Research paper

Application of Computer Simulation in EV31A Magnesium Alloy Casting Process Using MAGMASoft Software

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Abstract: Carrying out technological tests and research is indispensably connected with high costs and elongation of implementation time of new casting technologies and their modifications in industry. Hence, the application of specialised computer software, enabling the simulation and analysis of metallurgical and casting processes in modern foundry industry is of special interest.

The present work presents an experimental application of MAGMASoft software in casting process of EV31A magnesium alloy structural element of helicopter engine. The results of computer simulation have been compared with industrial cast of the simulated element, fabricated in the same conditions. It has been revealed that the computer simulation provides a complex information on the analysed process, leading to reduction of costs and time, connected with technological tests in implementation of new casting technologies.

Keywords: magnesium alloy, EV31A, MAGMASoft, simulation, casting, foundry.

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1. Introduction

Development of structural elements for aerospace and automotive industry is focused on the decrease of weight and simultaneous increase of mechanical properties at both ambient and elevated temperature [1-2]. Hence, in the design process of modern aircraft engines the new generation of magnesium alloys is of special interest. This group of modern lightweight alloys is characterised by the low density, enabling the enhancement of flight dynamics, as well as good high temperature mechanical properties [3].

Analysis of research reports and literature confirms the intense cooperation of modern industry with research centers, leading to replacement of recently used cast alloys by newly developed alloys exhibiting better application parameters. One of the widely employed group of cast magnesium alloys are Mg-Al alloys, with addition of other alloying elements. Although they show excellent casting properties, good tightness, machinability and mechanical properties, as well as relatively good corrosion and hot cracking resistance, these properties are limited to 120˚C [4]. The significant deterioration of properties of Mg-Al alloys in temperature exceeding 120˚C has been attributed to the presence of α-Mg+$Mg_{17}Al_{12}$ eutectic compound, with low melting point of 437˚C and precipitates of brittle $Mg_{17}Al_{12}$ intermetallic phase located on grain boundaries of α-Mg solid solution [5].

To overcome the problem of intergrain cracking of castings (described cracking phenomena has been observed in turbine engines, operating in extreme conditions in the vicinity of fairings and anti-icing valve mount, where the temperature is around 151˚C and 175˚C) it is necessary to replace Mg-Al alloy with modern Mg-RE sand-casting alloy, characterised by working temperature up to 200÷300˚C, what is associated with essential changes in fabrication of casting molds and liquid alloy preparation [2, 6-7]. Among the commercial magnesium alloys, the best high temperature properties are presented by WE43 and WE54 alloys and are achieved by the addition of expensive rare earth elements (mainly neodymium) and yttrium [8-9]. A good alternative for these alloys is the modern EV31A alloy, containing gadolinium instead of yttrium. Its properties are slightly lower, but still meet the requirements for many applications in the automotive and aerospace industry [10]. Different physicochemical properties of newly used alloy, such as fluidity and solidification rate cause also the substantial changes in mold pouring process and casting solidification. The design process of new casting technology requires its verification, what may be achieved by conducting expensive technological tests. However, the costs and implementation time could be reduced by application of specialised software, enabling the detailed simulation and analysis of casting process, such as MAGMASoft [11-13].

In the present work the analysis of casting process of new EV31A magnesium alloy helicopter turbine engine element based on computer simulation using MAGMASoft software has been carried out. The novel character of presented research is motivated by the fact, that EVA31A is relatively new alloy, therefore the information on its casting process simulation, as well as alloy databases are strongly limited. Results of computer simulation have been compared with identical casting, obtained in technological test, confirming an important role of computer simulation in design process of new casting technologies.

2. Materials and Methods

The research material was sand cast EV31A magnesium alloy with the composition given in Table 1. The MAGMASoft software database does not include sufficient data on EV31A alloy for the correct simulation of casting process. As this alloy is increasingly applied in industrial practice, it is important to support the sufficient data, including thermo-physical and physiochemical properties. A set of simulation input parameters, including density, specific heat and thermal conductivity in the funticon of temperature, as well as liquidus and solidus temperatures has been measured and presented in the previous work by Jarosz, Kiełbus and Dybowski [14].

Table 1. Chemical composition of EV31A magnesium alloy (wt. %)

Gd	Nd	Zr	Zn	Mn	Fe	Ag	TRE	Mg
1.2	2.7	0.49	0.4	0.001	0.003	0.01	4.2	Balance

The commercial engine inlet body have been sand casted using commercial EV31A alloy under the inert atmosphere of Ar (6 dm³/min), CO_2 (6 dm³/min) and SF_6 (0.16 dm³/min). Casting temperature has been set to 760÷780°C with previous homogenization of the melt by stirring (30÷120 rpm, 20 min.). The visual examination of the casting has been carried out and X-Ray images (AGFA apparatus) have been acquired.

