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Die Casting and New Rheocasting

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1. Introduction

1.1 The high-pressure die casting process

The high-pressure die casting process (HPDC) is a rapid solidification process leading to formation of rapid solidified castings. There are some specifics of the process. The casting of a molten alloy into a mold is complete within several milliseconds. A significant quenching effect and a high production rates are possible. The application of high-pressure enables good contact between molten alloy and die wall that enables: the increase in cooling rate, the increase in heat flow and heat transfer coefficient at the die-melt interface as well as the formation of a net shape casting. Casting defects such as shrink holes which generate by the shrinkage during solidification are reduced. Components with complicated shapes are produced directly from a liquid state even for a molten alloy with high viscosity.

By taking these facts into account, it is expected that much larger shapes and dimensions can be formed in various alloy systems by the high pressure die casting process.

The characteristics of HPDC process (Andersen, 2005, Vinarcik 2003), are high velocity of melt during filling the die and high solidification rate of the component. Such circumstances demands more sophisticated approach to the study of phenomena during HPDC process.

Among others an integrated virtual and rapid prototyping methodology is proposed for advanced die-casting manufacturing using a hot-chamber process (Ferreira et al., 2007). This approach enabled optimization of the die-casting manufacturing technology parameters and reduced the lead-time of die-casting designs.

The physical, mechanical and esthetical properties of the components are directly dependent on process conditions during casting; the die temperature, the metal velocity at the gate, the applied casting pressure, the cooling rate during die casting, the geometrical complexity of the component and the mold filling capacity. All that affects also the integrity of the cast components. If these parameters are not controled properly, various defects within the finished component may be expected. The applied casting pressure is crucial during the solidification of high integrity parts. The effects of process variables on the quality of the cast components with in-cavity pressure sensors delay time and casting velocity were

examined by Dargusch in 2006. He found that the porosity decreases with increasing pressure and increases with higher casting velocity (Dargusch et al., 2006, Laws et al., 2006).

The latest development of rheocasting process is based on the principles of HPDC. The material in semi-solid state is pressed into the tool cavity. That enables faster solidification and better productivity. Due the narrow temperature window the optimization of the new rheocasting process demands precise control of process parameters.

Presented is development of the microstructure of the semi-solid slurry and the rheocast component and an overview of observed defects in components produced by new rheocating process. A comparison between the simulated porosity and experimental determined porosity is presented.

1.2 Evolution of the microstructure at new rheocasting process

Evaluation of the microstructure of the components, manufactured by rheocasting proces, revealed the outgrowths on the surface of primary globular α_{Al} crystall grains. The outgrowths can grow into dendrites that are not suitable for the new rheocasting process. The explanation of these phenomenon is in the theory of solidification.

The alloys with dendritic microstructure in two phase region are not suitable for the new rheocast process, because dendritic solidified material has no isotropic properties. Discovery of Flemings, that material with globulitic microstructure in two phase region (L+α) behaves thixotropic, enabled the further development of hot working in semisolid state (Giordano at all 2002, Müller-Späth at all, 1997, Wabusseg at all, 2002, Kaufmann at all, 2001, Hall at all, 2000, Curle at all, 2010, Curle at all, 2011, Cabibbo at all, 2001, Kapranos at all, 2001) like thixocasting and new rheocasting (NRC) (Sereni, 2005). The efforts to introduce the hot working in semi solid state (Blazek at all, 1995) exists also for steels but these efforts are less sucessful due higher temperatures.

Hot working in semi solid state bases on preparation of wrouth material with more or less globulitic forms of solidified primary phase, surrounded by molten material. Free Gibb's molar energy of globular form is presented by equation (1).

$$\Delta G_L = \frac{2\gamma}{R} \tag{1}$$

Where R represents radius of bent interphase boundary and γ interphase free energy between liquid/solid. Evident is the equality with the classical theory of nucleation, where the free energy, necessary for formation of nucleus with critical radius R*, equals (2)

$$\Delta G_\gamma = \frac{2\gamma}{R^*} \tag{2}$$

In the case of equilibrium among the phases solid/liquid and due the influence of curvature of solid phase after Gibbs-Thomson the ΔG_L equals ΔG_γ . Taking into account this balance and with supposition that specific surface energy of solid phase is isotropic, than from both expression for ΔG_L and ΔG_γ follows that free energy is proportional to the lowering of the temperature, as shown in equation (3)

$$\Delta T_R = \frac{2\gamma}{\Delta S}\frac{1}{R} \tag{3}$$

Where ΔS is the difference in entrophy solid/liquid, R is radius of curvature of interphase surface and γ is free energy of the surface solid/liquid. Round nucleus is stable until R > R* and are remelted when R<R*.

At the begining of the growth the nucleus is stable R >R* and possible are only smal outgrowths with lower radius r <<R*. The outgrowths remelt in the case that $\Delta T_R > |\Delta T_L + \Delta T_C|$, where ΔT_R express the undercooling due the curvature of the outgrowth, ΔT_L is undercooling due the local temperature of the melt, ΔT_C is the contribution of constitutional undercooling because of the melt composition. Until the ΔT_R is high enough the nondendritic globulites can grow. With increasing size of solid globules, the larger outgrowths on the surface are possible and they can develop further into dendrites.

As the primary phase α_{Al} grow further in semi solid region (mixture of solid-liquid state) the importance of the $|\Delta T_L + \Delta T_C|$ increases. For the further growth of globulites both, ΔT_L and ΔT_C must be reduced, which is possible either by forced mixing of the melt or with slower cooling rate.

The NRC process bases on lower cooling rate during the growth of primary phase in the preform (slurry). Due the influence of mixing and diffusion at slower cooling rates, the distribution of solid phase, near the contact solid/liquid is more equal compared to distribution of solid phase at rapid cooling of the melt. This enables lower constitutional undercooling ΔT_C. At lower ΔT_C the Gibbs-Thompsons effect increases the stability of the interphase surface. Thus, lower cooling rate accelerates the growth of globulites (Zhu at all, 2001, Uggowitzer at all, 2004).

The cells and dendritic solidification is a consequence of constitutional undercooling which means the temperature of the melt at solidifying front is lower compared to equilibrium solidification.

