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Improvement of Al-Si Alloy Fatigue Strength by Means of Refining and Modification

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Abstract

The paper presents results of a study concerning an AlSi7Mg alloy and the effect of subjecting the liquid metal to four different processes: conventional refining with hexachloroethane; the same refining followed by modification with titanium, boron, and sodium; refining by purging with argon carried out in parallel with modification with titanium and boron salts and strontium; and parallel refining with argon and modification with titanium, boron, and sodium salts. The effect of these four processes on compactness of the material, parameters of microstructure, and fatigue strength of AlSi7Mg alloy after heat treatment. It has been found that the highest compactness (the lowest porosity ratio value) and the most favorable values of the examined parameters of microstructure were demonstrated by the alloy obtained with the use of the process including parallel purging with argon and modification with salts of titanium, boron, and sodium. It has been found that in the fatigue cracking process observed in all the four variants of the liquid metal treatment, the crucial role in initiation of fatigue cracks was played by porosity. Application of the process consisting in refining by purging with argon parallel to modification with Ti, B, and Na salts allowed to refine the microstructure and reduce significantly porosity of the alloy extending thus the time of initiation and propagation of fatigue cracks. The ultimate effect consisted in a distinct increase of the fatigue limit value.

Keywords: Al-Si alloy, Fatigue limit, Refining, Modification

1. Introduction

The reason for which aluminum-silicon alloys are so broadly used in automotive, machine-building, and household-appliance industry consists in low weight and high performance characteristics of the material. Al-Si alloy castings are used as important components of structures subject to cyclically variable loads, sometimes at resonance frequencies. Favorable performance properties of Al-Si alloys are due mainly to their microstructure, in particular the size, shape, and distribution of silicon and intermetallic phase precipitates in the matrix.

The effect of microstructure refinement by the way of modification, favorable from the fatigue strength point of view, can be weakened by increased porosity of the alloy.

A number of studies point out that the increase of value of the secondary dendrite arm spacing (SDAS) is usually linked to an increase of pore sizes which become then decisive for fatigue strength of alloys [1–4]. In absence of porosity of the material, cracks initiate on silicon precipitates [5, 6].

It is a well-known fact that refining Al-Si alloys results in a decrease of gaseous porosity, whereas titanium and boron added to the liquid metal refine phase α(Al) dendrites [7–9] and contribute additionally to reduction of gaseous porosity. Additions of sodium or strontium influence positively the silicon precipitates morphology [10, 11]. On the other hand, introduction of an addition of strontium to liquid metal results in increased susceptibility of the alloy to development of gas porosity [12, 13] which has an adverse effect on mechanical properties and fatigue strength [14, 15].

Research reports concerning the issue of the effect of diversification of the aluminum-silicon alloy production process on the fatigue strength of the obtained material are hardly available in technical literature of the subject which lacks explicit opinions in scope of the effect of modification of the alloy with titanium and boron and with sodium or strontium, in particular in case of the fabrication process involving simultaneous barbotage refining and modification, on fatigue strength of the final product.

Studies concerning the subject seem to be of importance, especially to design engineers developing high-loaded and vital cast parts and components, who are offered new knowledge broadening the range of available options and encouraged to take decisions on using Al-Si alloys to manufacture cast parts operated under critical conditions. The present study was devoted to determining the effect of processes including combined refining and modification of liquid metal on compactness (porosity ratio), microstructure, and fatigue strength of industrial aluminum-silicone alloys.

2. Experimental

The material selected for the study was a hypoeutectic aluminum-silicon alloy (AlSi7Mg) prepared in conditions typical for production in an aluminum foundry.

To ensure high compactness and diversify microstructure of the alloy by the way of controlling the cooling rate, special wedge-shaped castings molds were designed similar to those proposed in [16, 17], provided with an additional feeder on the thicker side and a steel chill at the base.

The program of the study assumed that four different processes would be applied to treat the liquid metal and thus four different variants of the alloy would be obtained and examined, namely: an alloy refined conventionally with hexachloroethane, without any modification (Process I); an alloy in which the refining with C_2Cl_6 is followed by modification with titanium, boron, and sodium (Process II); an alloy for which the liquid metal is refined by purging with argon with the use of the spinning rotor method and, at the same time, modified with titanium and boron salts and metallic strontium (Process III); and an alloy obtained by simultaneous rotor-assisted purging with argon and modifying with titanium, boron, and sodium salts (Process IV). For each variant of the alloy, self-curing sandmix molds were constructed. To measure the alloy cooling rate in those wedge areas where interaction with the chill was weaker, in four molds, one for each alloy treatment process, thermocouples were installed with their junctions located centrally in four cross sections of the mold corresponding to distance of 50 mm from chiller surface. Thermocouples were shielded in tubes made of 0.35-mm sheet steel, each tube having outer diameter of 1.75 mm. Temperature evolution after pouring the liquid metal into the molds was registered by means of ADAM 4018 multichannel digital thermometer. Based on the measured temperature waveforms, the alloy cooling rate was evaluated within the range of solidification temperatures.

