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Experimental and Simulation Tests on the Impact of the Conditions of Casting Solidification from AlSi9Cu3 Alloy on their Structure and Mechanical Properties

J. Hajkowski *, Z. Ignaszak
Division of Foundry, Poznan University of Technology,
Piotrowo 3, 61-138 Poznań, Poland
* Corresponding author: Email address: jakub.hajkowski@put.poznan.pl

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Abstract

The impact of casting conditions on microstructure a and mechanical properties was described, especially for cast products from AlSi9Cu3 alloy. Particular attention was paid to the parameters of dendritic structure: DAS 1 and DAS 2. Selected mechanical properties (by static tension test) of test castings made using basic technologies of casting: GSC - gravity sand casting, GDC - gravity die-casting and HPDC - high-pressure die-casting, are presented for cast-on test bars and cast separately. Casts were made of the same alloy AlSi9Cu3. Fractures and the zone near the fracture (after static tension test) was subjected to VT - visual tests, PT - penetration tests and metallographic tests. The condition of porosity (fracture zone) was also assessed. The analysis of virtual results was performed using the NovaFlow & Solid system together with the database and they were compared to experimental tests. This way of validation was applied in order to assess the correlation between the local rate of cooling and the size of DAS for GSC, GDC and HPDC technologies. Finally, the correlation between the parameters of structure and mechanical properties with regard to the impact of porosity was signalized.

Keywords: AlSi alloys, Microstructure and mechanical properties, DAS parameter, Gravity die- and high-pressure cast technologies, Virtualization in foundry and experimental validation

1. Introduction

Foundry is a technology for the manufacture of castings with predefined (controlled) local properties. Castings are always products with the gradient of properties on their cross-section. You can put a question - can we control this gradient consciously, e.g. using casting mold? As you know, the local properties of casting depend on the grade of alloy and technology of making the casting. Castings from Al alloys can be made in disposable sand molds (GSC), in metal (permanent molds) i.e. gravity die-casting (DGC) and high- pressure die casting (HPDC).

In castings from alloys in group Al-Si there are two basic phases: α solid solution and eutectic phase (α+β). Due to the presence of also such elements as Fe, Cu, Mg, Mn in these alloys, they crystallize additionally intermetallic phases and can affect mechanical properties of castings. Few per cent additives of the elements listed can create low per cent heteronodal solid solutions (substitute atoms) or/and intermetallic phases can form below (e.g. Al_2Cu, Mg_2Si $Al_8Si_6Mg_3Fe$, $Al_5Mg_8Cu_2Si_6$) and above (e.g. $Al_{15}(MnFe)_3Si_2$, Al_5FeSi) solidification temperature of silicon eutectic [1,2,3,4]. In order to modify the structure (next to one`s own exogenous nuclei - additional artificial substrates for nucleation) micro-additives are introduced to a liquid alloy as mortar containing Ti and B (fragmentation of phase α) and Sr (change in the form of silicon precipitations present in eutectic phase).

Cast products, besides ingots e.g. from continuous casting, are not subject to the process of plastic processing by rolling that is, castings are not subject to procedure, which causes, inter alia, the reduction of porosity with an increase of mechanical properties.

The factor acting in parallel, which conditions the change of the size and distribution of the individual components of structure is the cooling rate of the process of heat transfer from the casting into the mold. It has a significant impact on the process of nucleation and growth of grains [5], and on the kind of crystallizing phases. With the reduction of grain - the strength increase is observed. In the alloys Al-Si-Cu the presence of copper also causes the formation of intermetallic phases (e.g. Al_2Cu, $Al_5Mg_8Cu_2Si_6$) affecting mechanical properties, particularly for the reduction of plastic properties [1].

If you can differentiate materials of form locally, e.g. by introducing into the sand mold (GSC) metal chills [6] you can influence the structure and the properties of casting. The required, better properties in the selected zones are obtained in this way, close to the ones obtained by castings by casting to metal molds (GDC, HPDC).

Local changes of the structure of finished raw casting are also possible to obtain after the process of its casting using enriching treatments by means of unconventional methods. Here you can mention surface re-melting using laser or method GATW (Gas Tungsten Arc Welding), at a depth of individual mm, and a quick crystallisation and rate of self cooling of 10^2 - 10^3 K/s following this process [7]. This way allows a significant reduction of the size DAS (Dendrite Arm Spacing) and precipitations of eutectic silicon and affects the improvement of tribological properties and other operation properties of final part [8].

Mechanical properties of castings resulting from premises can be identified using samples, which can be obtained in different ways.

The factor with which you can identify the refining degree of dendritic structure is the distance between the arms of the dendrites of the first order (DAS 1) and the second order (DAS 2). For production castings, when the structure is obtained otherwise than by the crystallisation the oriented value DAS 1 is difficult or even impossible to identify, therefore the parameter DAS 2 is subject to identification, possible to determine also for dendritic equiaxial grains.

In the structure of casting the unfavourable and inevitable element of structure are voids or porosity. It can be minimized by using riser heads and/or chills in gravity casting, but it cannot be eliminated in 100%. Porosity in the castings from Al alloys can be of origin: shrinkage, gas (e.g. hydrogen) or mixed - gas-shrinkage [9]. In the pressure casting technology there are additionally gas pores in the form of air occlusions (entrapment), which are the result of the dispersion of the face of stream (free surface) of liquid alloy and occlusion of air trapped in the cavity of mold during its dynamic filling (in gaps of gating system even more than 50 m/s).