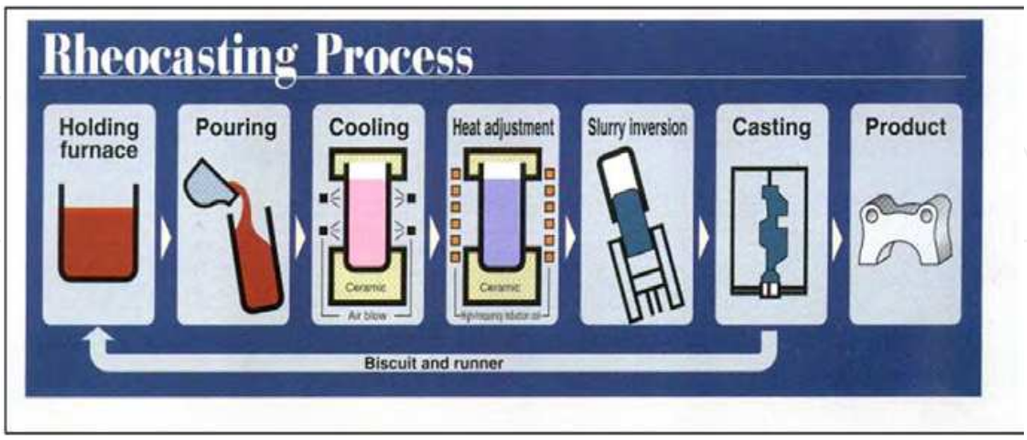


Fig. 1. Schematic presentation of new rheocasting process (NRC) with possibility of in situ recycling of material (From project documentation GRD1-2002-40422).

The formation of globulitic structure in the slurry demands first high cooling rate to get a high number of small nucleuses and after that to cool down the melt slowly (Sereni, 2005).

In comparison with thixocasting (Kapranos at all, 2000) the new rheocasting process (NRC), shematic presented in Fig. 1, has some additional benefits: continuous casting with electromagnetic stirring is not necessary, there is no cutting of the billets and no reheating of the cut pieces into the semi solid region for the forming in the die. NRC process (Sereni, 2005, Torkar at all, 2005) starts with liquid phase, followed by preparation of semisolid slurry that is directly transfered into the die of the press.

The main aim of the investigation was evaluation of the microstructure and presentation of the most often failures in real automotive component, manufactured by NRC process.

2. New rheocasting process

2.1 Material and preparation of slurry

Metallographic investigations of the microstructure of slurry (partly solidified preform, before the entrance into the press) and the component, both of hypoeutectic silumin A 357 were performed. Typical compositon of the alloy is presented in Table 1. The components were high pressure die cast on NRC device and then heat treated (T5, 6 hours at 170 ^{o}C).

Cu	Mg	Si	Fe	Mn	Ti	Zn	Sr	Al
0.2	0.4 – 0.7	6.5 – 7.5	Max. 0.2	Max. 0.2	0.05 –0.2	Max. 0.2	0.03	Rest

Table 1. Tolerances of chemical composition of A 357 alloy in wt. %.

The samples for metallographic investigations were cut from the slurry and from the component and prepared by standard metallographic procedure. The soundness of the components was checked by x-ray device. The detected failures were checked by metallography.

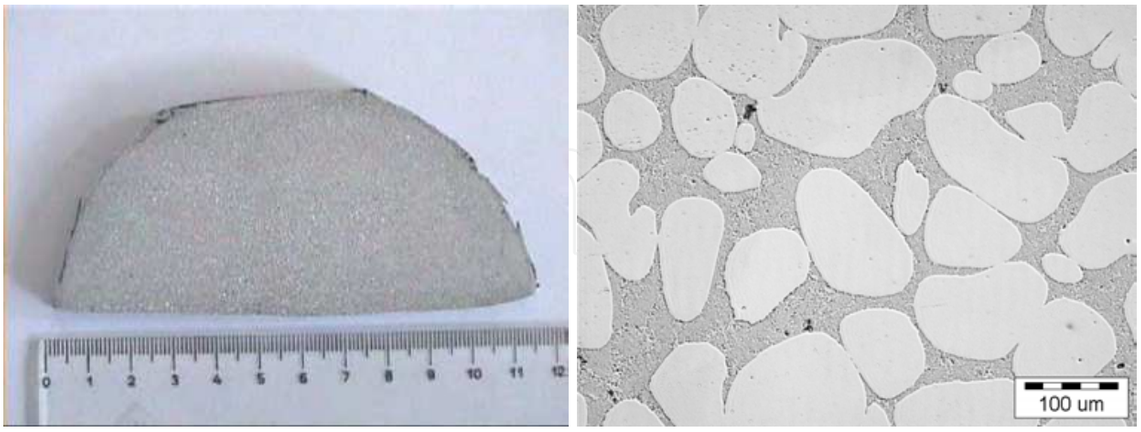
The microstructure was observed by the light microscope Nikon Microphot FXA, equiped with 3CCD- videokamero Hitachi HV-C20A in software analySIS for evaluation of the microstructure. The hardnes of the component was measured by Brinell.

2.2 Microstructure characterisation and defects presentation

The microstructure of the middle of the slurry is presented in Fig. 2a, b. We can observe the globules of primary phase α_{Al} and equally distributed eutectic among the globules. No other specifics were observed in the microstructure of the slurry. Similar microstructure was observed also at high pressure die cast component. The globules of primary phase α_{Al} are enveloped with eutectic (Fig. 3). Beside that, especially in thinner regions of the component, we can observe fingers like outgrowths (start of grow of dendrites) on the surface of globulites (Fig. 4).

There are two possibilities for the appearance of these outgrowths. First possibility is local change in undercooling, during the deformation in the die that enables the appearance of dendrites. The second possibility is not yet finished globularisation during cooling of slurry. More likely is the explanation with local change of undercooling and its influence on distribution of solidified phase during the process of deformation in the die. It is well known that higher undercooling and distribution of solid phase accelerates the formation of dendrites. The second possibility is denied based on microstructure (Fig. 2b), where no

outgrowths were observed and beside that the slurry was cooled down in more controlled temperature regime.



(a) (b)

Fig. 2. Cross section of one half of the slurry (a). Microstructure of the slurry (b).

The explanation of the appearance of the outgrowths and dendrites, observed in the microstructure of the component one can get in the theory of solidification. Until the contribution of ΔT_R is high enough, the surface of the growing nucleus is stable and the growth of globule proceeds. When the size of solid globule increases, increases also the possibility of development of outgrowth with higher radius that can degenerates into dendrite.

Studies (Zhu at all, 2001, Uggowitzer at all, 2004, Dahle at all, 2001) of the concentration profiles of solute in the melt during formation of the primary phase at different cooling rates, revealed that at higher cooling rates increases the concentration of solute in the melt near the S/L interface due redistribution of the melt on the interface and due short time for diffusion of the solute. Stability of the interface is fast destroyed. That enables the appearance of outgrowths and start of the dendrite grows on the surface of the primary phase α_A, (Fig. 5), as observed in the investigated component.

Lower casting temperature of slurry combined with the lower cooling rate, accelerates the formation of globular micro structure. The formation of the globular structure is accelerated also by the inoculation of the melt.

