USE OF SIMULATION TO PREDICT MICROSTRUCTURE AND MECHANICAL PROPERTIES IN AN AS-CAST ALUMINIUM CYLINDER HEAD – COMPARISON WITH EXPERIMENTS

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Abstract

This contribution aims to validate a newly developed add-on module to a commercial simulation software, which enables the prediction of the microstructure and mechanical properties of aluminium cast alloys under different casting conditions. The simulation of the casting process and the resulting microstructure and mechanical properties, permits a reduction of experimental testing and providing the best solution of process and material selections, thereby making the design and development process more cost efficient.

The simulation results are compared with the investigation of the microstructural and mechanical behaviours of an As-Cast Aluminium cylinder head processed by semi permanent gravity die casting. It is demonstrated that the predictions made by the simulations are comparable to the experimental results. In order to further enhance the quality of the simulation tool, it is of significance to gain more experience from comparisons with complex castings of different aluminium alloys, where the microstructure as well as the mechanical properties are carefully evaluated.

Riassunto

Il presente lavoro aspira a validare un modulo software di nuova concezione, e aggiuntivo al pacchetto commerciale di software di simulazione, che permette la predizione della microstruttura e delle proprietà meccaniche di leghe in alluminio in differenti condizioni di colata. La simulazione del processo di colata e delle risultanti microstrutture e proprietà meccaniche, permette la riduzione delle prove sperimentali e provvede al miglioramento della selezione di materiali e processi, consentendo inferiori costi di progettazione e sviluppo.

I risultati della simulazione vengono comparati con le indagini microstrutturali e di comportamento meccanico di una testa cilindri grezza in alluminio prodotta per colata a gravità. Si dimostra che le predizioni ricavate dalla simulazione sono comparabili con i risultati sperimentali. Al fine di migliorare ulteriormente la qualità degli strumenti simulativi, è vitale acquisire maggiori esperienze dal confronto con getti di maggiore complessità geometrica e in differenti leghe di alluminio, dove sia le microstrutture che le proprietà meccaniche siano attentamente analizzate.

KEYWORDS

Casting simulation, aluminium, process simulation, mechanical properties, semi permanent gravity die casting.

INTRODUCTION

The possibility to simulate the microstructure and mechanical properties of complex aluminium components enables the engineers to use the property variation obtained in Al-castings as an input to structural simulation programs such as ABAQUS, and thereby be able to make good progress in e.g. weight optimization issues. The mechanical properties of cast aluminium alloys are very sensitive to composition, casting process, which encounters mould filling and solidification behaviour, and post-processing such as thermal treatment. The coarseness of the microstructure and the type of intermetallic compounds that form and precipitate during solidification, are fundamental to the material behaviour.

Bringing the foundry process closer to the casting designer will lead to a more reliable and more optimised design of complex geometries. Improvement in the degree of integration between processing, metallurgical and mechanical properties of cast aluminium alloys will lead to a shorter lead-time, right from the first design attempt and sounder components which strengthen the competitiveness of the material and foundry industry. The linking between the process, microstructure and mechanical properties has been implemented in commercial simulation software that is described elsewhere [1]. Improved simulation tools will lead to greater usage of simulation technology in the design process and will lower the manufacturing and environmental costs. The simulation process are integrating the design process, manufacturing and material selection process providing knowledge on how the material behaviour and the resulting mechanical performance will be influenced by the manufacturing process. Therefore, enabling the simulation and integration of these processes will lead to substantial shortening of the development time, cost reduction and fewer risks.

This contribution will illustrate the facilities and opportunities that cast simulation of the mould filling, solidification behaviour and the resulting microstructure in terms of Secondary Dendrite Arm Spacing, SDAS, and the mechanical properties of the selected chemical composition and a component may deliver. The SDAS is described as a function of local solidification time, equation 1 [2-3], depicting the fineness of the microstructure constituents where t_s is the local solidification time, and C and n are constants which are related to the material:

$$SDAS = C * ts^n \qquad \text{Equation 1}$$

The validation of the simulation tool is based on commercial As-Cast cylinder head cast with the same alloy as the one used in the simulation and under similar circumstances.