The total amount of 1200 kg liquid metal for the purpose of the present study was prepared in Selas gas-fired furnace. Firstly, 300 kg of the metal was taken and moved to a pre-heated casting ladle with overall capacity of 400 kg. The metal was refined with hexachloroethane (C_2Cl_6) with the use of tablets known under trade name of Dursalit EG 281 (Process I). The refined liquid metal was then poured at temperature of 705°C to wedge molds, while samples of the alloy were taken for the purpose of analysis its chemical composition.

The rest of the liquid metal remaining in the casting ladle was subject to modification with titanium and boron by adding AlTi5B1 master alloy and with sodium by adding the metal in the vacuum-packed form known as Navac (Process II). The melt processed that way was poured at temperature of 705°C into wedge molds and its samples were taken for further chemical composition analysis.

Next, another 300-kg portion of the liquid metal was taken from Selas furnace to the pre-heated casting ladle. The process of refining and parallel modification was realized on the Foseco metal treatment station MTS 1500. Refining of the liquid metal was carried out for 5 minutes by means of argon purging method in which a spinning rotor was used to supply and disperse the inert gas. While the refining was continued, the Ti and B salts containing agent known commercially as Coveral MTS 1582 together with AlSr10 master alloy were introduced to the liquid metal (Process III). The whole treatment including simultaneous refining with argon by means of the spinning rotor method and modification with salts and strontium lasted for 8 minutes. The wedge molds were then poured with the liquid metal processed that way at temperature 705°C and samples were taken for the purpose of chemical composition analysis.

The remaining 300 kg of the alloy was transferred from the Selas gas-fired furnace into a pre-heated casting ladle. The process of parallel refining and modification was performed on the automated metal treatment station MTS 1500. The liquid metal was refined by purging with argon with the use of the spinning rotor method for the period of 5 minutes. With the refining still continued, titanium-boron salts traded under the name Coveral MTS 1582 and sodium salts known as Coveral MTS 1572 were dispensed (Process IV). The whole treatment of the liquid metal including parallel refining and modification lasted 8 minutes. The wedge molds were then poured with the liquid metal processed that way at temperature 705°C and samples were taken for the purpose of chemical composition analysis. The obtained wedge-shaped castings were subjected to heat treatment characterized with parameters proposed in [18]. The applied thermal treatment comprised hyperquenching (6 hours at 540°C / water at 20°C) followed by aging (8 hours at 175°C / air). Chemical composition of the examined alloy variants are given in Table 1.

Metallographic examination was carried out on specimens cut out from those wedge castings for which the temperature vs. time characteristic was measured. Examination of microstructure was carried out with the use of Neophot 2 optical microscope. Values of the porosity ratio characterizing individual specimens were determined in accordance with the methodology described in [19]. To determine values of SDAS parameter it was necessary to identify dendritic cells showing secondary arms. The methodology described in papers [20–22] was used for this purpose.

Table 1.
Chemical composition of AlSi7Mg alloy

Process	Element content, wt%								
	Si	Mg	Cu	Mn	Fe	Na	Sr	Ti	B	Al
I	7.06	0.32	0.01	0.01	0.09	-	-	-	-	to bal.
II	7.04	0.31	0.01	0.01	0.09	0.0138	-	0.15	0.01	to bal.
III	7.04	0.31	0.01	0.01	0.09	-	0.01	0.15	0.01	to bal.
IV	7.03	0.31	0.01	0.01	0.09	0.0068	-	0.15	0.01	to bal.

Each time, 100 cells were analyzed. In the process of determining values of the parameter λ_E, 350 consecutive crossings of the measuring line with single particles were taken into account. Observations of fatigue fractures were carried out with the use of JSM-5500 LV scanning electron microscope by JEOL. Example microstructures are presented in Figure 1.

The material for fatigue endurance test samples was cut out from the casting areas 50 mm away from the chill in which the observed cooling rate value was 0.49°C/s (Fig. 2). The geometry and dimensions of the test specimens are shown in Fig. 3.