In the microstructure of the component beside globules also some dendrites of the primary phase were observed. The presence of dendrites means that temperature regime of NRC process was not optimal. After the solidification the component was cooled in water and heat treated (T6).

The hardness of the component after heat treatment T6 was among 92-96 HB 5/250.

x-ray examination of the component revealed internal errors like shrinkage porosity (Fig. 6a, b), gas cavities (Fig. 7a, b) and large inclusion (Fig. 8a, b) that were confirmed also by metallography. Observed were also other irregularities like not filled form, overcasts on the surface, segregations, precipitates of silicon and dendrite formation (Fig. 9a-f).

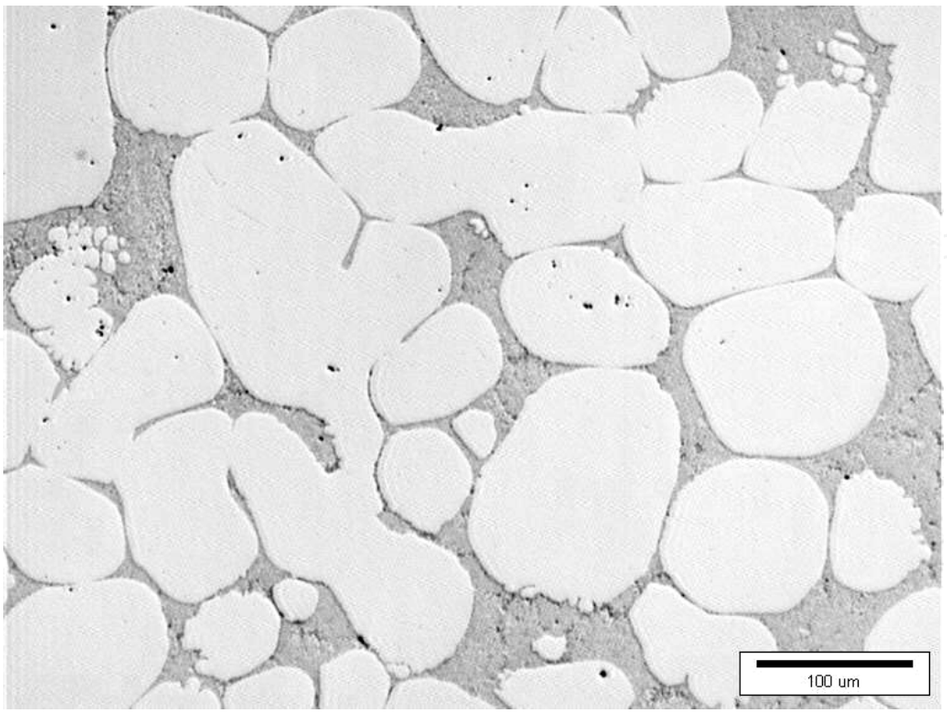


Fig. 3. Microstructure of the component.

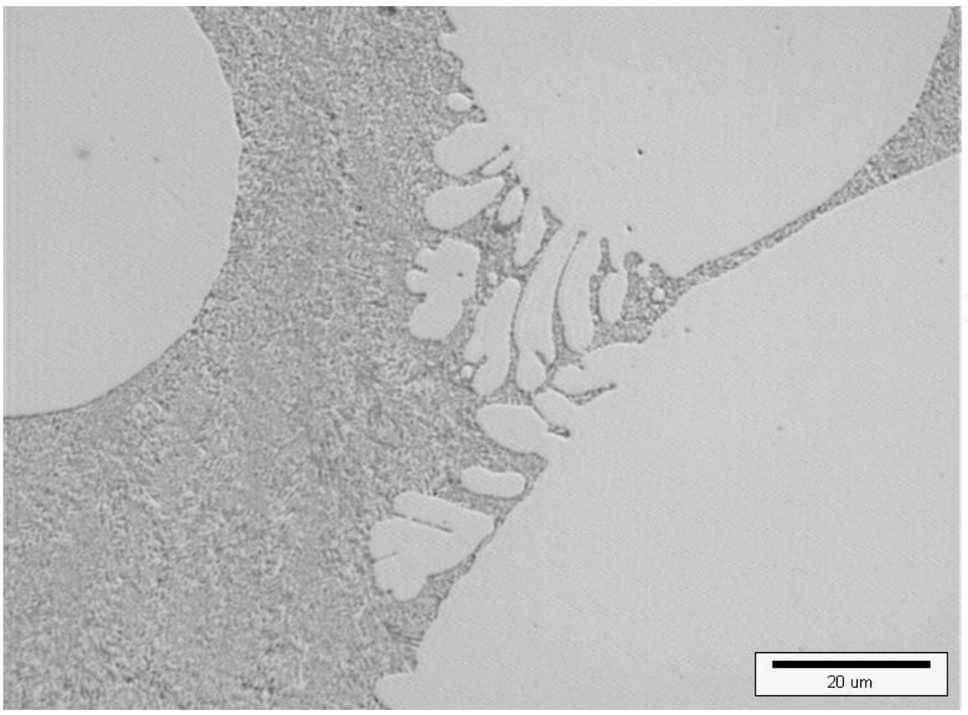


Fig. 4. Outgrowths from surface of globulitic grains of primary α_{Al} phase in the component.