MATERIALS AND EXPERIMENTAL METHODS

Commercial component

The commercial aluminium alloy that is commonly used when casting automotive component is A354. The cylinder head is produced by semi permanent gravity die where the moulds are of steel and the cores are of furan sand with binding agents. In order to obtain a high combination of both strength and elongation, these cylinder heads are also T6-heat treated. Out of the commercial component, some materials were cut and remelted into coins. These coins are then chemically analyzed in order to obtain the actual alloy composition which is presented in table 1. The following investigation concerns only the microstructural and mechanical properties in As-Cast conditions.

Table 1. Alloy composition of the As-Cast, AC, alloy A354

A354	Al	Si	Cu	Mg	Fe	Mn	Zn	Ni	Sr
AC	88,7	9,77	0,85	0,4	0,19	0,02	0,02	0,006	0,0014

Preparation of tensile specimens

Dividing the cylinder head into smaller parts, plate tensile test samples could be extracted and prepared from positions according to figure 1. In order to determine the different quantities of the microstructure such as SDAS and iron rich intermetallics, the fractured tensile samples where grinded and polished. Thereafter, a light microscope and image processing software were used.

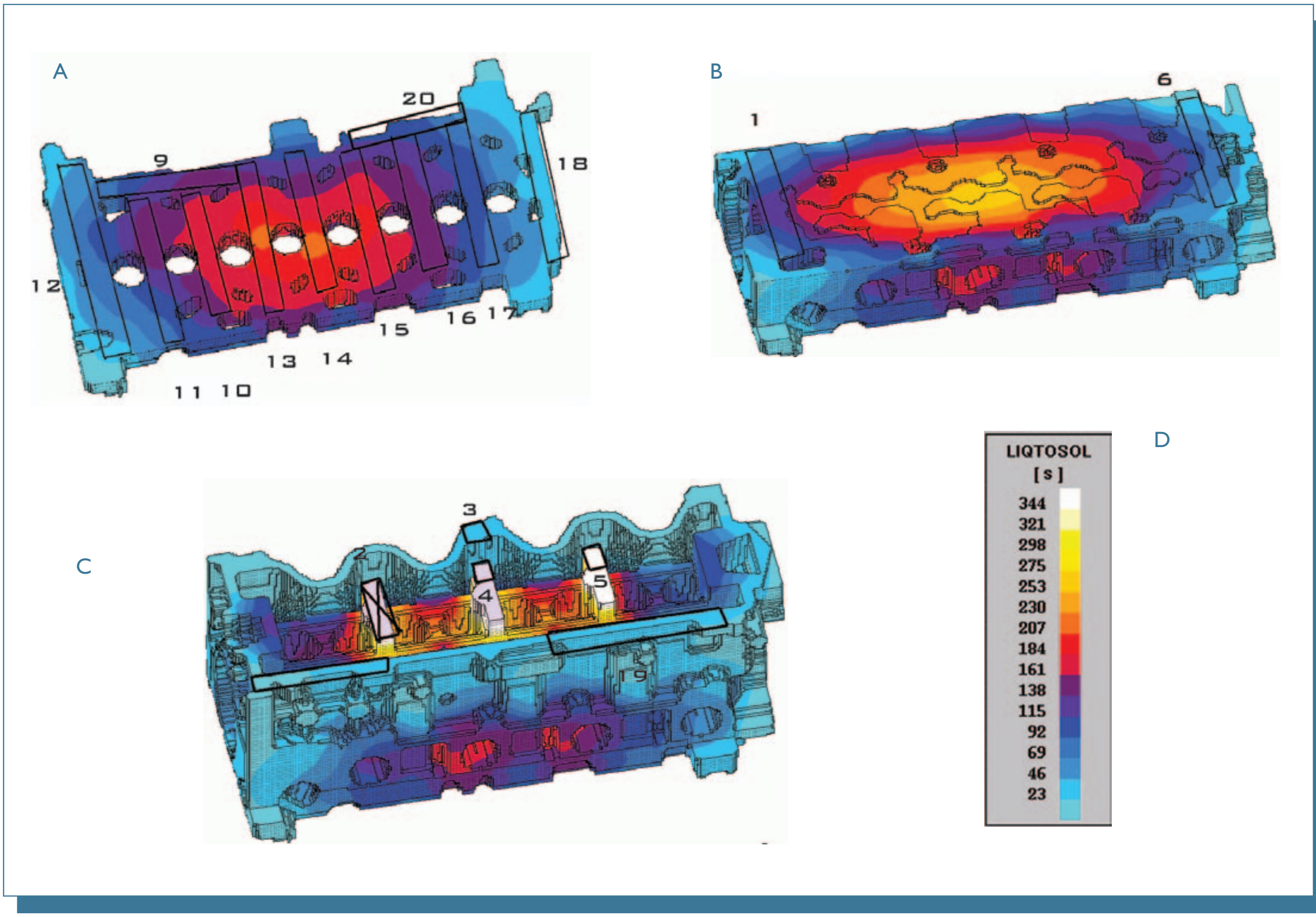

Fig. 1: Illustration of the location of the plate tensile test specimens where a) is the bottom section, b) is the mid section, c) demonstrates the entire geometry and d) denotes the time from liquid phase to solid phase for the different sections of the cylinder head.