In order to verify the potential of computer simulation in new casting technology implementation, the simulation of mold pouring and solidification of engine inlet body casting has been conducted. In the simulation two modules of MAGMASoft software have been used: MAGMAfill and MAGMAsolid. A new MAGMA5 computing option (SOLVER 5) has been applied, due to the better simulation of actual casting process conditions. The 3D model of investigated element have been prepared using *Unigraphics NX2* software. The developed 3D model is an image of the actual dimensions of the casting, as well as construction of the casting mold (Figure 1).

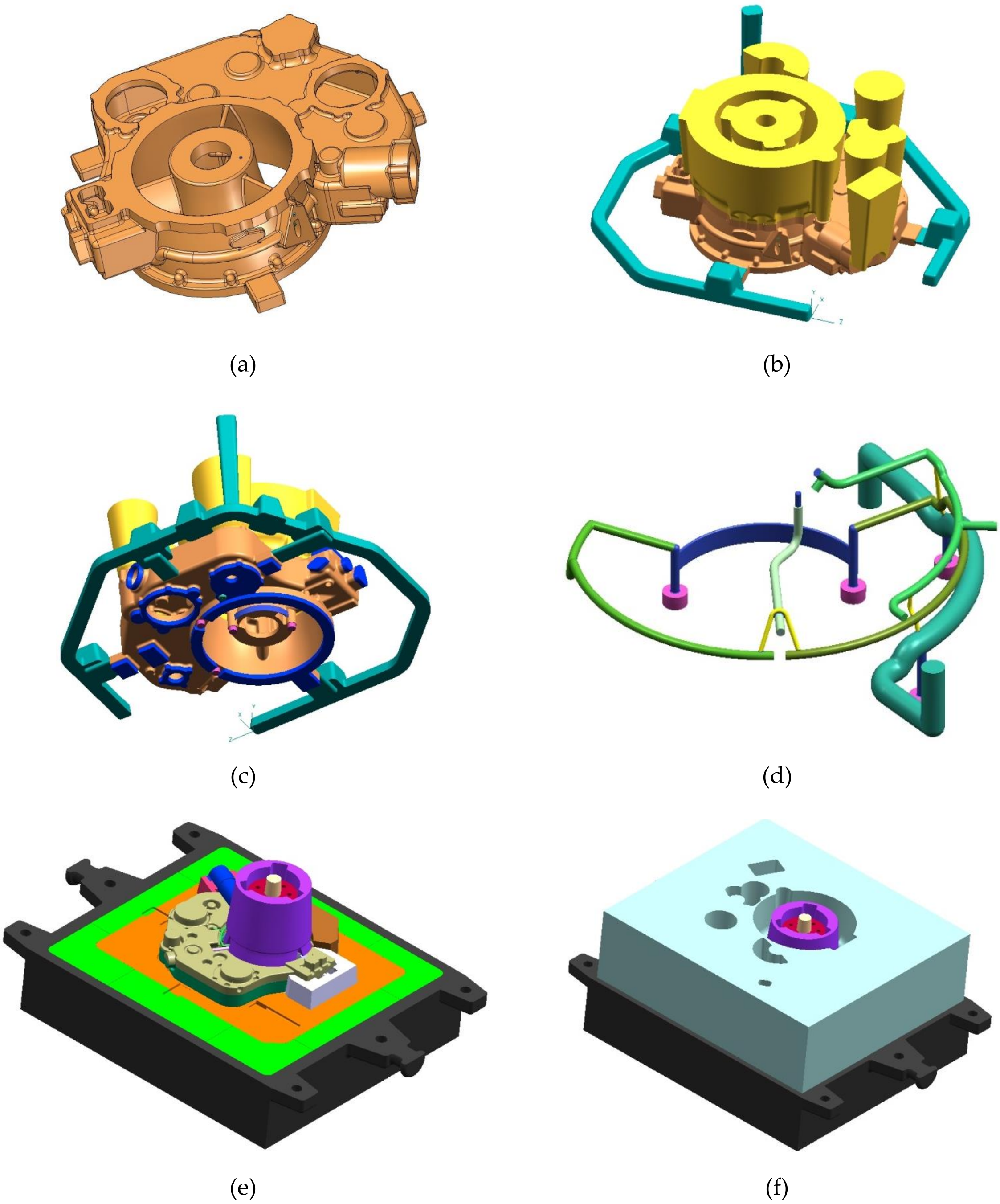


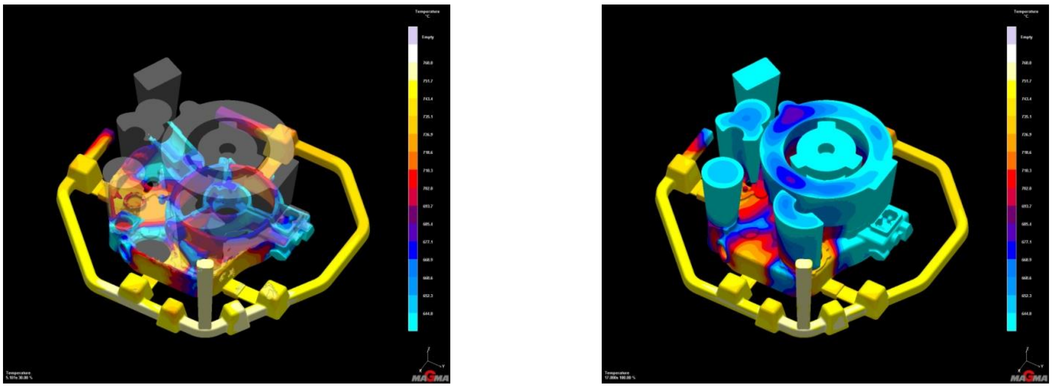
Figure 1. 3D model of investigated engine inlet body casting: (**a**) 3D solid of casting; (**b**) 3D solids of casting, gating system and runners; (**c**) 3D solids of casting, gating and cooling systems; (**d**) 3D solid of Cr-Ni tube collector embedded