Service life strength of die cast aluminum alloys with respect to the materials inhomogeneities originating from the casting technology

PhD dissertation

by

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Budapest, 2022.

1. Introduction

In the automotive industry environment protection, recyclability, economy and functional integrity are more and more important factors. Not just during the production, but even during the operation too. That is the why lightweight alloys and mainly the aluminum alloys are the optimum choice for parts where they can offer significant advantages as a lightweight, attractive appearance, excellent processability, and high corrosion resistance besides the complete recyclability. The automotive market for light metal shapes continues to grow at an increasing rate. In particular, the aluminum-silicon (Al-Si) and aluminum-silicon-copper (Al-Si-Cu) cast alloys are widely used in different application fields, because of their good castability. The development of production technology is having a major and complex impact on the industry and, through this, on meeting new and latent needs. The impact of technology development can be studied by several disciplines, I have been examined their impact on material technology in my work.

The automotive industry is a key demand-forming sector, and the results of development can save lives and affect health. Fulfillment of technical, quality, and other criteria is important due to the impact of the industry on society. Mass production requires great organization and thoughtful technical development. Among the vehicle components, both the number and weight ratio of cast aluminum parts are high. The use of aluminum alloys reduces the total weight of vehicles, thereby reducing fuel consumption and emissions, and has a positive effect on the reusability of the raw material. Casting satisfies economical, and energy-efficient production. The geometry of cast products, as a function integration requirement, has technical rather than complexity limitations.

Casting technologies offer a versatile advantage to meet the listed needs, a large number of technology variants are available (sand casting, precision casting, permanent mold casting, etc.). The selection of casting technology is critical for the mass production of die castings. One of the most frequently used technologies of casting applied for aluminum alloys is the high pressure die casting (HPDC), which is a near-net-shape technology. The process ensures high surface smoothness and excellent dimensional and shape accuracy for the castings. HPDC is a highly productive manufacturing process. The cycle time for small parts cast in a multi-cavity tool can be a few seconds, and even large parts only about one minute. The quality of castings (pressure tightness, strength, surface quality, dimensional accuracy, etc.) can be produced with different parameter combinations. The surface quality of the finished product depends on both the surface quality of the mold and certain parameters. Die casting guarantees the best (shortest) casting cycle time. The precise heat management of the mold cavity ensures fast and intensive cooling, thus also promoting a short cycle time and a fine grain structure in the casting.

The HPDC technology is a suitable method to produce aluminum and low-melting alloy castings, which provide good quality parts. These aspects are as follows: high surface smoothness and excellent dimensional and shape accuracy, accompanied by relatively low production costs. During the die casting process, the molten metal is injected into a metal mold at high speed and solidifies under high pressure. The multiplication pressure can be used to reduce the size and number of material discontinuities due to consistency change. The applications of aluminum die castings are normally (however not totally) limited to non-structural components that do not require a heat treatment or welding. Porosity causes more rejected castings than any other reason.

In addition to the favorable properties, the difficulties of the technology must also be mentioned. In cold chamber die casting of aluminum alloys air, and other gases are often trapped in the metal, because of the turbulence of the alloy as it is forced into the die cavity at high pressure and speed. This phenomenon can cause porosity in the casting, which may affect the mechanical properties of the product. In structural applications, it can act as a stress concentrator and, therefore, create a site where cracks may occur. The defects can be divided into several groups according to their location (volumetric defect, surface defect, dimension deviation, mechanical imperfection). The complexity of the cavity geometry has a direct effect on the turbulent flow of the melt during tool filling. Furthermore, the turbulent flow of melt, especially during filling of the tool's non-vented pockets, or in the vicinity of cross-sectional changes in the closed mold, can cause material discontinuity during solidification. That is why the mold design directly affects the quality of the castings. An additional problem is the fact that porosity in casting may not always be immediately apparent. If discovered after subsequent secondary processing, customer dissatisfaction can be extreme. One possible solution to reduce or avoid material discontinuity is vacuum assistance. Attempts to develop methods of vacuum-assisted die casting were introduced into cold chamber die casting machines. This use of vacuum in the die casting process is an innovative development.