RESULTS OF THE TENSILE AND MICROSTRUCTURE PROPERTIES OF THE AS-CAST CYLINDER HEAD

The tensile performance of the plate tensile tests is presented in the graph in figure 2a. The tensile test curve of sample10, figure 2b, shows an appreciable combination of stress and strain. Therefore, this particular curve is used as a reference in order to clearly demonstrate the performance of the rest of the samples from the different locations and the inherent potential of the alloy that could be approached with this particular alloy and casting process.

The microstructure of aluminium cast alloys are widely defined as the distance of the spacing between the dendrite arms in terms of secondary dendrite arm spacing, SDAS. Figure 3a presents the tensile performance of the tensile test samples in relation to the corresponding microstructure. Figure 3b is also illustrating the length of the iron rich needles, Al_5FeSi-β-phase, which act as stress raisers and deleteriously affecting the soundness and performance of the cast material.

Generally, when iron is present, it is assumed that the iron-rich Al_5FeSi-needle-shaped precipitates are degrading the performance of the tensile properties why its length and influence are considered in this investigation, figure 3b. In this case, the data are quite scattered to be able to draw any conclusions. Nevertheless, a trend is revealed pointing out that higher solidification rates, SDAS, promote the formation of long iron-rich needles and also that longer SDAS is lowering the overall mechanical properties that have been measured in this study.