Discontinuities in the form of porosity, irrespective of origin reduce the active sectional field (interpretation called LOV - Loss of Volume [8,9]. The operating tension in the weakened cross-section by porosity should be referenced in the calculations of structure of final product to limit stresses of material averaged structurally. They can also be the place of the initialization of cracking in conditions of fatigue stresses and its further propagation during real operation. The method of forecasting such a threat known as LEFM (Linear Elastic Fracture Mechanics) and refers to the ratio of the intensity of stress, the excess of which will cause the development of discontinuities [8,9,10].

The objective set in this study is to determine the effect of casting on mechanical properties taking into account the degree of fragmentation of the structure (DAS 2) and the presence of discontinuities. Tests of castings made in three kinds of molds were performed (GSC, GDC and HPDC). A correlation between the rate of cooling was done, resulting from the technology applied and the size of DAS 2, with regard to the occurrence of porosity.

2. State of art

The impact of the size of grains in the structure of alloys before or after plastic processing is in a simplified way described in the literature by means of empirical dependence called Hall-Petch formula [11,12]. On its basis it is possible to explain the increase of the yield point with the reduction of the size of grains, defined most by analysing the image of metallographic specimen. The formula H-P was originally developed for steel, for conditions of the advantage of grains of one phase, with clearly outlined limits and with the minimum quantity of other structure ingredients.

$$\sigma_p = \sigma_0 + \frac{K_y}{\sqrt{d}} \tag{1}$$

where: σ_0- tension needed to overcome the resistance of one`s own crystallographic lattice) for a specific material and conditions of its fabrication, *d*- characterizes the size of grain or subgrain. K_y -is the coefficient which takes the orientation of grains i.e. critical stresses of glide taking into account the locality of stress concentration [13].

In the structure of casting the size of grain can be described with a direct parameter e.g. Feret diameter. The application of substitute parameter in the form of DAS, or average thickness of the branch of dendrites, causes that the values of constants in the above formula are not unambiguous and require a separate procedure of tests.

The Hall-Petch equation has been modified by Marckrott [14] and is an attempt to take into account the occurrence of e.g. two phases in the structure of material.

In the literature on the relations of strength properties of castings from Al alloys and parameters of structure they are analysed most often without any information about the condition of the porosity of the samples tested. However, it is common knowledge that mechanical properties of castings depend not only on the parameters of structure and its components for a particular type of alloy (for its given metallurgical quality), but also on the technology of making the casting. The structure of casting is not perfectly compacted, it contains discontinuities (porosities). and decreasing mechanical properties to a different extent. It is therefore to be assumed that the results of these tests and empirical formulas developed apply to samples, assuming there is no porosities in their structure.

From fairly numerous articles on the growth of dendrites of phase α in Al-Si alloys the ones as an example were selected [15-21] describing the impact on this growth in thermal crystallization conditions. The dependencies quoted therein allowing to assess DAS (distance between the arms of dendrites) based on bases of the theory of nucleation and growth are in form:

$$DAS\ 1 = a_1 \cdot f\,(\tilde{A}, m_L, C_0, k_0, D, G_L, V_L) \qquad (2)$$

$$DAS\ 2 = a_2 \cdot f\,(\tilde{A}, C_0, k_0, T_F, D, G_L, V_L) \qquad (3)$$

where $\tilde{A}$ - the Gibbs-Thomson coefficient, m_L - the liquidus line slope, k_0 - the solute partition coefficient, C_0 - the alloy composition (solute amount), D - the liquid solute diffusivity, G_L - the temperature gradient in front of the liquidus isotherm, V_L - the dendrite tip growth rate,

The values a_1 is the DAS 1 calibrating factor and a_2 is the DAS 2 calibrating factor, with depend on the alloy composition and T_F - the fusion temperature of the solute.

The dendrite arm spacing given to Bouchard-Kirkaldy model [18] refers is that of the initial dendritic growth. The calibrating factor is incorporated to take into account among other uncertainties and growth correction for secondary spacings (DAS 2).

As results from the analysis concerning the solidification front morphology an important parameter influencing the shaping of dendritic structure is the rate of cooling R, which is a scalar product of gradient G_L and growth rate V_L in the dendrite tip area. If in the system casting-mold there is no possibility of independent impact on G_L and V_L (as in the case of directional solidification [17]), the local time of solidification binds?? both parametres automatically. Thus, inter alia, Kattami and Flemings [19] and Feurer and Wunderlin [20] proposed the dependence of DAS 2 (as more important) only on the local time of solidification (t_{sol}), material coefficient (M) and empirical coefficient K=5.5.

Marking $A=K\cdot(M)^{1/3}$, the following results:

$$DAS2 = K\cdot(M\cdot t_{sol})^n + C = A\cdot(t_{sol})^{1/3} + C \qquad (4)$$

where constituents of the coefficient M is in the form identical to the above functions to assess DAS 1 and DAS 2 (3) and (4).

The relationship (4) can be referred to Fig.1 on which the results developed on the basis of the tests described in [15,16]: relation DAS 2 with the cube root order of local time of solidification were described.