My dissertation aims to investigate the effect of the vacuum-assist method on volume defects (gas porosity, shrinkage) and their effect on mechanical properties and the service life strength. The statistical evaluation of the data was performed by life data analysis. The life data analysis is also known as the Weibull analysis. The two-parameter Weibull distribution model was applied to deal with the variation in mechanical properties. The material discontinuity and their characteristics (location, morphology, measure, etc.) have been examined by X-ray and computed tomography (CT), and then after the tensile or fatigue examinations, the results and the failure modes were related back to the CT scans. This feedback of the results was supported by the investigation of the grain structure by light optical microscopy (LOM) and scanning electron microscopy (SEM). Additional aims were to evaluate the fracture resistance, and to determine indirectly the threshold stress intensity value (ΔK_{th}) of cast

AlSi9Cu3(Fe) alloy containing small-sized natural or artificial defects in uniaxial fatigue load.

2. Objectives

According to the literature search and confirmed in the foundry where the specimens were cast, although AlSi9Cu3 (Fe) alloy is a widely used and tested die casting alloy, no data are available on the effect of vacuum-assist high pressure die cast (VPDC). The recently published topic is the positive effect of vacuum-assist on the post-processability of castings (heat treatment, welding, riveting, etc.), its extent and especially its numerical (quantitative) effect are unknown. Furthermore, there is no clear explanation for the improvement of strength and fatigue properties due to vacuum-assist. Based on the literature research, I have discovered that there is currently no exact 3D non-destructive material testing standard for the series qualification of castings relevant for durability, which contain inhomogeneities resulting from the technology. However, it should be emphasized that the natural material discontinuity (gas porosity) is a necessary feature of die casting technology. The aim of my work is not only the development of vacuum-assist technology but also the study of the effect of a given technology on a material, which cannot stand without a thorough knowledge of the technology.

Based on the wide and careful literature search, the following objectives have been set. In order to fulfill the objective below experiments and studies were design to explore them. The tested AlSi9Cu3 (Fe) alloy samples were produced by horizontal cold chamber die casting and its process variant of vacuum-assisted die casting.

1. The extension of material test results of vacuum-assisted AlSi9Cu3(Fe) aluminum alloy, and determination standard sterngth and strain values.
2. The effect of vacuum level on gas porosity (independently of technology parameters) and through this on the standard strength and strain values.
3. The investigation of the effects of vacuum technology on the material structure qualitatively and quantitatively. Determination of fatigue strength over the service life (up to 2 10^6 cycles) and endurance range (up to 10^7 cycles) with load asymmetry of R=-1 and R=0.1.
4. To determine the specifics of the position of the porosities, which causing fatigue fractures during fatigue test by microscopic examination, and feedback with the result of preliminary CT examination.
5. To determine the characteristics of the inhomogeneities causing fatigue fracture based on the applied non-destructive examination by features of shape, sphericity, and size.
6. To determine indirectly the threshold stress intensity value (ΔK_{th}) of cast alloy containing small-sized natural or artificial defects in uniaxial fatigue load.
7. To evaluate the fracture resistance and the critical defect size and this effect on the fatigue strength in the endurance range.

3. Materials and methods

The experiments were performed with AlSi9Cu3(Fe) (EN AC 46000, 383.0) casting aluminum alloy. This grade of aluminum alloy is widely used because it is a relatively cheap (1950-2050 EUR/T) casting material. However, the Authors have to note that this alloy has not been extensively examined from a vacuum-assisted die casting point of view. Another reason for choosing this alloy is in its favorable mechanical properties. These favorable mechanical properties are due to the alloy’s silicon and relatively high copper content, which provides the possibility of precipitation hardening. In this way, the favorable strength values can be further increased by heat treatment. The aluminum ingots were melted in a gas-heated furnace. The liquid aluminum was treated by rotary degassing with nitrogen gas for 6 minutes. During the casting of the test pieces, two heats were used, which were dosed with automatic ladling from a resistance-heated holding furnace. The mechanical properties of aluminum-silicon alloys are strongly dependent on the size and shape of the grain structure. The microstructure is strongly influenced by alloying, cooling rate, and melt treatment methods. The copper alloying gives one of the highest available strength and hardness values. The iron is considered to be fundamentally unfavorable in the case of wrought alloys and is considered an impurity. However, in the case of casting alloys, the benefits added against the adhesion of die tools. The specimens were tested in the ‘T1’ condition, which means controlled cooling of casting and natural aging. The test was performed 8 days after casting, which guarantees the natural aging condition for the samples.