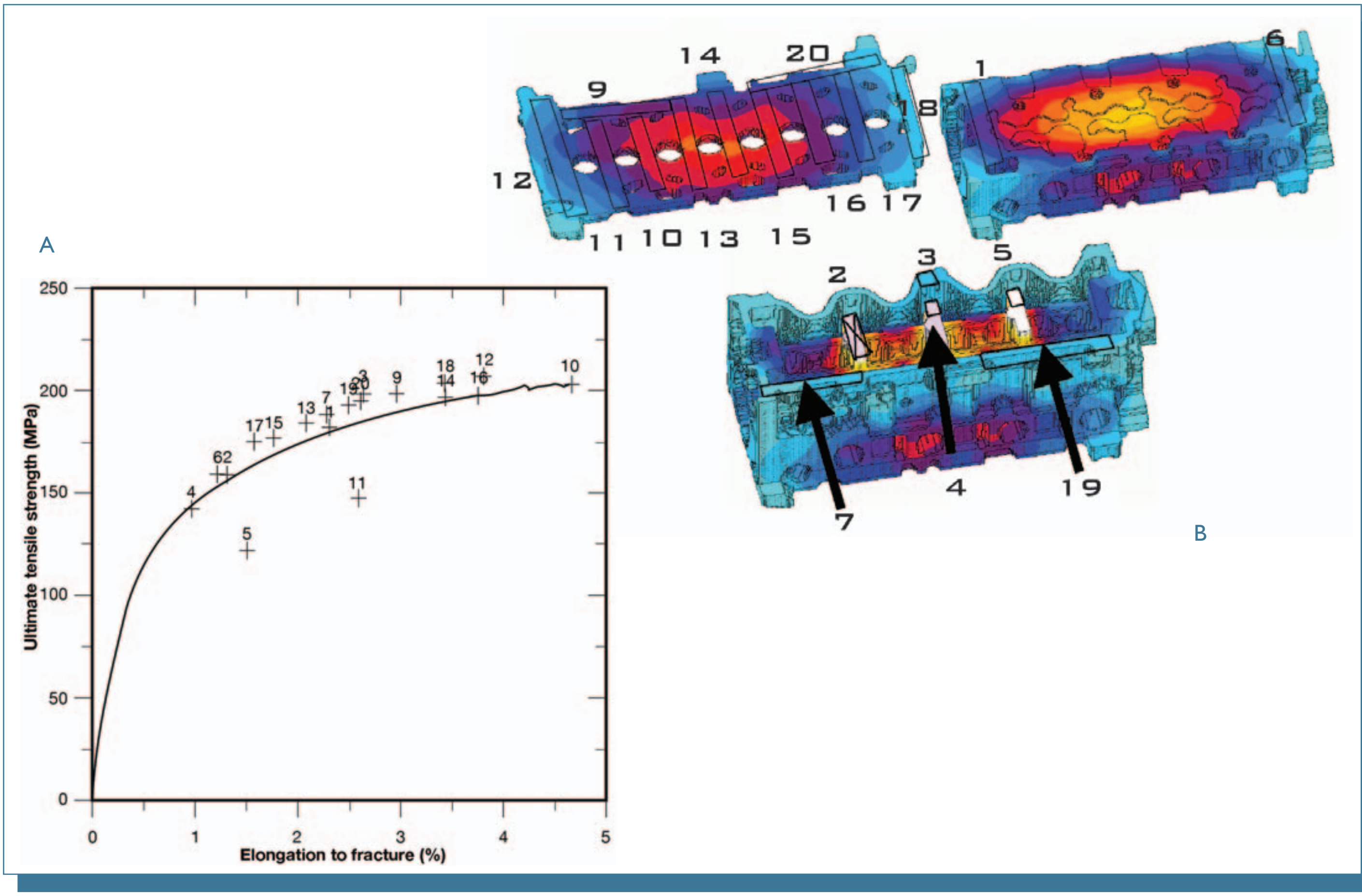

Fig. 2: Presents the tensile performance of the as cast cylinder head and b) illustrates the position of the tensile samples.