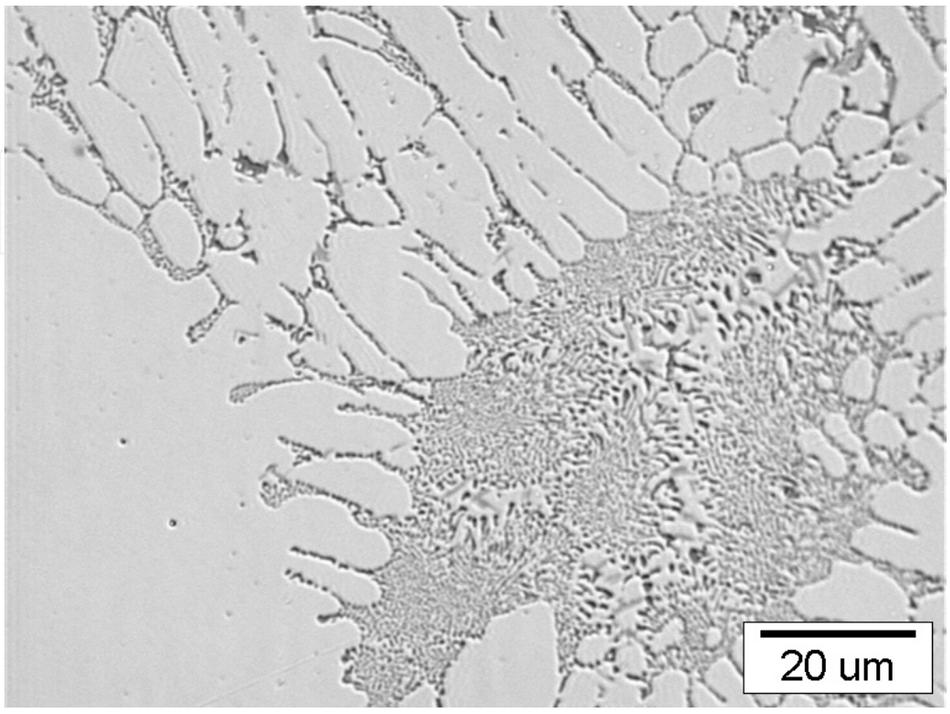
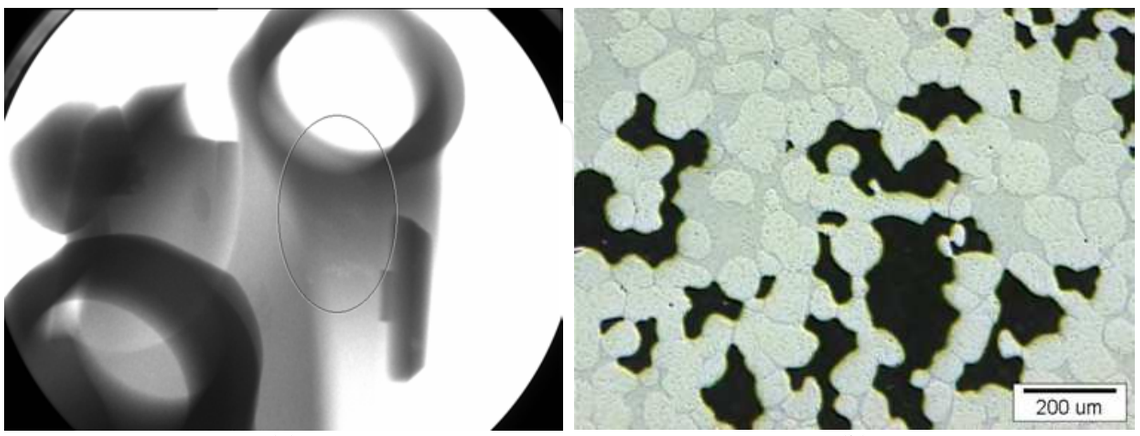
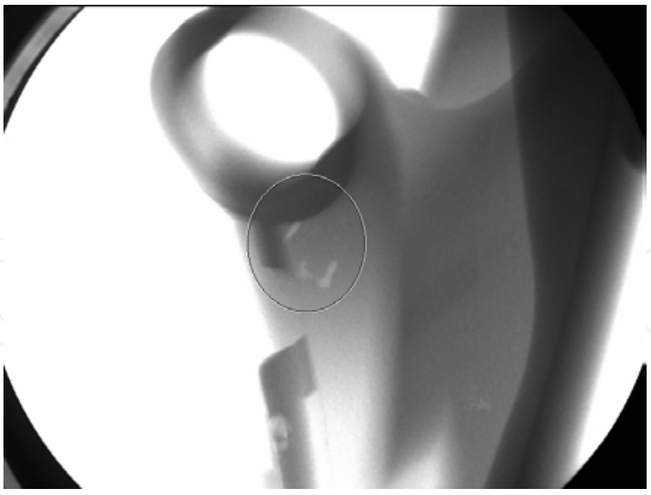


Fig. 5. Dendrites of primary α_{Al} phase in the component.

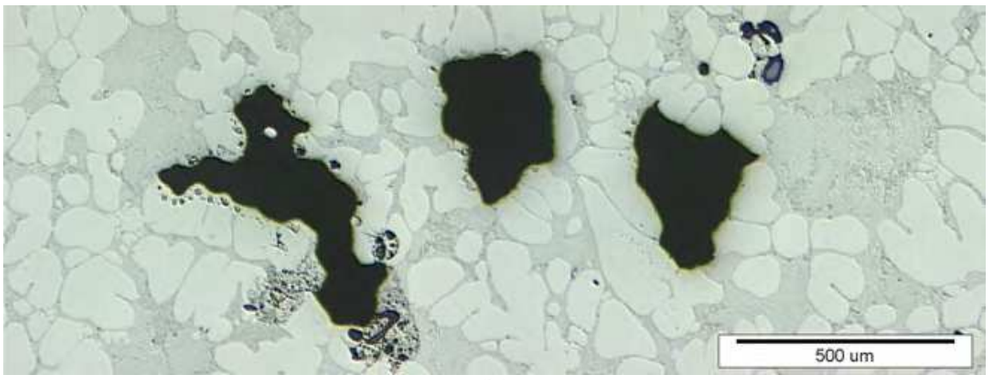


(a) (b)

Fig. 6. (a) Radiograph of internal defect in the component (b) Central shrinkage porosity confirmed by metallography.

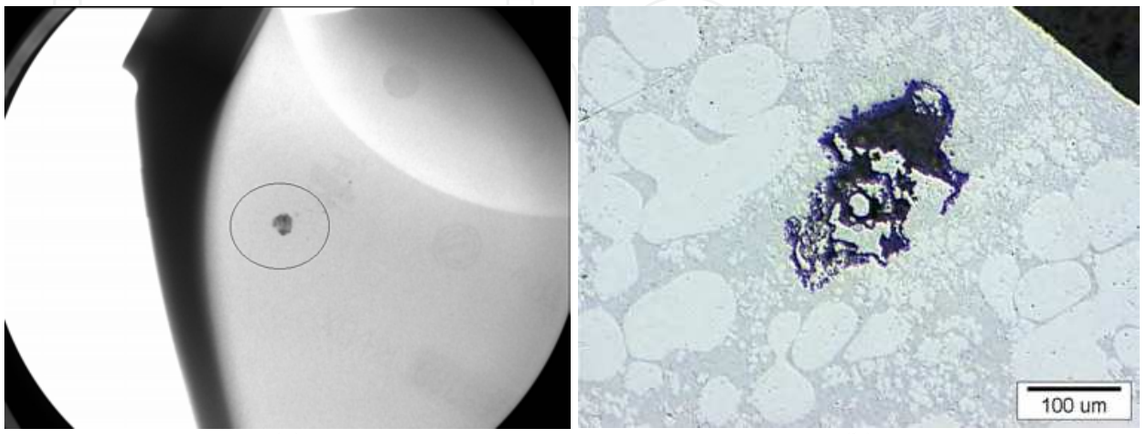


(a)



(b)

Fig. 7. (a) Radiograph of internal defects (b) Combination of shrinkage and gas porosity, confirmed by metallography.