Cast test samples were produced by horizontal cold chamber die casting machine OMS 450. The machine was equipped with a vacuum system consisting of a vacuum pump and vacuum valves, in order to evacuate the air and other gases, which entrapped in the mold cavity and the injection sleeve system. The vacuum system was connected directly to the die tool’s venting system. The vacuum valve is located at the top of the die tool, preventing the flow of metal into the vacuum system. The adjusted pressure was atmospheric in the case of conventional HPDC and a few different absolute pressures in the case of VPDC. Each casting cycle is consist of the next steps: 1) the first step is to close the die tool halves; 2) secondly, the liquid metal poured into the filling chamber; 3) the third step is filling the mold cavity (casting); 4) the fourth operation is to open the die tool halves; 5) and then remove the casting (ejection) from the mold cavity; 6) finally, the cooling of the tool halves and the spraying of the release agent are closing the process. The casting operation has three main sub-operation as the first stage, second stage, and third stage. The tests were done at the following key process parameters: the plunger velocity during i) the first stage was 0.5 m/s, while during the ii) second stage it was set to 2.8 m/s, the iii) third phase intensification pressure was 704 bars. The plunger velocity in the first stage depends mainly on the state of the developing fluid wave in the shot sleeve before the beginning of the injection stage. The velocities of different stages were determined by filling simulations. Other factors that affect product quality are the mold temperature, molten metal temperature, and the speed of the injection stages, that is the why, these parameters were fixed during experimental casting. The repetition of the production cycle is only subject to strict controls and with the manufacturer's high operational discipline, gives the same casting quality throughout the product's life cycle.

The kinds of natural defects are shrinkages (cavity and sponge), gas porosity, inclusions, and oxides. Typical casting defects massively influence the mechanical and fatigue properties. The effect of the defect features on fatigue strength can be characterized by its position, morphology, and size. Pore shape and pore orientation also influence the fatigue life. There are several possibilities for classifying the inhomogeneities based on literature. According to their appearance, the inhomogeneities can be divided into three groups: 1) morphology or location of defect (internal, external, geometrical); 2) the metallurgical origin of defects (gas pores, solidification shrinkage, etc.); 3) a specific type of defects (the same metallurgical phenomenon may generate various defect). Other classifications are possible according to the formation of inhomogeneities: i) in the liquid state, ii) during solidification, iii) and in solid-state as well. The most common material defects in aluminum during the die casting of a given alloy are 1) oxide film inclusion due to oxidation of the melt; 2) air entrapment (gas porosity); 3) change of state (shrinkage porosity); 4) precipitation of compound phases.

Destructive and non-destructive material testing methods were performed and evaluated primarily based on industry standards for casting defects. Each of the inhomogeneities is related, as it is conceivable that a surface defect (cold flow, defective tool filling, open pore, etc.) can simultaneously cause a deviation in shape fidelity, a surface aesthetic defect, and its presence can impair the resistance of the piece to fatigue. Each of these inhomogeneities is related, as it is seen that a surface defect (cold flow, filling defect, open pore, etc.) can cause simultaneously a deviation in shape, a surface imperfection defect, and its presence can lose resistance of the casting to fatigue.

The evaluation of computer tomography (CT) data of casting defects and their correlation with the mechanical and strength properties are still lacking and desired. CT enables to establish the link between porosity and fatigue crack initiation. Voids can be detect by radioscopy as well, but due to the over-conservative safety regulations, the investigations may result in unnecessary high reject rates. Thus, the effect of detectable material inhomogeneities on failure can be more accurately predictable than before by destructive material testing.

4. Summary of the dissertation

Casting is one of the leading component manufacturing processes in the industry, where pieces are obtained by casting (injecting) metals in a liquid state into a casting mold. The casting process is well automated, and the successive products have the same characteristics. Among the variations of the casting processes, the castings were produced by horizontal cold chamber high pressure die casting (HPDC) and the variants of its technology. In my dissertation, I dealt with the material testing of the HPDC aluminum AlSi9Cu3(Fe) alloy. The increase in demand for light metal castings and the rise in requirements (heat treatment, welding, and riveting) have resulted in the spread of vacuum venting technology (VPDC). Vacuum venting is preferred for castings, subjected to post-processing (heat-treatment, welding). However, its effect is less known and even less published topic.