in the casting; (**e**) 3D solids of base plate, 21 assembled mold cores and Cr-Ni tube collector; (**f**) 3D solids of assembled mold with cores in casting-ready state.

Because of the complex shape of the casting, the 3D model mesh has been densified locally to eliminate computing mistakes (the MRS mesh generated by MAGMASoft may be the source of mentioned mistakes due to its stair stepped shape).

3. Results and discussion

3.1. Simulation and analysis of mold filling process

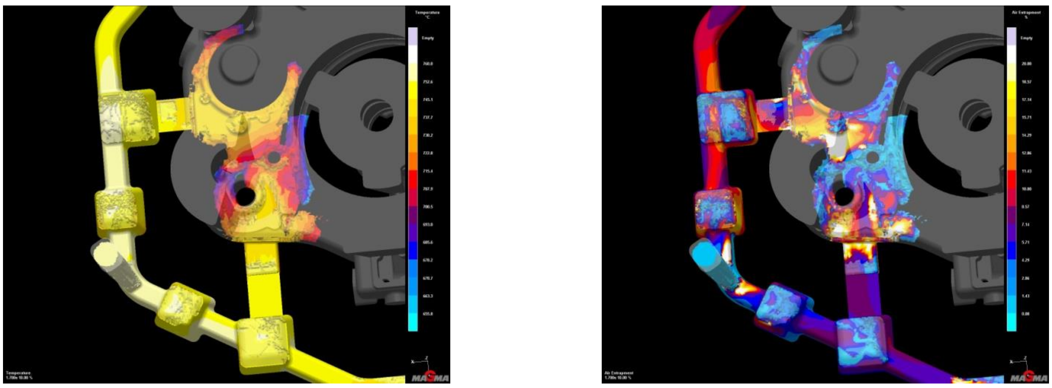
Simulated mold filling process shows the stages of liquid alloy flow through the individual elements of mold interior. The construction of filling system, comprising four filling gates allows a uniform temperature gradient and minimalises a probability of high volume overheatings (Figure 2).



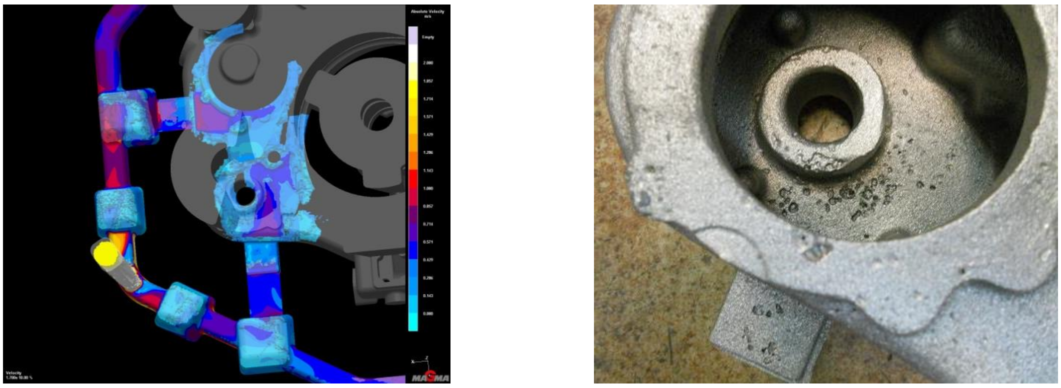
(a) (b)

Figure 2. 3D image of temperature gradient: (**a**) 30% of mold filling; (**b**) 100% of mold filling.