(a) (b)

Fig. 8. (a) Radiograph of internal defect (b) Oxide inclusion, confirmed by metallography.

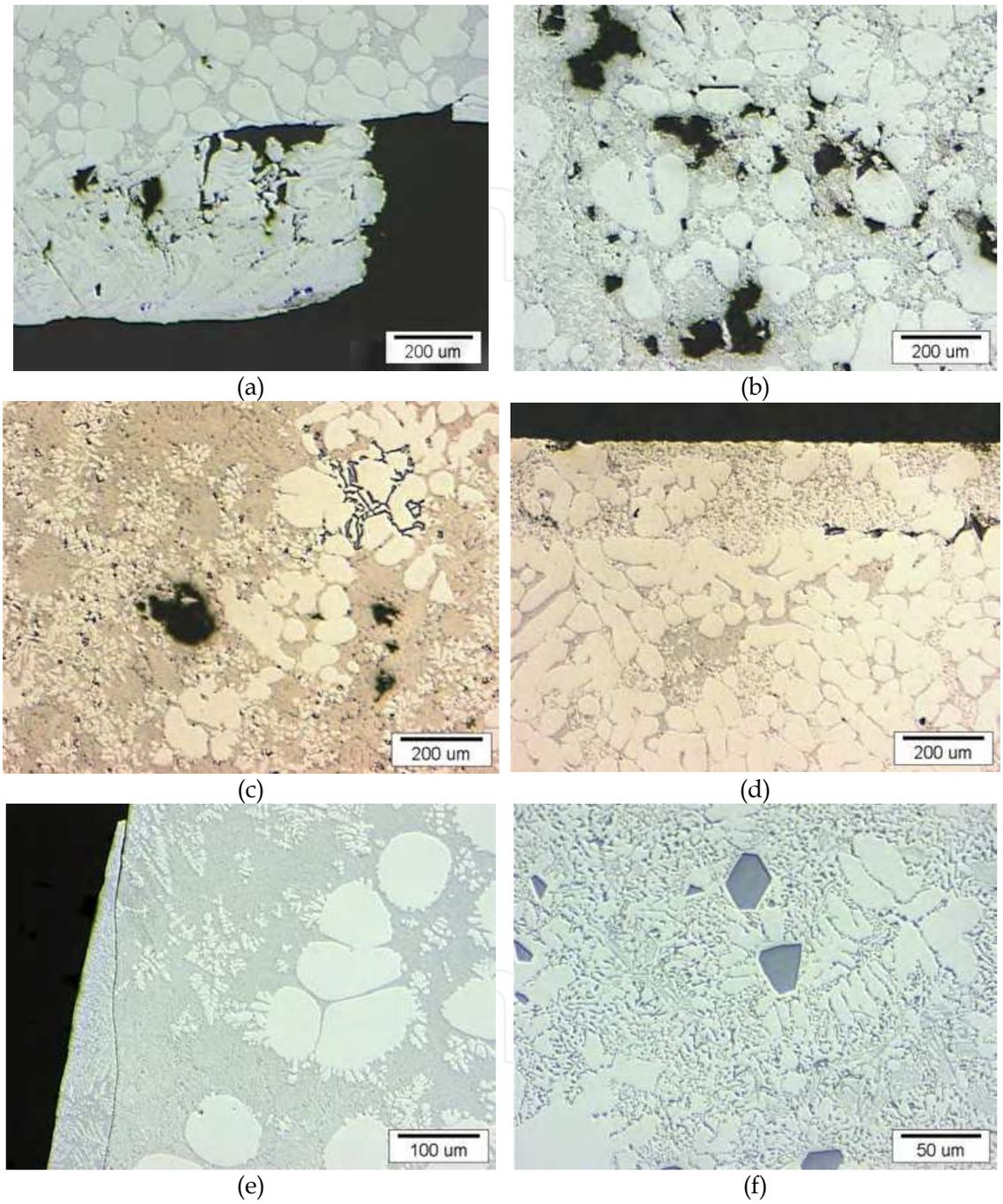


Fig. 9. (a) Not filled surface in the component. (b) Central shrinkage porosity in the component. (c) Eutectic, segregation and porosity. (d) Overcast near the surface of the component. (e) Cold weld on the surface of the component. (f) Microstructure of investigated alloy contains primary crystals α_{Al} dendrites, eutectic and non equilibrium primary crystals of β Si.

Based on metallographic examinations of the rheocast components we can observe the presence of several typical surface and internal defects that should be eliminated. Necessary is more precise control of parameters of preparation of slurry from the melt and at pressing and solidification in the die.

2.3 Conclusions on rheocasting

The microstructure of the slurry is homogenous and with equal distribution of primary solidified globular grains.

Compared to slurry, more irregularities in the microstructure were observed in the high pressure die cast components.

The formation of outgrowths on globular grains of primary phase α_{Al} and formation of dendrites is a consequence of local changes in undercooling in the semisolid state, during deformation of material in the die.

In the rheocast component the following failures were observed: the primary α_{Al} phase in the form of dendrites, internal defects as central macro- and micro porosity, gas porosity, segregations and inclusions.

On the surface the typical defects were not filled edges of thin wall regions, overcasts, cracks and appearance of blisters during heat treatment.

All these defects show that the temperature regime of investigated new rheocasting process was not yet optimal.

Further R&D is necessary to reduce internal defects by optimization of new rheocasting process parameters, to increase yield and to reduce production costs per component.

3. HPDC shrinkage simulations

The process of high pressure die casting (HPDC) was developed for manufacturing of a large variety of products with high dimensional accuracy. The process is faster and enables more economical production of aluminium automotive components (Dargusch et al., 2006). The rapid development of numerical simulation technology and the solidification simulation of casting has been taken as an effective tool for modeling the casting process and improving the quality of casting (Vijayaram et al., 2006, Dobrzansky et al., 2005). The use of simulation software saves time and reduces costs for the casting system design and the use of materials.

The porosity of the castings can be studied with destructive testing as visual check after machining and non-destructive testing as x-ray microscopy and image processing technology which can provide more detailed information of the gas pores and shrinkages. It is also observed that the chemical composition of the alloy affects the porosity in the cast components, grain refinement and modification (Cleary at al., 2006, Petrič et al., 2011). Now it is commonly accepted that the shrinkage and the gas entrapment are two major causes of porosity. The shrinkage porosity is associated with the "hot spots" in the casting. The gas porosity is caused by entraped air in the injection system and cavity, gas generated from burned lubricants, water in the cavity and hydrogen gas. The entrapped air is

unwanted product of high velocity of alloy caused by turbolent flow during injection process.