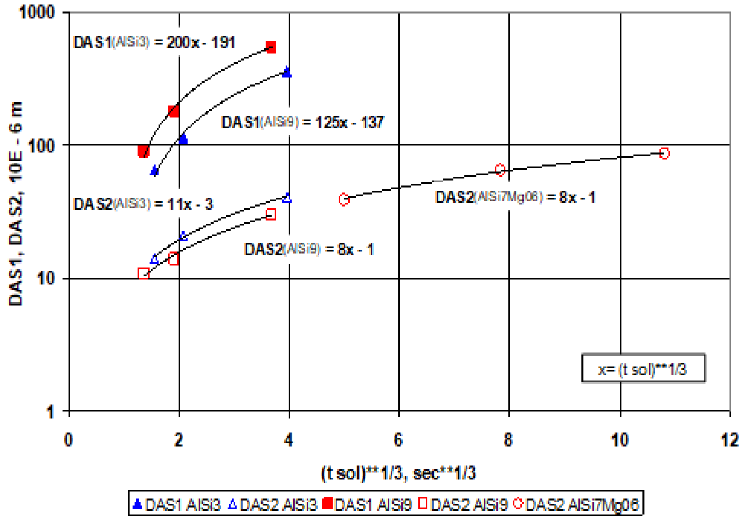

Fig. 1. The relationship DAS 1 and DAS 2 from the cube root of local solidification time developed on the basis on the results of experiments described in [15,16]

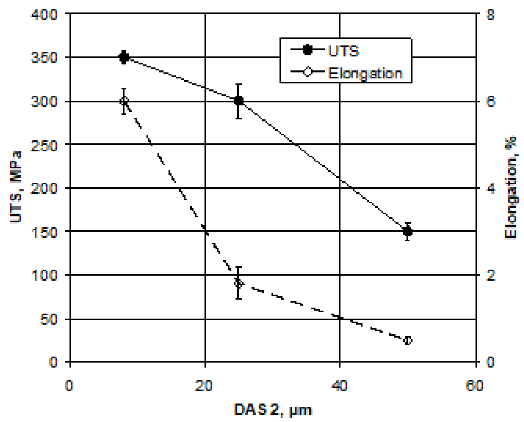

Fig. 2. The dependence of ultimate strength (UTS) and elongation (A) on DAS 2 for ASi9Cu3 alloy [21]

The charts in Fig.1 show that the actual empirical relation $DAS\ 2= A\cdot(t\ sol)^{1/3}+C$ (A= 8 to 11) is close with its nature to the relationship (4), in spite of the fact that it applies to different hypoeutectic alloys Al-Si.

In turn, the relationship DAS 1 from $(t_{sol})^{1/3}$ indicates a more complex impact of the parameters of experiment in the form of a significant impact of the value of free term (C), reducing by more than 100 μm the distance of the major arm axes of DAS 1 in relation to the term $A\cdot(t_{sol})^{1/3}$. This may be due to the scenario of the experiment (oriented solidification - mostly directional, on the chill) and the impact of the increasing amount of eutectic phase with the increase of Si content. The fact of about 10 fold relation of arms DAS 1 / DAS 2 was confirmed.

It should be noted that in case of different experimental procedure than the one solidification oriented, only the value DAS 2 is a reliable parameter of the degree of the fragmentation of the structure of equiaxial grains (prevalent in the structure of castings with a small thickness of walls, in the technology of execution in which the forced directional action of heat transfer) was not applied.

Example of the relation of structure (DAS 2 parameter) with the material parameters (UTS and A) is shown in Fig. 2.

Simultaneously it's known that the existence of gas-shrinkage porosity in the castings is inseparably linked with the mechanisms of their formation. They can be classified as follows [5,9,22]:

- shrinkage porosity (Fig.3d) - is due to the increasing density of packing the atoms during transition from the liquid to the solid state. This kind of porosity can be easily identified, on the metallographic specimen, even with a unaided eye; dendrite tips of α phase were rapidly deprived of the possibility of growth due to the lack of the liquid phase in their immediate vicinity,
- gas porosity of hydrogen type (Fig.3b,c,e) - is created during the process of solidification, when the atomic hydrogen dissolved in liquid alloy is pushed in front of solidification causing the increase of its concentration until the reaching the limit concentration solubility according to diagram of Sievert [23]. Nucleation and increase in volume of gas pore takes place then [24]. Morphology of the bottom of porosity is predominantly smooth, tips of dendrites are rarely seen as in case of porosity of shrinkage origin. Hydrogen can also desorb in emerging shrinkage porosity creating the gas-shrinkage porosity already described (Fig.3f).
- gas porosity - air entrapment - porosity of this type is most commonly observed in castings produced by casting pressure method (HPDC). It results from the dynamic way of introducing a liquid alloy to the cavity of mold and dissipation of the face of stream introduced to the cavity of HPDC mold. In addition, during the movement of the piston in the blasting chamber, the waving of the free surface of liquid alloy can take place, causing the trapping of air already at the entrance to the gating system. Then it is introduced together with the liquid alloy to the cavity of mold.

