss/body.pe