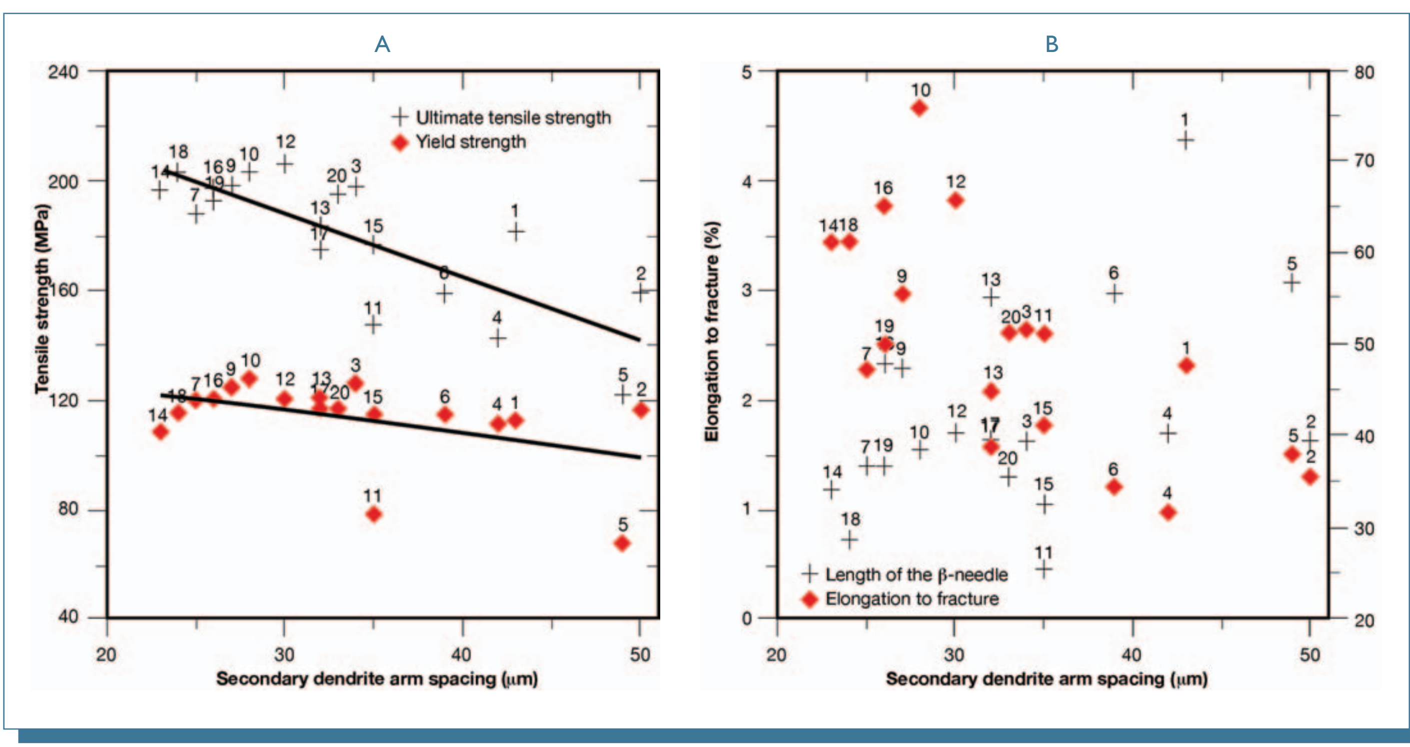

Fig. 3: Presentation of the tensile performance in relation to corresponding SDAS is illustrated: a) Tensile strength versus SDAS and b) is elongation to fracture and β-phase versus SDAS.

RESULTS AND DISCUSSION OF THE EXPERIMENTAL AND SIMULATION INVESTIGATION

The utilization of cast simulation is of significance when designing and developing cast components. Since cast simulation takes into consideration the casting process, which determines the final quality and soundness of a casting, the solidification process, resulting microstructure and mechanical properties could be predicted; therefore a reliable simulation results can be achieved.

EXPERIMENTAL AND SIMULATION RESULTS OF THE SECONDARY DENDRITE ARM SPACING, SDAS

As initial conditions for the solidification and cooling simulation, the temperature distribution of all parts of the casting and mould are calculated. It is obvious from figure 4a and b, that the simulation of the casting process enables the prediction of the local solidification time by means of SDAS rather precise. The bottom section is illustrated in figure 4a, and entire geometry is seen in figure 4b. The upper section in figure 4b is the last part to solidify due the placement of the feeder at that particular place. The figures that are placed on the different sections of the cylinder head are presenting the experimental values.