The dissertation aims to study the effect of inhomogeneities resulting from the production of castings on strength and durability by material testing of castings produced by HPDC and VPDC. The results in the dissertation have responded to the goals, and the novelties recognized in the meantime were published in international and national journals. The results were also used to formulate the novelties in these points. Among the mechanical properties, the elongation at break value is highlighted, which showed an increase of ~50 % in the case of AlSi9Cu3 (Fe) alloy produced by the vacuum-assisted high pressure die casting (VPDC). The HPDC castings, due to the peculiarities of the technology, are not suitable for subjecting heat treatment processes that include solution heat treatment. At the temperature of the solution heat treatment, the mechanical properties decrease, and the enclosed gases expand. The surface of the piece becomes blistered, and the workpiece or casting deforms. Vacuum-assisted casting is one of the processes by which castings become post-processable (heat treatment, riveting, welding). The results of the fatigue tests also showed that the decrease in the amount of porosity significantly increased the fatigue life of the pieces at a given load level and significantly reduced the scatter of the number of cycles to failure, which increased the reliability. Finally, the feedback on the results obtained by CT examination after fatigue tests showed that despite the significant variability of the detected defects, the defects causing the failure were only in a narrower range. The Kitagawa-Takahashi (KT) method proved to be a correct indirect procedure to determine the threshold stress intensity range based on the fatigue test results. The KT method can be used to determine the effect of the defect size on the fatigue strength at the given number of cycles to failure.

New Scientific contributions

1st thesis statement: The examination of AlSi9Cu3(Fe) alloy tensile samples produced by vacuum-assisted high pressure die casting showed that in the case of a cavity pressure range of 80 ± 5 mbar, the strength and elongation values increased significantly. The vacuum-assisted die casting process can significantly reduce the gas porosity and improve the mechanical properties. Comparing the mechanical properties of the samples produced by conventional venting with the values of the castings produced with a vacuum support: the proof strength ($R_{p0.2}$) increased by 7 %; the ultimate tensile strength (UTS) increased by 10 % improvement; the elongation at break (A) increased by 50 %. [1, 2, 5]

2nd thesis statement: In the case of AlSi9Cu3(Fe) alloy castings produced by vacuum-assisted die casting, a linear relationship was established between the gas porosity and the strength and strain values of the samples, measured by the standard tensile test. The equations of the fitted straight lines are written by the equation $y = mx + b$, where y is the strength or strain values in question ($R_{p0.2}$, UTS, A), x is the porosity value, the values of m and b at the 50 % reliability (R 50 %) and at 95 % reliability (R 95 %) levels are given in the following table. The equations are valid in the porosity range of 0.4–1.2 % at the 95 % (C 95 %) confidence level. [1, 2, 6]

Parameters (C 95 %)	$R_{p0.2}$ (MPa)		UTS (MPa)		A (%)	
	R 50 %	R 95 %	R 50 %	R 95 %	R 50 %	R 95 %
b	174.3	174.1	318.3	310.2	3.02	2.35
m	–15.5	–20.6	–42.7	–54.6	–1.24	–1.02

3rd thesis statement: The fatigue tests of AlSi9Cu3(Fe) alloy castings produced by vacuum-assisted (80 ± 5 mbar) die casting showed that the number of failures due to casting defects was reduced by 42.5 % at the 95 % confidence level. I have been shown that the application of vacuum support did not affect the slope of the Wöhler-curve but increased the number of cycles up to failure. The number of cycles up to failure of the samples produced by vacuum-assisted die casting have been increased by 20 % for R = –1 load asymmetry and by 16 % for R=0.1 load asymmetry at 50 % reliability and at 90 % confidence level. [3, 4, 7]

4th thesis statement: By the examination of AlSi9Cu3(Fe) alloy vacuum-assisted (80 ± 5 mbar) die castings I have been shown that the fatigue cracks due to inhomogeneities did not start from the surface but from the internal material discontinuity below the molded fine-grained layer, having 0.63 ± 0.22 mm thickness from the free surface. [4, 7]

5th thesis statement: The geometrical features of the porosities of AlSi9Cu3(Fe) alloy samples produced by vacuum-assisted (80±5 mbar) die casting, which caused the failure of fatigue specimen was determined by their sphericity (Ψ), shape factor (S), and defect size (D_v). The vacuum-assist has improved the ranges of the geometric features: sphericity was reduced by 68 %, the shape factor was reduced by 55 %, and the defect size was reduced by 94 %. [4, 7]

6th thesis statement: The examination of the smooth and notched fatigue samples produced by AlSi9Cu3(Fe) alloy vacuum-assisted die castings have been shown that the Kitagawa–Takahashi approach is a reliable indirect method to determine the stress intensity factor threshold range (ΔK_{th} = 1,8 MPa $m^{0,5}$). [8]