Presented are results of simulation of the HPDC of Al-Si9Cu3 casting in the H13 steel die and comparison between the simulated and experimental porosity.

3.1 Material and the casting system

The alloy used for die casting was aluminium-silicon-copper alloy (Table 1), marked by less affinity to shrinkage and internal shrinkage cavities and very good castability.

Si	Cu	Fe	Mn	Mg	Zn	Ni	Cr
10.38	2.73	0.82	0.25	0.34	0.82	0.04	0.04

Table 2. Chemical composition of Al-Si9Cu3 alloy in wt %.

ALSI H13 chromium hot work tool steel was used for the die. This steel has higher resistance to heat cracking and die wear caused by the thermal shock associated with the die casting process. The casting system with a shot sleeve and a plunger are presented on Figure 10. Presented are gates and runner system with two cavities and the final product, an automotive component.

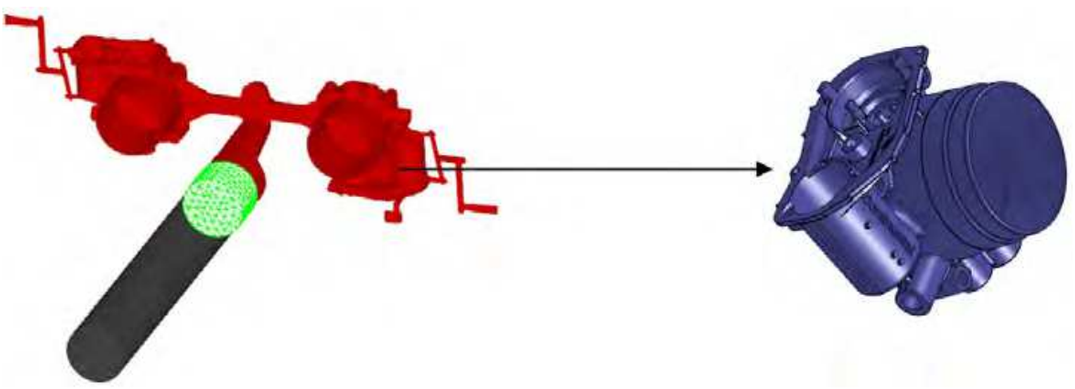
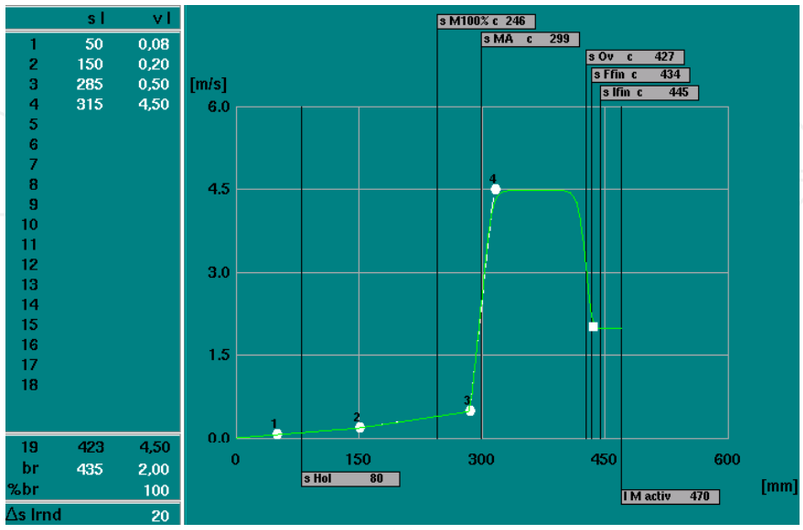


Fig. 10. Casting system; shot sleeve with plunger, gates and runner system, two cavities and the casting component.

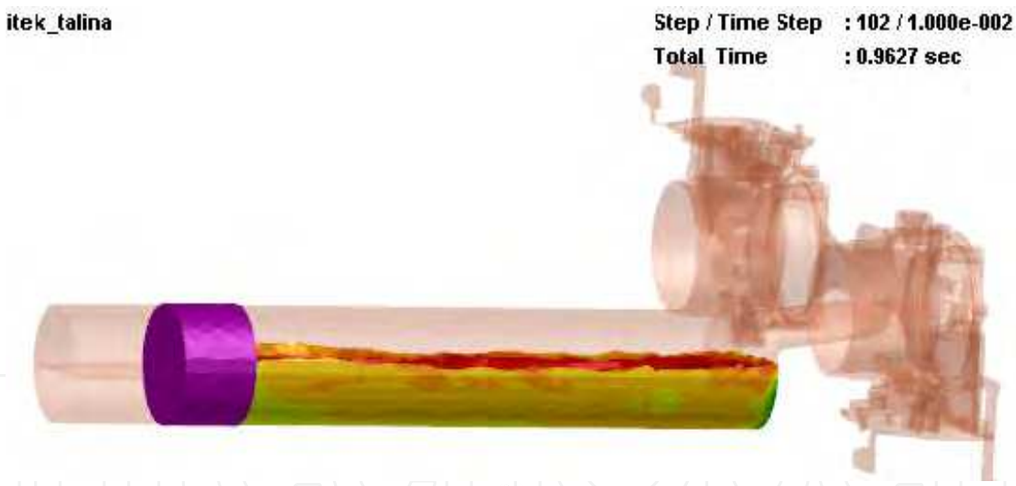
3.2 Characteristics of HPDC process

The casting process is divided into four phases: pre-filling, shot, final pressure phase and ejection phase. In the pre-filling phase, the molten metal is injected by plunger, which forces the metal with a low velocity through a horizontally mounted cylindrical shot sleeve up to the gate. The shot sleeve is usually partially filled with molten metal, in an ammount that depends on the volume of the cast component. The fluid flow and the amount of empty space are affected by plunger motion, shot sleeve dimensions and amount of metal in the sleeve (Thorpe et al., 1999). In short shot phase the plunger is accelerated to high velocity and sufficient venting of the die cavity is practically impossible. In the final pressure phase, solidification of the casting is completed and in the ejection phase, moulded part is removed, die halves are sprayed and positioned back to repeat the cycle.

The industrial HPDC process started with plunger, that has four different speeds, as it is shown on shot profile in Fig. 11a. The volume fraction in Fig. 11b shows that no wave and no air entrapement were formed.