The total impact of the presence of porosity and fragmentation of the structure (characterized by the size of DAS) on the properties identified in the fatigue test [25] is shown in Fig.4. It can be observed that porosity affects the decrease of mechanical properties in a greater degree. That observation is consistent with the hypothesis of LOV mechanism (Loss of Volume), understood as a reduction of the active field of cross-section transmitting the load and LEFM (Linear Elasticity Fracture Mechanics), related to the initiation of cracking during fatigue tests.

The analysis of bibliography, including our tests shows that the tightness of the structure of alloy is estimated with the use of the measurements of density of the samples taken from the casting ("dichte index" - index of porosity) is linked to the fragmentation degree of the main phases of alloy (DAS of α phase is an essential distinguishing parameter [22]). In metallurgical process you can be use treatments of modification by introducing of artificial germs to nucleation and in this way also influence DAS.

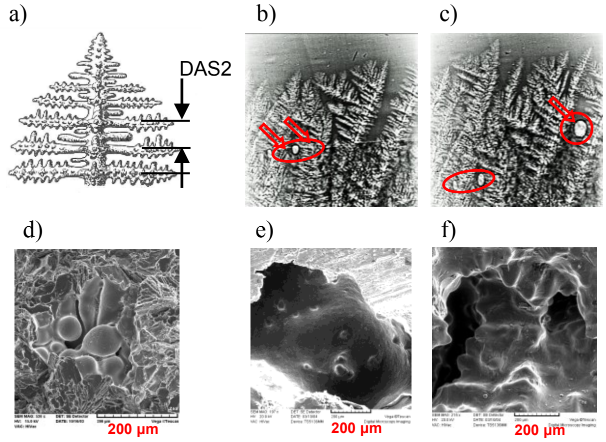

Fig. 3. Images of relationships between DAS and gas-shrinkage porosities: a - scheme of primary dendrite branch and DAS 2 dimension [17], b, c – two stages of crystallization on the dendritic solidification front generation of hydrogen bubbles (by X-ray image) [24], d - shrinkage porosity, e – gas porosity, f – Mixed (gas & shrinkage) porosity (SEM, destructive testing)

The intentional influence on the gradient of mechanical properties should be related to the operation requirements of the products cast. Most of these properties can be obtained using special methods of casting or using the method of surface treatment to the refining of structure [7,8].

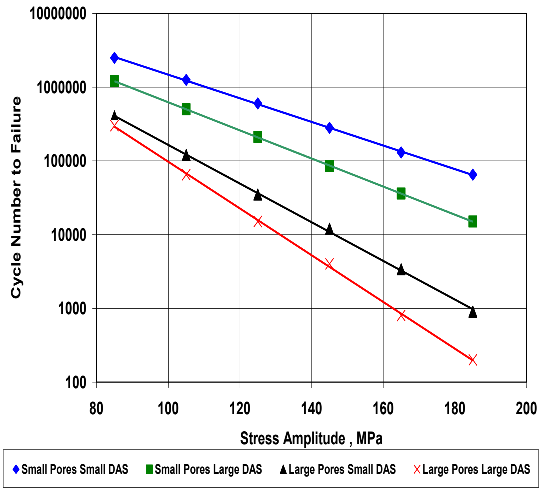

Fig. 4. Example of analysis of simultaneous effects on the fatigue life, as a function of stress amplitude (case of R= -1), for four combinations of DAS and maximum pore size (Small Pores-30µm, Large Pores-1000µm, Small DAS-22µm, Large DAS-74µm). Example for AlSi7Mg0,3 alloy (356), based on [25]

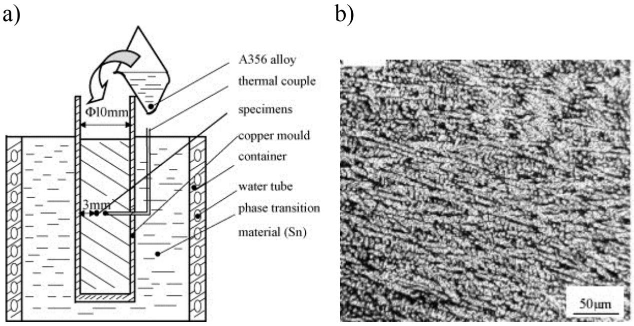

Fig. 5. Scheme of the stand for casting of samples in the mold of copper submerged in the tin medium with phase transformation (a) and the micro-structure of sample from alloy A356 (DAS1=10-11μm, DAS2=5-6 μm) (b) [26]

In [26] the impact of the intensive heat transfer between the cylindrical casting Φ10mm, made of A356 and the mold made as a combination of coat made of Cu and tin alloy, was indicated (Fig.5a). The effect of intensive heat transfer is shown in Fig.5b.

The application of laser treatment in the surface zone [27] causes further reduction of DAS1 and DAS2 (Fig.6).

Reaching such reduction of DAS value in castings with a greater thickness is not possible in the conditions of casting to permanent molds, even in the conditions of HPDC technology. The above examples of extremely intense heat exchange are a reference to the limits of DAS value. As it will turn out later in the article, only in the superficial layer of pressure castings (Fig.10) is it possible to achieve the value DAS2 = about 8 μm.