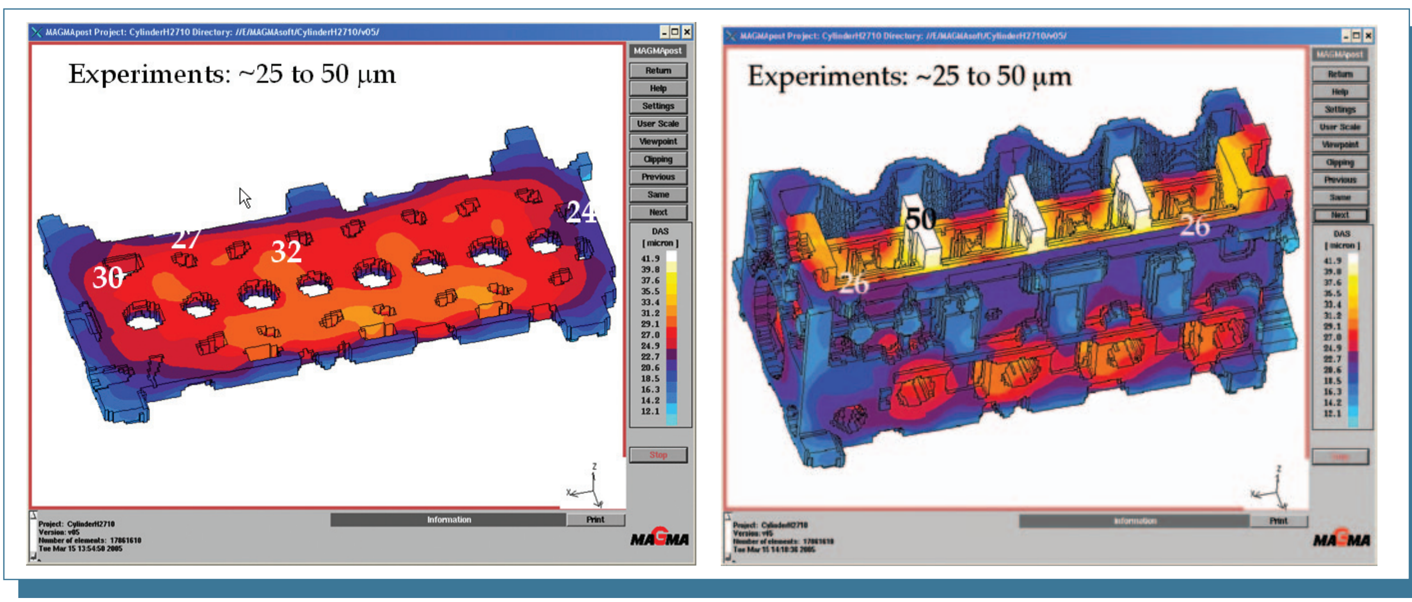

Fig. 4: A comparison between the experimental obtained SDAS and the simulated results. The values that are presented on the sections of the cylinder head are the experimental ones.

EXPERIMENTAL AND SIMULATION RESULTS OF THE MECHANICAL PROPERTIES

The mechanical properties are then calculated, based upon accurate die filling and solidification simulations. The influence of defects such as porosities or harmful intermetallic phases are incorporated in the calculations and assumed as degrading the mechanical performance, especially the ultimate tensile strength and elongation to fracture, by nearly 60%. Today, there exists lack of quantified correlations between defect formation and the mechanical behaviour for aluminium cast alloys, thereby applying that kind of assumptions.

As demonstrated in figure 5, the mechanical properties of the aluminium cast alloy are predicted by using the newly developed add-on module to the commercial simulation software MAGMAsoft. As depicted, the simulation results seem to be reliable, reproducing the experimental data with a good accuracy. The yield strength as seen in figure 5a and b are less sensitive to defects why their influence is not taken into consideration. The ultimate tensile strength is greatly reproduced, but the simulation of the elongation to fracture needs improvement to some extent. Nevertheless, the data of the elongation to fracture that are provided by the simulation tool is appreciable and it should be born in mind that the quality at each part of the casting is depending on the level of defects at the actual zone that is studied and at the neighboring areas.