Application of multiple filling gates reduces the temeperature differences, what has a beneficial influence on risers charging during the solidification process. On the other hand the risk of liquid metal fluxes collision appears, causing the turbulences and filling disorders. Hence, the significant turbulences, occuring during the fulxes collisions may result in the formation of casting defects, such as cold shuts, misruns, gas porosity and secondary oxidation of liquid magnesium alloy (Figure 3d). *Velocity* criterion shows the exceeding of critical value of flow speed (0.5 m/s), what may lead to division of the main liquid alloy flux and increase of oxidation risk (Figure 3c). In the same time the *AirEntrapment* parameter determines the percent content of air entraped in the flowing liquid metal. In the moment of fluxes collision and exceeding of critical flow speed the amount of air entraped in liquid alloy reaches over 20% (Figure 3b). Moreover the occurring turbulences might cause the metal penetration and erosion of mold material, leading to entrapment of small inclusions of molding material in the structure of casting.



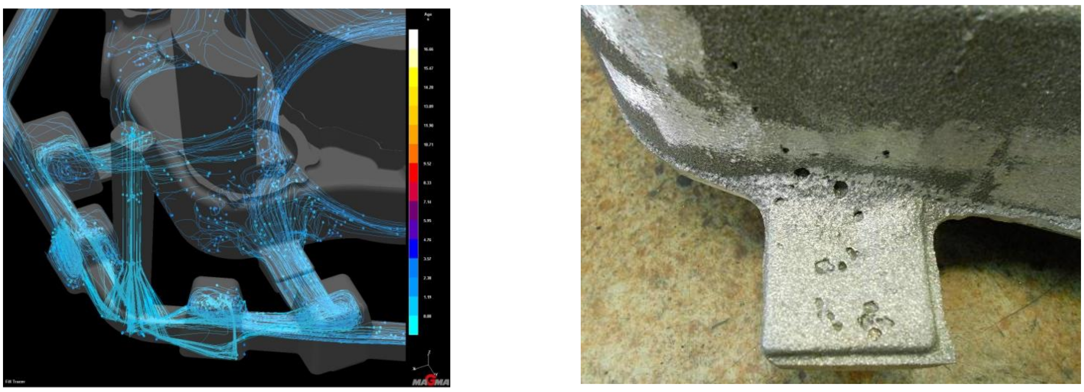
(a) (b)



(c) (d)

Figure 3. Effects of turbulences, occuring during the mold filling process (10% of mold filling): (**a**) Temerature gradient; (**b**) Air entrapment; (**c**) Flow speed; (**d**) Porosity and casting defects of real casting in areas, indicated in MAGMASoft simulation.

MAGMASoft simulation has confirmed the risk of formation of oxide inclusions with a high accuracy in comparison with the real casting. The mentioned defects suorce from the turbulent flow of liquid alloy, caused by the complicated design of the mold and shape obstacles, like protrusions, recesses and winding channels (Figure 4). Additionaly the complexicity of mold filling process, affected by many different factors, that may determine the mutual deceleration of the liquid melt fluxes alters the mold pouring time.



(a) (b)

Figure 4. Effects of turbulent flow of the melt on final casting: (**a**) Trajectories of melt fluxes; (**b**) Oxides, insclusions and porosity in the vicinity of gate.

The final result of mold filling simulation is presented in Figure 5 and has been determined according to criterions of maximum fluxes length (maximum value of 1900 mm) and overall filling time (17 s).