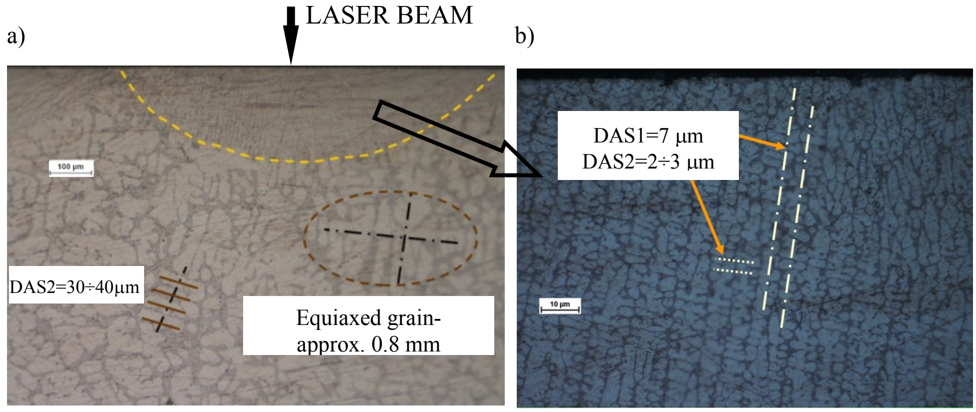

Fig. 6. The microstructure of sample after remelting with the use of laser; the distance between the arms of dendrites - DAS 1 (of the first order) and DAS 2 (of the second order) [27]: a) remelted zone and zone, which was not remelted (native), (b) remelting zone detail

3. Methodology of real and virtual studies

The alloy tested (AlSi9Cu3 i.e. AC-46000) was melted in the gas furnace and subjected to the process of gas refining using the rotor, and argon to remove hydrogen and powdery deoxidizing agent. The alloy after the refining process was tested as regards the degassing degree on the basis of density index [8], and the test of chemical composition using a spectroscopic method (Table 1).

A series of pressure castings HPDC was made, obtaining a sufficient number of cast-on test samples for tests of mechanical properties (identical conditions of casting as in case of production casting). As a comparison gravity samples were cast to the sand mold (GSC) and samples with the round cross section to permanent mold (GDC). The diagrams of samples are shown in Fig.7.

Table 1.
Standard and experimental average chemical composition of the AlSi9Cu3 alloy

	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti
						[%]					
min	8	-	2	-	0,05	-	-	-	-	-	-
max	11	1,3	4	0,55	0,55	0,15	0,55	1,2	0,35	0,25	0,25
exp.	**8,81**	**0,81**	**2,20**	**0,22**	**0,32**	**0,04**	**0,07**	**0,97**	**0,06**	**0,017**	**0,05**

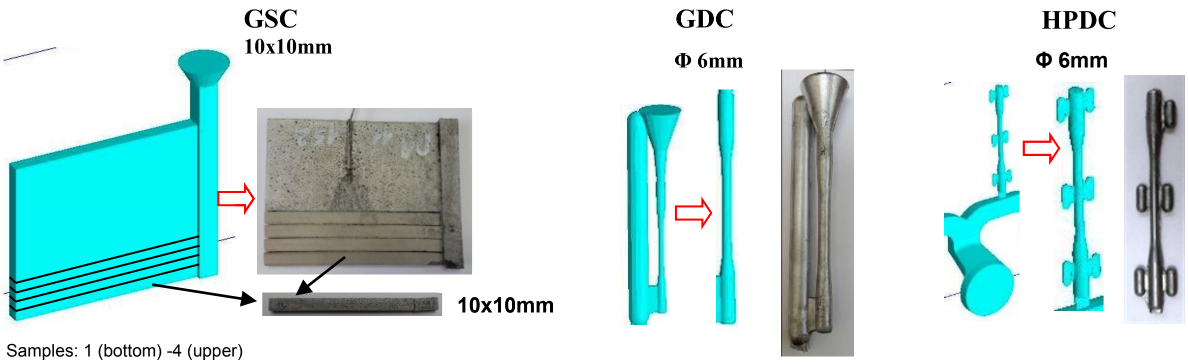

Fig. 7. Views of samples from alloy AlSi9Cu3 intended for tests (CAD geometries and experimental samples)

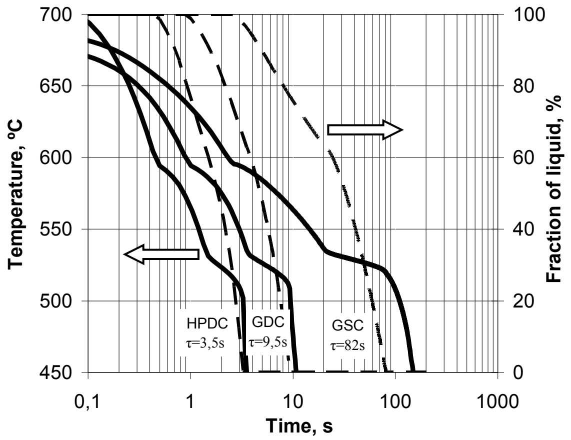

Fig. 8. Curves of solidification (continuous curves) and curves of decrease of the liquid phase fraction (dashed curves) test samples (technologies HPDC, GDC and GSC) obtained by virtualization by the simulation system NF&S. Times of solidification were indicated for F_{liq}=0.