(a)



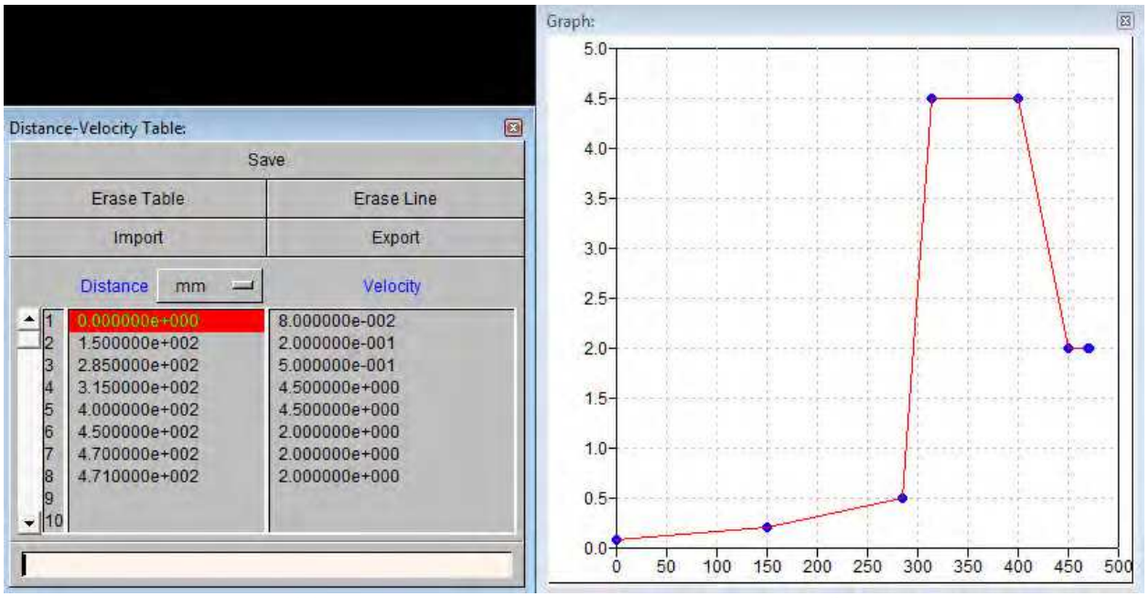
(b)

Fig. 11. (a) Shot profile with four different plunger speeds. From process computer of HPDC machine. (b) Volume fraction picture of alloy and empty space in the shot sleeve.

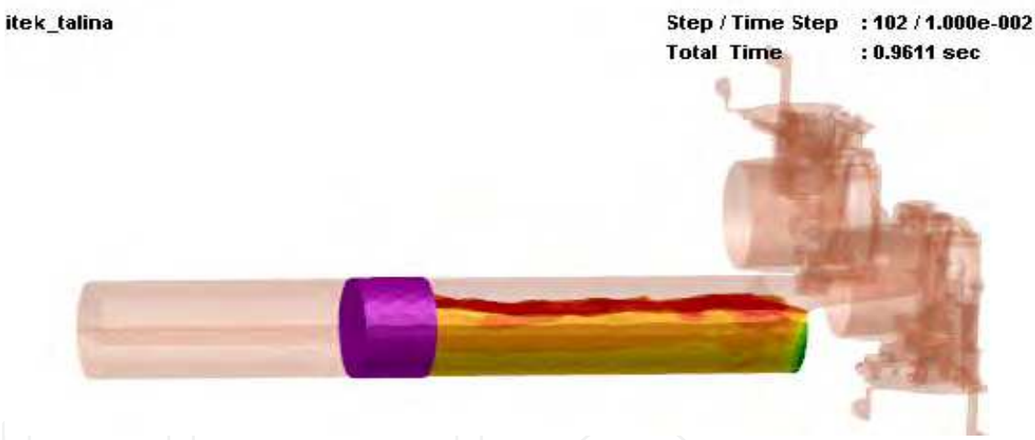
3.3 The shot sleeve simulation

The movement of the plunger was simulated by three different plunger speeds with FEM-based software ProCast. The simulation is shown on shot profile in Fig. 12a, b. The volume fraction in Fig. 12c shows no wave and no air entrapement.

The set up time was minimised, the plunger speed optimized and the industrial HPDC process was shortened for 0,48 s.



(a) (b)



(c)

Fig. 12. (a,b) Shot profile with three different plunger speeds. (c) Volume fraction picture of alloy and empty space in the shot sleeve.

3.4 The shrinkage porosity simulations

The shot sleeve simulation results were used as boundary condition for cavity filing simulations and shrinkage porosity simulations. Basic study in this paper was the shrinkage porosity. Fig. 13a, b shows simulated shrinkage porosity "red spots" in left and right casting. After 9 cycles of casting the constant conditions on the die were established and after 10 cycle we cut the left side casting to examine two red spot of simulated shrinkage porosity (Fig. 14a,b and 15a,b).

The two cross sections of left casting (Fig. 14b, 15b) show good agreement with the simulated results of shrinkage porosity (Fig. 13a, 14a and 15a).

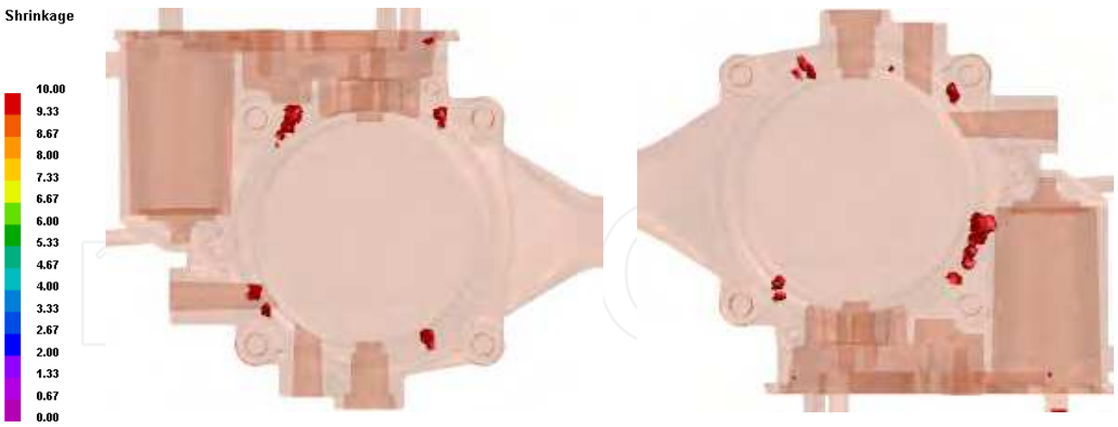
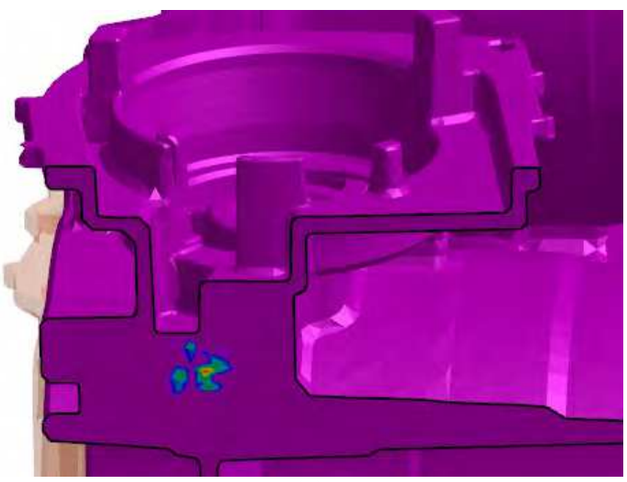
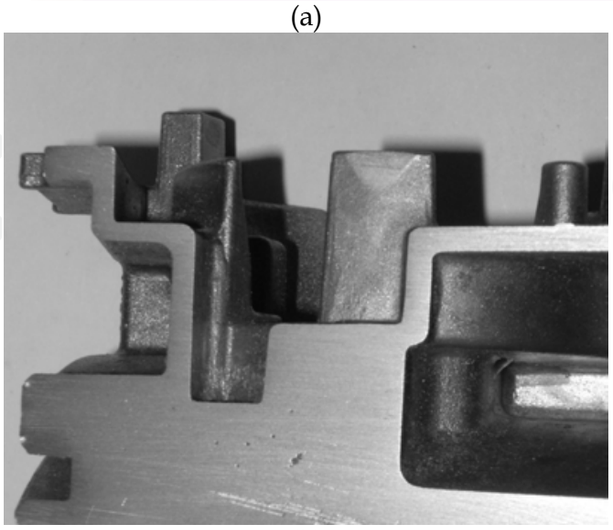