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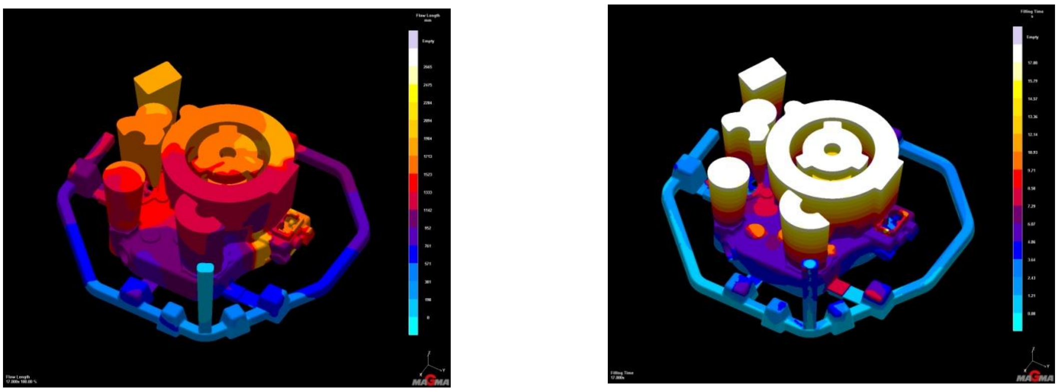
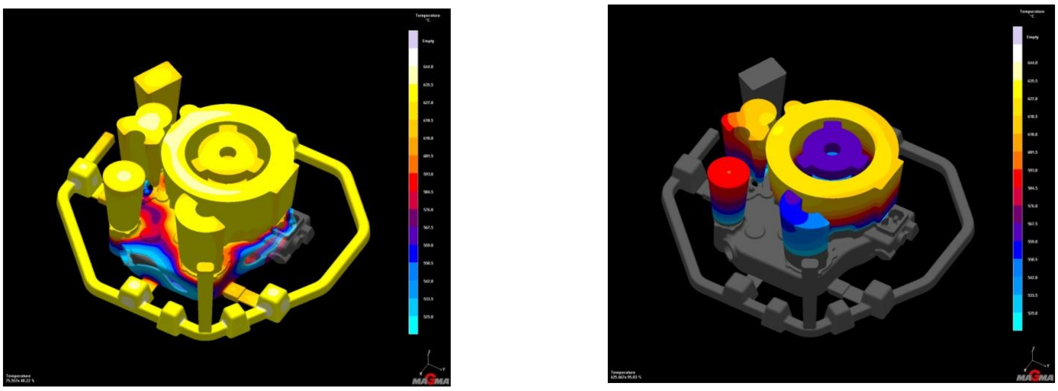


(a) (b)

Figure 5. Final result of mold filling simulation: (**a**) Maximum fluxes length; (**b**) Overall filling time.

3.2. Simulation and analysis of casting solidification process

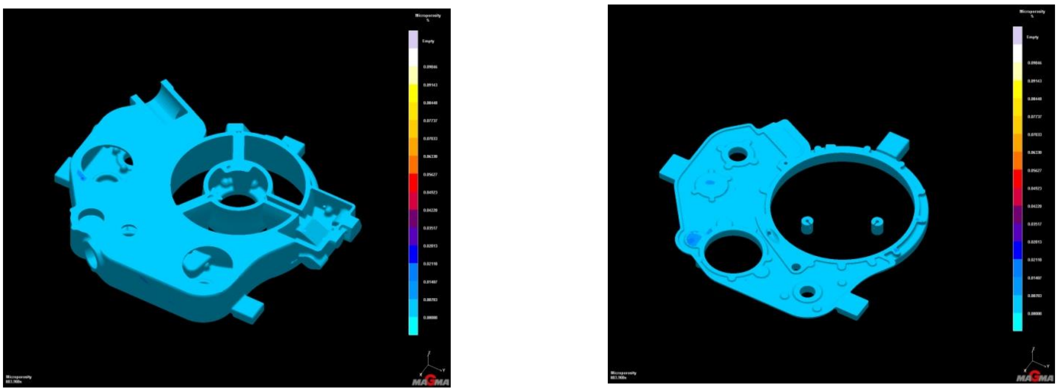
EV31A magnesium alloy is characterised by relatively high volume shrinkage. Hence, the effective charging of casting thermal centers with liquid alloy is needed. Elements controlling the solidification process, such as risers, ensure the constant charging of thermal centers with liquid alloy and compensating the volume shrinkage. In the same time the application iron coolers accelerates the heat dissipation from overheated parts of the casting and causes the transfer of the volume shrinkage to the vicinity of risers (Figure 6).



(a) (b)

Figure 6. Simualtion of temperature gradient during the solidification of the casting: (**a**) 40% of solidification; (**b**) 95% of solidification.