*[Average database parameters of simulation tests – **GSC**: initial alloy temp. - 686°C, initial sand mold temperature – 20°C sand mold conduct. – 0,8 W/m·K, density - 1600 kg/m³, specific heat - 1000 J/kg·K. **GDC**: initial alloy temp. - 686°C, initial mold temperature – 260°C, die heat conduct. 32 W/m·K, density 7600 kg/m³, specific heat 600 J/kg·K, heat transfer coefficient on die mold – casting interface – 800 W/m²K. **HPDC**: initial alloy temp. - 710°C, initial mold temp. – 170°C, mold heat conduct. 30 W/m·K, density 7600 kg/m³, specific heat 600 J/kg·K, average heat transfer coefficient on mold – casting interface – 2000 W/m²K]*

Samples for the tests of mechanical properties (cast to the sand mold and permanent and HPDC mold) was assessed for the presence of porosities and DAS 2 values were identified microscopically on the chosen sections of samples.

Virtual tests using the simulation system NovaFlow&Solid (NFS) of casting individual samples for variants of technology applied were also performed. The objective of tests was to validate the presence of porosities and estimate the time of solidification (Fig.8) in the centrally located (thermal hot spot) zones of castings, with the estimate of DAS correlation with the conditions of solidification.

4. Results analysis of experimental and virtual tests

Test results shown in Fig.9 using the testing machine Instron 3365 of the mechanical properties of samples made with the application of three technologies, show a considerable variation of parameters UTS, Re and A (respectively Ultimate Tensile Strength, Yield Strength, Elongation. The best properties were obtained for HPDC, successively GDC and the smallest for GSC.

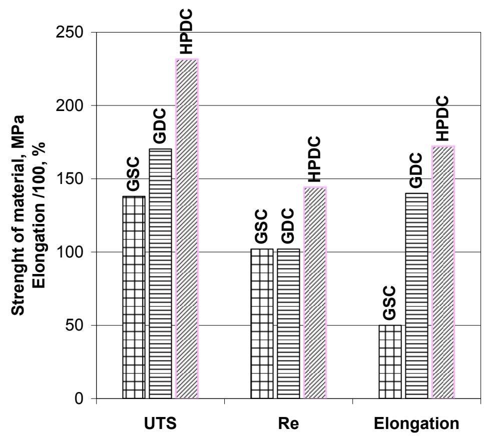

Fig. 9. Comparative summary of test results of mechanical properties (UTS, Re and A) for three technologies (DSC, GDC AND HPDC)

Test results of sample microstructure (Fig.10) confirm the expected relationship of DAS size with the technology applied translated directly on the rate of heat transfer from the casting to the mold depending mainly on thermal molds characteristics and mold-casting heat transfer coefficient. The largest size of DAS was obtained for GSC 45÷75 μm, for GDC 8÷12μm and the smallest for HPDC (sample UTS) 3÷10mm.

On the basis of the tests of parameter DAS 2 performed and estimated on the basis of simulation calculations and local time of solidification (for small-sized samples made in conditions of three technologies) in relation to the formula DAS2=A*$(t_{sol})^{1/3}$ (free term C is assumed as zero) - the following ranges of values of the coefficients A were calculated:

- for GSC: DAS2 (μm) ≈ 10 is 15·$(t_{sol})^{1/3}$

- for GDC: DAS2 (μm) ≈ 4 to 6·$(t_{sol})^{1/3}$
- for HPDC: DAS2 (μm) ≈ 2 is 5·$(t_{sol})^{1/3}$

These results do not fit within the hypotheses presented in [15,16], where the values of DAS 2 depend only on the average rate of cooling the casting t_{sol}. Represented during the solidification time. On the basis of our tests it can be assumed that the coefficient A should recognize also the value of local undercooling acting dynamically on nucleation processes and growth of phase α, depending on the heat shock during the initial period of the crystallization of alloy.