Fig. 13. (a, b) Shrinkage porosity simulation on left and right castings.

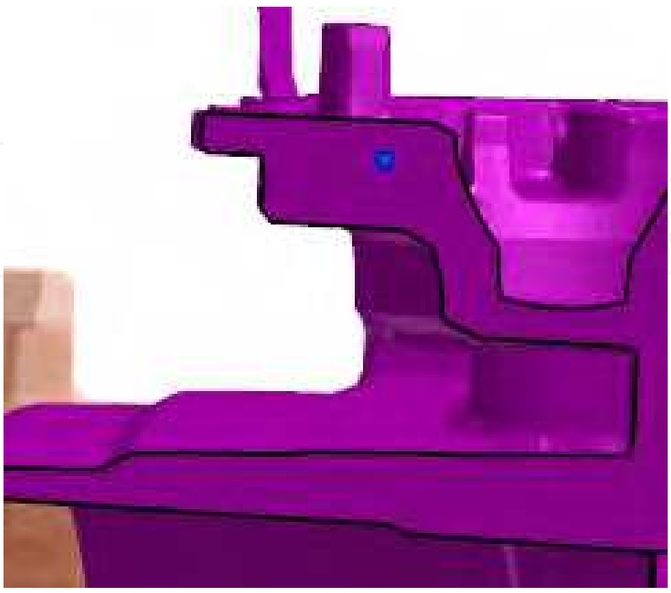


(a)

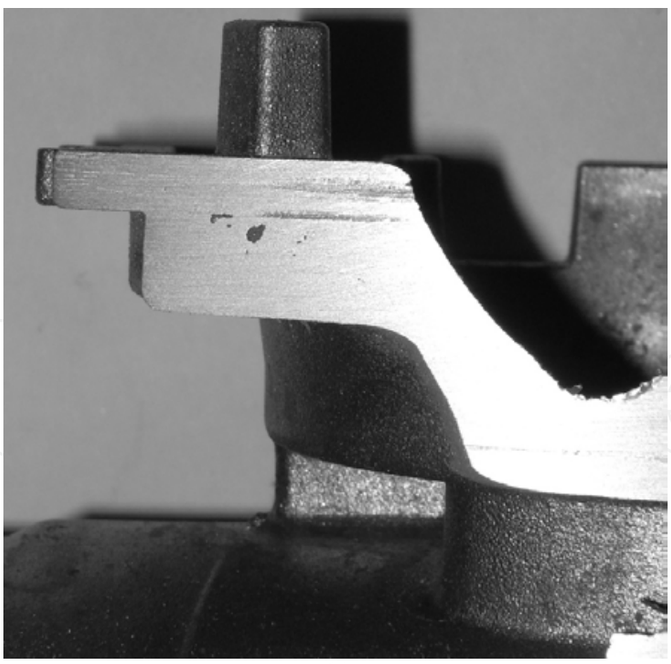


(b)

Fig. 14. (a, b) Shrinkage porosity in left casting: simulation and cross section.



(a)



(b)

Fig. 15. (a, b) Shrinkage porosity in left casting: simulation and cross section.

3.5 Conclusions on porosity simulations

In the present work the porosity of automotive components has been analyzed with ProCast, FEM-based software. The most important conclusions obtained are:

- The shot sleeve simulation gives valuable information for the final quality of the components by minimising the volume fraction of the empty space during the first stage of the HPDC process. The volume fraction shows no wave and no air entrapement.
- The shot sleeve simulation gives savings in lead time by minimising the set up time during the shot stage of HPDC process. The shot stage of HPDC process set up time was shortened for 0,48 s.
- The shot sleeve simulation gives also information of the location of the shrinkage porosity in castings, called "red spots". The shrinkage porosity in cross section of real automotive component show good agreement with the results of simulations.

4. Acknowledgment

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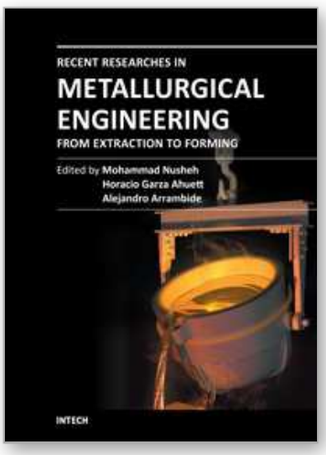
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Recent Researches in Metallurgical Engineering - From Extraction to Forming

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Metallurgical Engineering is the science and technology of producing, processing and giving proper shape to metals and alloys and other Engineering Materials having desired properties through economically viable process. Metallurgical Engineering has played a crucial role in the development of human civilization beginning with bronze-age some 3000 years ago when tools and weapons were mostly produced from the metals and alloys. This science has matured over millennia and still plays crucial role by supplying materials having suitable properties. As the title, "Recent Researches in Metallurgical Engineering, From Extraction to Forming" implies, this text blends new theories with practices covering a broad field that deals with all sorts of metal-related areas including mineral processing, extractive metallurgy, heat treatment and casting.

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