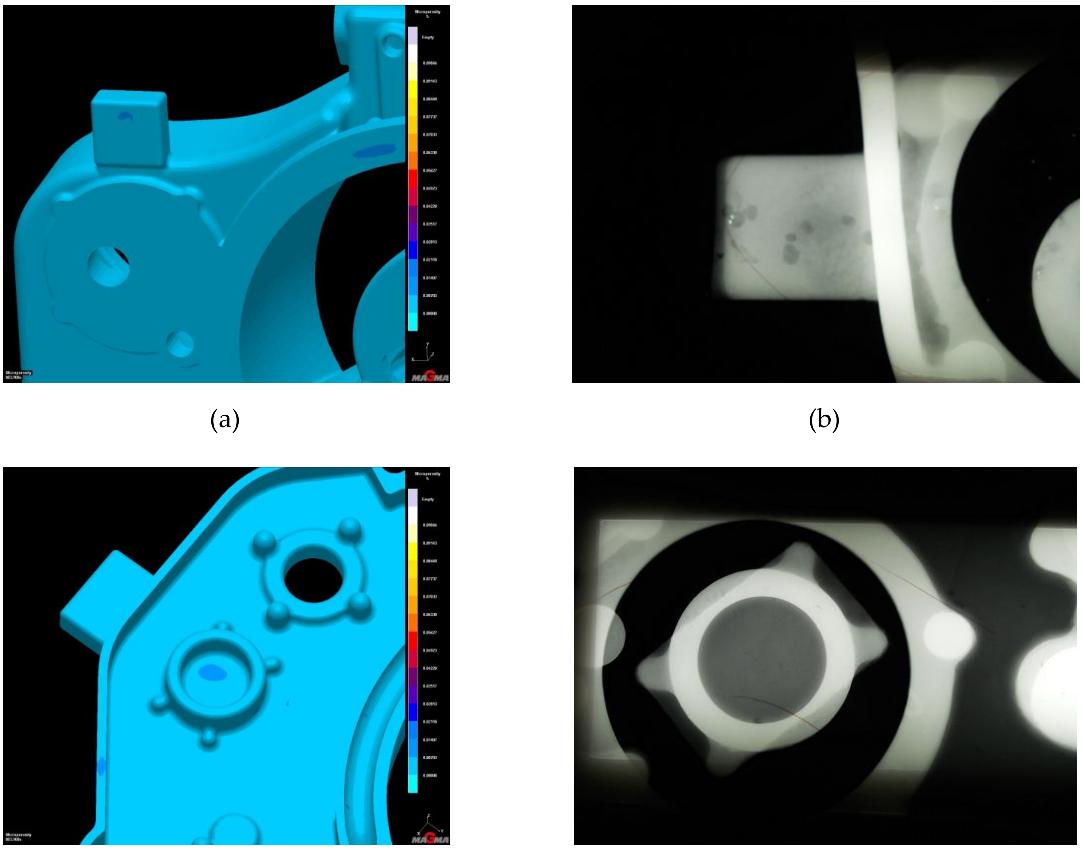
Despite the application of highly developed cooling and charging systems, as well as efforts on preventing the microporosity formation, the disortions of solidification process in industrial conditions are possible. The complex shape of the casting, overheatings and insufficient charging of heat centers with liquid alloy favors the apperance of local crystalisation fronts are the reason of casting shrinkage deffects formation. The mentioned defects tend to from in the vicinity of gates and runners, where the solidification time is relatively long in comparison with other parts of the casting, despite of presence of coolig elements (Figure 7).



(a) (b)

Figure 7. Simulation of microporosity formation: (**a**) upper part of the casting; (**b**) lower part of the casting.

The results of MAGMASoft simulation have been confirmed by the technological test and X-Ray examination of the real cast. Groups of oxide and nonmetallic inclusion appears together with microporosity in the vicinity of gates, runners and risers (Figure 8).



(a) (b)

(c) (d)

Figure 8. Analysis of shrinkage deffects: (**a**) Microporosity in the vicinity of gate (simulation); (**b**) Correspongind X-Ray image of the vicinity of gate (real casting); (**c**) Microporosity in the vicinity of riser (simulation); (**d**) Correspongind X-Ray image of the vicinity of riser (real casting).