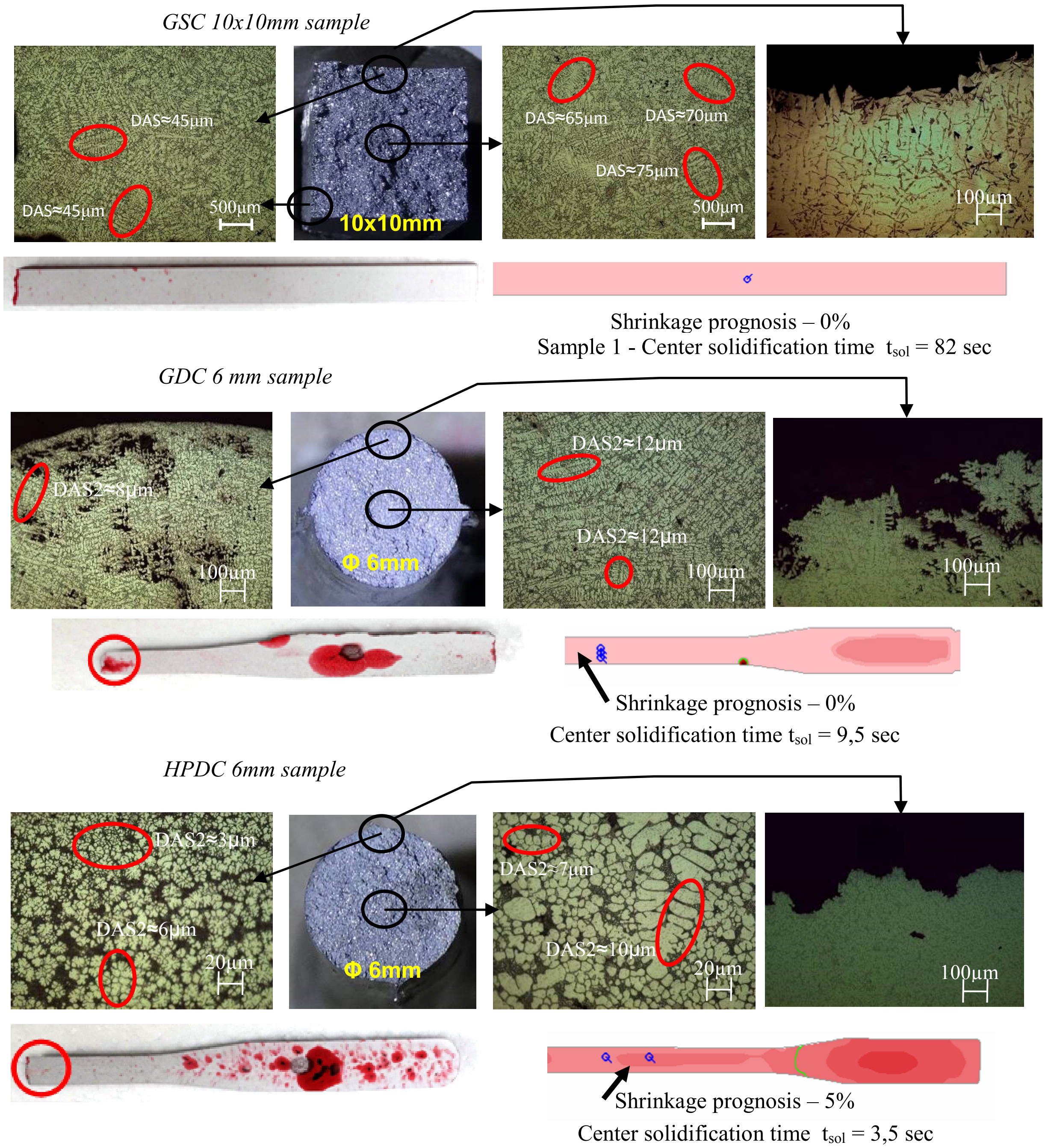

Fig. 10. Test results comparison of the micro-structure of samples for tests of mechanical properties solidifying in three kinds of molds for the identification of DAS values and fractures (respectively in mold-casting interface central area of samples). Simulation tests carried out in NFS system were summarized for each variant and times of solidification are presented. Micrographics in cross section to the fracture were also shown, indicating the presence of the diversification of porosity in the zone of fractures

The results of UTS tests are shown in Fig.11 for samples shown in Fig.7.

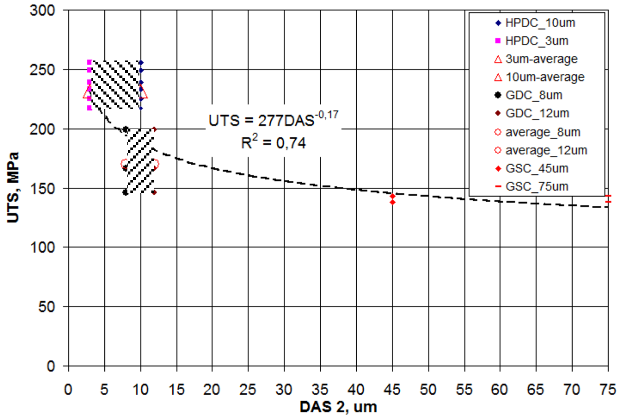

Fig. 11. Summary of test results of UTS for samples made using methods GSC, GDC and HPDC in the function of the range of values DAS2 measured in the fracture zone. The function UTS=f(DAS 2) is indicative

5. Conclusions

The article presents an analysis of the state of knowledge and the results of own research of the effect of the pour point of cast alloy AlSi9Cu3 on chosen parameters of the structure and mechanical properties. It has been demonstrated that the formula which can be found in the literature, which make the values DAS 2 dependent only on solidification time should be treated with caution. Dynamic phenomena which are not recognized in such a simplified approach influence DAS 2 values. In the empirical formulas suggested for DAS 2 coefficients depend on the intensity of cooling (A variable from 2 to 15).

In addition, it has been demonstrated that mechanical properties of samples GSC, GDC and HPDC connected with the tests of structure in the areas of fracture indicate the dependence of the strength on DAS 2, deviating from linear dependence when interval of variability DAS includes range from several to several dozen microns.

As far as the pressure castings are concerned, it turns out that the decisive factor affecting the reduction of local strength properties is the presence of porosity in the structure. These discontinuities in the material identified by the non-destructive testing - RT and CT (for 3D geometry) and also PT method after cutting the chosen casting section - were confirmed in decisively reduced values UTS of sample cut from the production casting (not described in this paper). This fact should revise the approach of the recipients of castings to the conditions of acceptance, in the summary to the requirements as to mechanical characteristics defined most often on cast-on test bars or cast separately.

The end question is still open. What is the reasonably limit of grains refinement characterized to DAS structure parameters, while taking into account the achievable minimum microporosity level is obtain the optimal mechanical and exploitation properties, taking into account the cost effective.