7th thesis statement: By the examination of the fatigue samples produced by AlSi9Cu3(Fe) alloy vacuum-assisted die castings, the effect of the defect size on the durability have been determined in the form of the following relation:

$$\sigma_{fN} = D_{geo}\, A^{-0,25} \qquad (1)$$

where, σ_{fN} is the fatigue strength (MPa), D_{geo} is the parameter of the fitted curve according to the geometrical features ($D_{geo\ internal} = 65.8\ MPa \sqrt[4]{m}$ in the case of an internal defect, $D_{geo\ surface} = 62.8\ MPa \sqrt[4]{m}$ in the case of surface defect), A is the size of the inhomogeneity (porosity) being searched (mm). The above relation is valid for a number of cycles up to failure of 10^7, shape factor of S = 2.9–4.2 and a range of detected defect sizes D_v = 0.01–0.40 mm^2. [8]

5. Practical applications and proposals for further research

The direct use of the research results in Fémalk Ltd. in casting design was realized during the research. Fémalk Ltd. is a foundry that adopts my research. The results themselves are valuable data, the experiments designed to extract them, the sampling procedures, the applied statistical methods support the daily engineering work. The CT scans data described in my work were performed by the Österreichisches Gießerei-Institut (ÖGI) carried out on the castings of Fémalk Ltd. in the framework of a joint project, which aims to create the VDG P203 standard (casting porosity requirement based on CT procedure).

According to vacuum-assisted casting, the increase in strength is a further research topic for the extension of heat treatment processes to achieve further strength increment. Furthermore, the welding is possible technically of HPDC castings produced with vacuum-assist. Based on the published results, the plan is to extend the developed procedures to other commonly used casting alloys. The implementation of the listed plans was already underway at the time of dissertation writing.

6. Publications published in the subject of dissertation

[1] Szalva P., Orbulov I.N.: The effect of vacuum on the mechanical properties of die cast aluminum AlSi9Cu3(Fe) alloy, International Journal of Metalcasting (IJMC), 13, 4, 853-864 (2019), DOI: 10.1007/s40962-018-00302-z; IF: 0,779

[2] Szalva P., Orbulov I.N.: The effect of vacuum degree on the porosity and mechanical properties of die cast AlSi9Cu3(Fe) alloy by life data analysis, Resolution and Discovery (RaD), 3, 2, 33-38 (2018), DOI: 10.1556/2051.2018.00061; IF: -

[3] Szalva P., Orbulov I.N.: Influence of vacuum support on the fatigue life of AlSi9Cu3(Fe) aluminum alloy die castings, Journal of Materials Engineering and Performance (JMEP), 29., 9, 5685-5695., (2020) DOI: 10.1007/s11665-020-05050-y; IF: 1,476

[4] Szalva P., Orbulov I.N.: Fatigue testing and non-destructive characterization of AlSi9Cu3(Fe) die cast specimens by computer tomography, Fatigue & Fracture of Engineering Materials & Structures (FFEMS), 43, 9, 1949-1958 (2020) DOI: 10.1111/ffe.13249; IF: 2,555

[5] Szalva P.: Vákuum támogatott nyomásos alumínium öntvények fogyóelektródás védőgázos hegesztése, BKL (Bányászati és Kohászati Lapok) – Kohászat 151., 1., 14-18 (2018)

[6] Szalva P.: A vákuumos kilevegőzés hatása a nyomásos alumínium öntvények mechanikai tulajdonságaira, BKL (Bányászati és Kohászati Lapok) – Kohászat 152., 5-6., 9-15 (2019)

[7] Szalva P., Orbulov I.N.: A vákuumos kilevegőzés hatása a nyomásos öntéssel gyártott alumíniumöntvények kifáradási tulajdonságaira, BKL (Bányászati és Kohászati Lapok) - Kohászat 153., 4., 23-29 (2020)

[8] Szalva P., Orbulov I.N.: Effects of artificial and natural defects on fatigue strength of a cast aluminum alloy, Fatigue & Fracture of Engineering Materials & Structures (FFEMS), Vol., Issue, 1-5 (2021) DOI: https://doi.org/10.1111/ffe.13564, IF: 3,031

Acknowledgement

The research reported in this paper has been supported by the KDP, Ministry of Innovation and Technology, and the National Research, Development and Innovation Fund. The research reported in this paper is part of project No. BME-NVA-02, implemented with the support provided by the Ministry for Innovation and Technology of Hungary from the National Research, Development, and Innovation Fund, financed under the TKP2021 funding scheme. The research reported in this paper and carried out at BME was supported by the NRDI Fund (TKP2020 NC, Grant No. BME-NCS) based on the charter of bolster issued by the NRDI Office under the auspices of the Ministry for Innovation and Technology.