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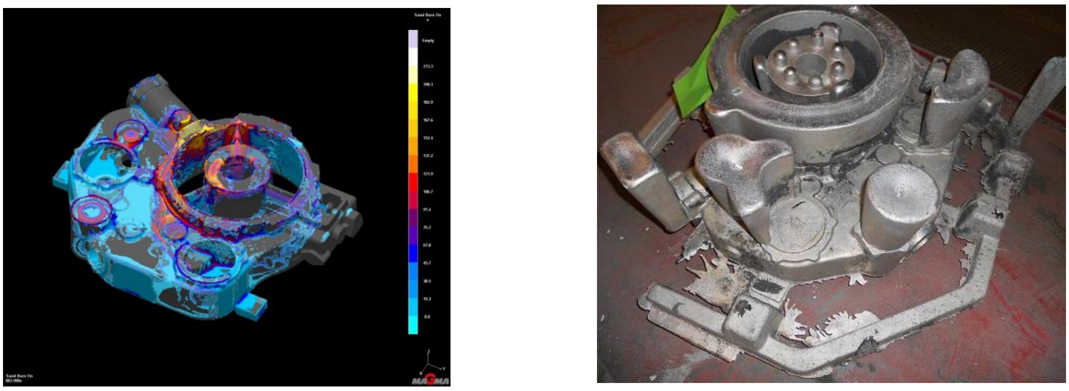
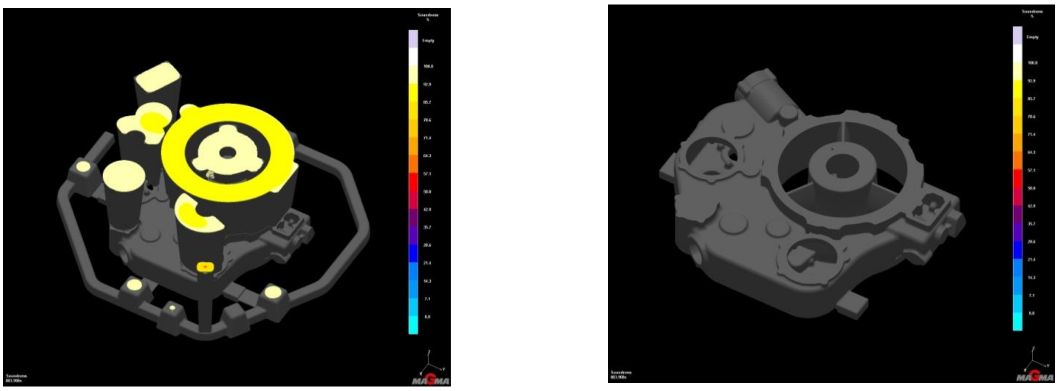
High temperature of the melt, local overheatings and lengthening of solidifcation time causes the burns of molding material and its adhesion to the casting surface (Figure 9), resulting in the increase of the surface roughness, which needs the further machining, rising the element's production costs and time.



(a) (b)

Figure 9. Molding material burns and adhesion: (**a**) MAGMASoft simulation; (**b**) Real casting.

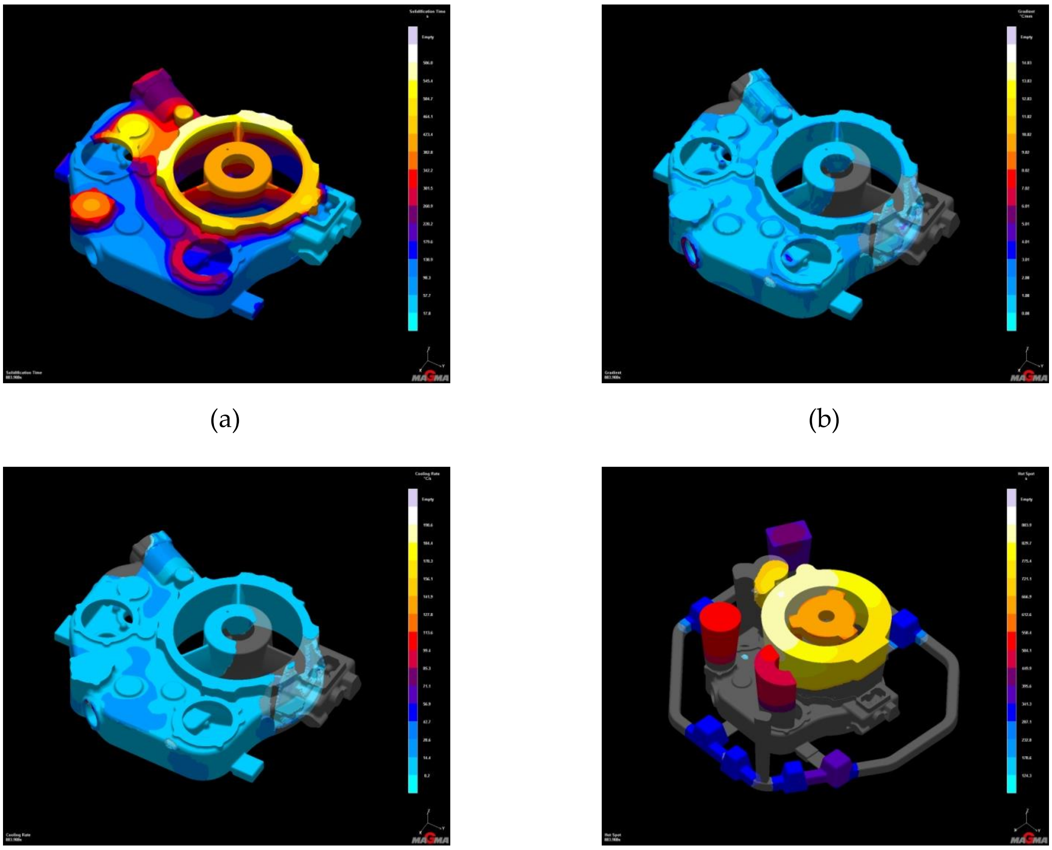
The simulation of engine inlet body solidification process required the consideration of some additional criteria, due to the fact, that the occurring deffects are not directly determined by the standard quality criteria (*Soundness* and *Porosity*). Specific properties of EV31A alloy, especially the problem of different contaminations presence are factors difficult to determine in the mathematical model of simulation software. The results of *Soundness* criterion, determining the internal quality of the casting indicates only the defects in the sprue and charging system. However, the casting itself is free of shrinkage and porosity (Figure 10).