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References

[1] Shabestari, S.G. (2004). The effect of iron and manganese on the formation of intermetallic compounds in aluminum–silicon alloys. *Materials Science and Engineering A*. 383, 289.

[2] Martinez, D.E.J., Cisneros, G.M.A., Valtierra, S. & Lacaze, J. (2005). Effect of strontium and cooling rate upon eutectic temperatures of A319 aluminum alloy. *Scripta Materialia 52*, 439.

[3] Pietrowski, St. (2001). *Silumins*. Publ. House of Lodz Univ. of Tech., Poland (in Polish).

[4] Cáceres, C.H. et.al., (1999). The effect of Cu content on the level of microporosity in Al-Si-Cu-Mg casting alloys, *Scripta Materialia*. 40(5), 631.

[5] Campbell, J. (2015). *Complete Casting Handbook*. 2nd Edition., Butterworth-Heinemann.

[6] Orłowicz, A.W. & Mróz, M. (2003). Application of Arc Electric For Forming Structure and Fusion Zone Geometry on Al-Si Alloy Castings. *Archives of Foundry*. 3(10), 81 (in Polish).

[7] Ignaszak, Z., Popielarski, P. & Hajkowski, J. (2013). Sensitivity of models applied in selected simulation systems with respect to database quality for resolving of casting problems, *Defect and Diffusion Forum*. 336, 135.

[8] Ignaszak. Z. & Hajkowski, J. (2015). Gas-and Shrinkage Porosities in Al-Si High-Pressure Die-Castings-Virtualization and Experimental Validation. *Defect and Diffusion Forum*. 364, 80.

[9] Ignaszak, Z. (2011). Conditions and perspectives for non-destructive testing of castings before they service. part II *Welding Technology Review*. 83(13), 41 (in Polish).

[10] Hall, E.O. (1951). Proc Phys. Soc. B64, 747.

[11] Petch, N.J. (1953). J. Iron Steel Inst. 174, 25.

[12] Bernsztejn, M.L. & Zajmovskij, W.A. (1973). *Structure and mechanical properties of metals*. WNT, Poland, (in Polish)

[13] Tensi, H.M. & Högerl, J. (1994). Metallographische Gefuge-Untersuchungen zur Qualitatssicherung von AlSi-Gussbauteilen. *Metallwiessenschaft und Technik*. 48(10), 776.

[14] Kurz, W. & Fisher, D.J. (1992). *Fundamentals of Solidification*. Trans Tech Publ., Switzerland.

[15] Peres, M.D., Siqueira, C.A. & Garcia, A. (2004). Macrostructural and microstructural development in Al–Si alloys directionally solidified under unsteady-state conditions. *Journal of Alloys and Compounds*. 381, 168.

[16] Steinbach, S. & Ratke, L. (2005). The effect of rotating magnetic fields on the microstructure of directionally solidified Al–Si–Mg alloys. *Materials Science and Engineering A*. 413-414, 200.

[17] Bouchard, D., Kirkaldy, J.S. (1997). Prediction of dendrite arm spacings in unsteady- and steady-state heat flow of unidirectional solidified binary alloys. *Metall. Mater. Trans. B*. 28, 651.

[18] Hunt, J.D. & Lu, S.Z. (1996). Numerical modeling of cellular/dendritic array growth: spacing and structure predictions. *Metallurgical and Materials Transactions A*. 27, 611.

[19] Kattamis, T.Z. & Flemings, M.C. (1984). *Trans. Metallurgical Society of AIME*. 15A, 1081.

[20] Feurer, U. & Wunderlin, R. (1977). Einfluss der zuzammensetzung und der erstarrungs-bidingungen auf die dendritenmorphologie binarer Al-legierunger. *Fachbericht der Deutschen Gesellschaft fiir Metallkunde, Oberursel*. 1.

[21] Olofsson, J. et.al. (2014). Characterisation and investigation of local variations in mechanical behaviour in cast aluminium using gradient solidification, digital image correlation and finite element simulation. *Materials and Design*. 56, 755.

[22] Hajkowski, M. et.al. (2012). Mechanical Properties of Al-Si-Mg Alloy Castings as a Function of Structure Refinement and Porosity Fraction. *Archives of Foundry Engineering*. 12(4), 57.

[23] Hufnale, W. (1983). *Aluminium-Taschenbuch,* Aluminium-Verlag, Dusseldorf.

[24] http://folk.ntnu.no/ragmat/

[25] Major, J.F. (1994). Porosity Control and Fatigue Behavior in A356-T61 Aluminum Alloy. *AFS Transactions*, 97, 901.

[26] Zhang, L.Y., Jiang, Y.H., Ma, Z., Shanc, S.F., Jia, Y.Z., Fanc, C.Z. & Wang, W.K. (2008). Effect of cooling rate on solidified microstructure and mechanical properties of aluminium-A356 alloy. *Journal of Materials Processing Technology*. 207, 107.

[27] Ignaszak, Z. & et al. (2013). Cellular Automaton Method Applied for Microstructure Prediction of Al-Si Casting Treated by Laser Beam. 4th International Conference on Integrity, Reliability and Failure - IRF'2013, Funchal 23-27 June 2013, Madeira Portugal.