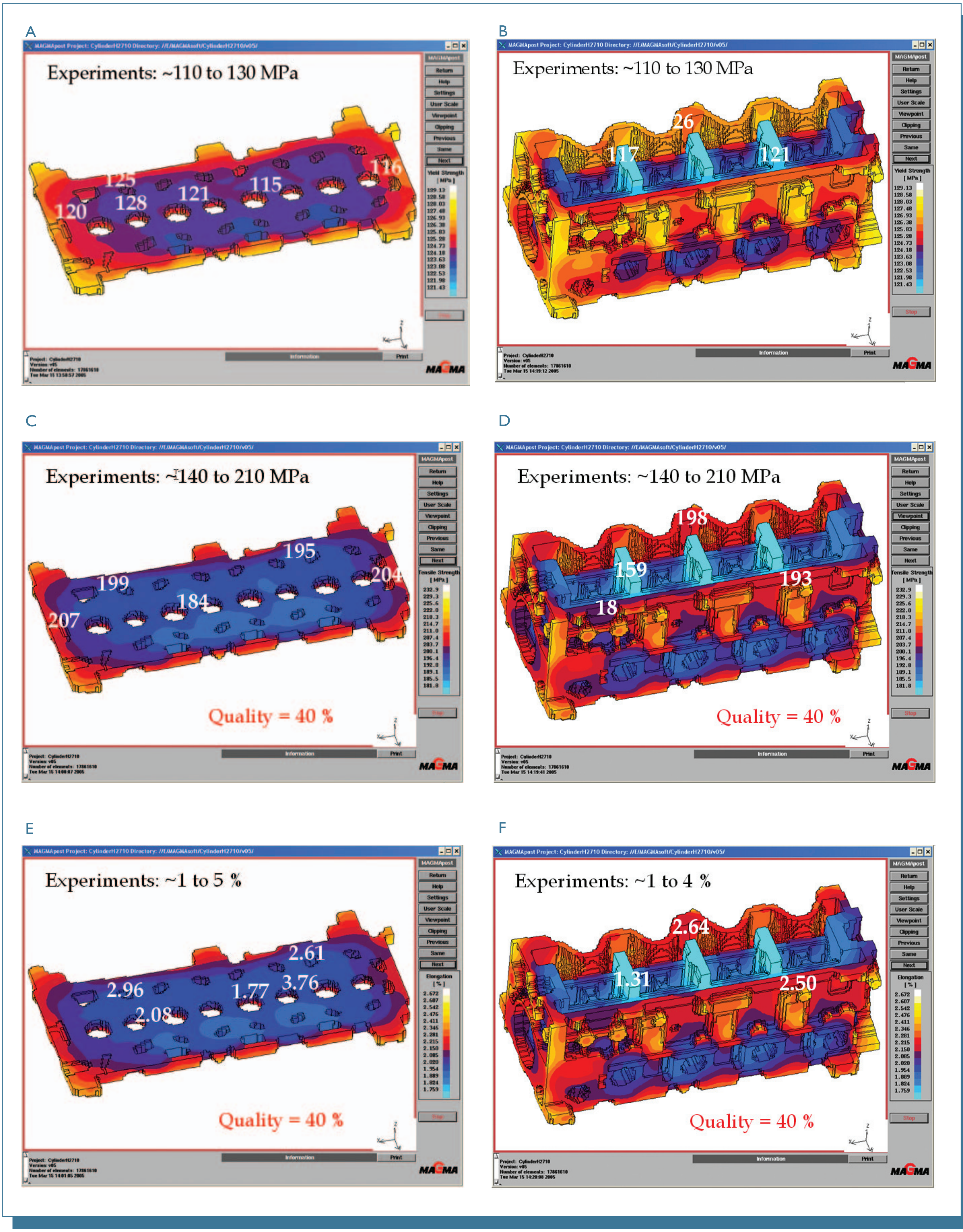

Fig. 5: Illustration and comparison of the mechanical properties from experimental and simulation results. A quality value of 40% means that only 40 % of the expected value is reached: a-b) is the yield strength, c-d) is the ultimate tensile strength and e-f) is the elongation to fracture.

CONCLUDING REMARKS

The development and increased accuracy of simulation tools will provide the casting designers the ability to consider the manufacturing and material selection conditions at early stages in the design process. The benefits of this kind of simulations are, beside optimizing the casting process and predicting the mechanical performance of complex components, the cost effectiveness and the shorter time to market.

Additionally, it should be mentioned that this simulation tool is still under development and comprises only Si levels up to 12%, Cu up to 4%, Mg levels up to 0.5% and Fe up to 0.7%. The iron level will be extended up to ~1-1.5 %, which are levels found in high pressure die cast components. More research should be devoted to developing means to understand and model to role of micro-, and macro porosity, the iron rich constituents and other impurities on the mechanical properties of these kinds of engineering alloys.

REFERENCE

1. Magnus Wessén, Ingvar L Svensson, Salem Seifeddine, Jörgen Olsson, Wilfried Schäfer, MCWASP, (2006).
2. Campbell J, Castings, 2nd Ed, Butterworth-Heinemann Ltd, Oxford (2003), ISBN 0 7506 4790 6.
3. P. Kumar, J.L. Gaindhar, AFS Transaction, (1997), pp. 635-638.

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