(a) (b)

Figure 10. Visualisation of *Soundness* criterion (X-Ray): (**a**) Casting with charging system; (**b**) Casting.

The described inaccuracies have determined the necessity of analysis of other criteria, such as mold overheating rate, cooling rate, solidification time, etc. (Figure 11). The synthesis of these results enabled the estimation and analysis of critical casting parts in terms of probability of shrinkage defects formation (microporosity, shrinkage cavities, etc.).



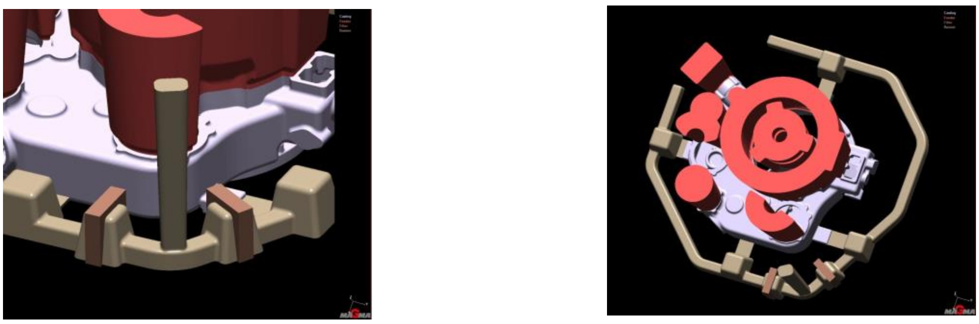
(a) (b)

(c) (d)

Figure 11. Analysis of shrinkage deffects formation probability: (**a**) Solidification rate simulation; (**b**) Gradient of heat dissipation per surface unit; (**c**) Heat dissipation rate simulation; (**d**) Hot Spots simulation (the latest solidifying parts of casting).

4. Summary

The results of computer simulation of engine inlet body casting process enabled the identification of potential problems and factors, causing the decrease of final casting quality. The obtained results have been confirmed with high accuracy in the technological tests, comprising casting of investigated element and its analysis in industrial conditions. Excessively high flow speed of liquid alloy, revealed in the conducted research determine the application of solutions, leading to the decrease of flux speed and reduction of flow turbulences (Figure 12).



(a) (b)

Figure 12. Applied solutions of problems identified during the conducted research: (**a**) 10ppi ceramic filters; (**b**) Icrease of gates hight from 7 mm to 12 mm.

10ppi ceramic filters have been introduced in deslagging basins and the height of gates has been increased from 7 mm to 12 mm. Additionally, applied ceramic filters will protect the casting contamination with nonmetallic inclusions and primary oxide inclusions, formed during the melting process.

It has been revealed, that the computer simulation is an interesting tool in implementation of new casting technologies in foundry industry. Its application may result in significant cost and time reduction, due to the possibility of replacing some technological tests with computer simulation.

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Author Contributions: R. Jarosz and A. Kiełbus conceived, designed and performed the experiments; R. Jarosz, A. Kiełbus and A. Gryc analysed the data; A. Gryc summarise the results and wrote the article.

Conflicts of Interest: The authors declare no conflict of interest.

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