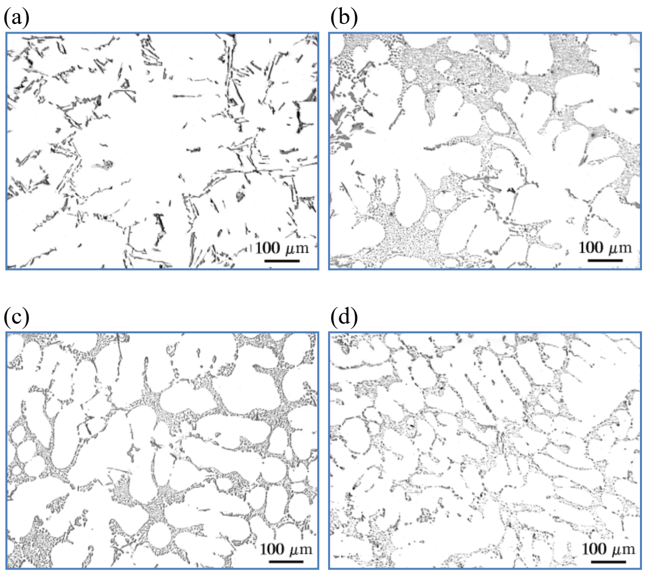

Fig. 1. AlSi7Mg alloy microstructure after: (a) refining with C_2Cl_6 (Process I); (b) refining with C_2Cl_6 followed by modification with Ti, B and Na (Process II); (c) refining by purging with argon and parallel modification with Ti salts, B salts, and Sr (Process III); and (d) refining by purging with argon and parallel modification with Ti, B, and Na (Process IV)

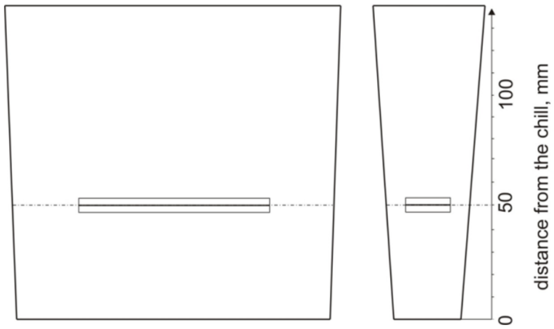

Fig. 2. Locations from which material samples for microstructure examination and specimens for fatigue strength tests were taken

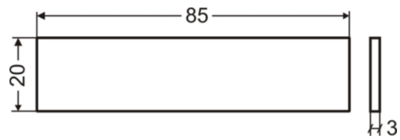

Fig. 3. Geometry and dimensions for fatigue strength test specimens as per PN-76/H/04326-5

The fatigue strength tests were carried out under periodical stresses generated by subjecting specimens to flat swinging on GZ-1 device [23] in accordance with PN-76/H/04326-5 standard, with the adopted forced vibration frequency of 73 Hz.

3. Research results

Results of measurements of the porosity ratio and the fatigue limit for all the four AlSi7Mg alloy variants obtained by means of four different liquid metal treatment processes are summarized in Table 2.

Table 2.
Values of selected parameters of microstructure for four variants of the treatment process used to obtain AlSi7Mg alloy

Process	SDAS, µm	λ_E, µm	Porosity ratio *P*, %	Fatigue limit Z_{f}, MPa
I	62.2	11.1	0.809	62.0
II	52.8	6.1	0.920	71.1
III	51.6	5.4	0.747	78.0
IV	50.1	5.2	0.511	82.9

Thermal treatment: hyperquenching (6 hours at 540°C / water 20°C), aging (8 hours at 175°C / air)

Results obtained in the course of fatigue tests were used for plotting corresponding fatigue curves. Figures 4–7 shows respective plots (Wöhler diagrams) for four variants of AlSi7Mg alloy subjected to Processes I–IV described above and in conditions after heat treatment.

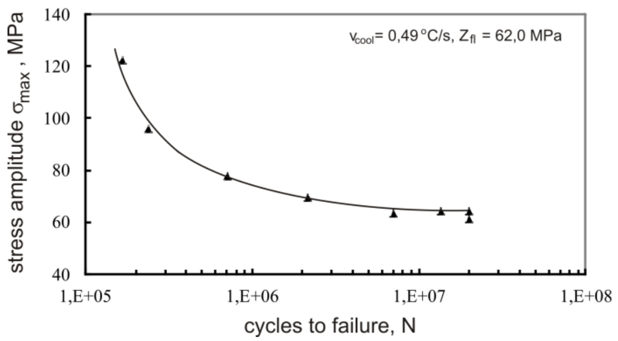

Fig. 4. Wöhler diagrams for specimens of AlSi7Mg alloy subject to Process I and heat treatment (hyperquenching: 6 hours at 540°C / water 20°C; aging: 8 hours at 175°C / air)

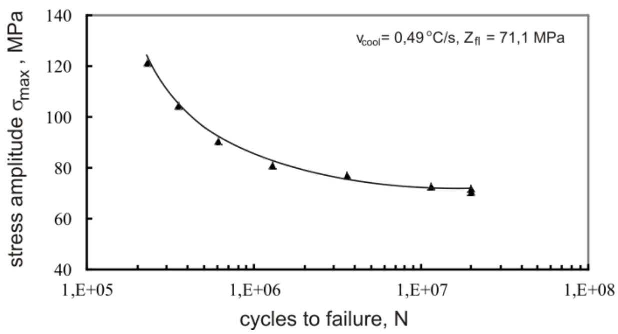

Fig. 5. Wöhler diagrams for specimens of AlSi7Mg alloy subject to Process II and heat treatment (hyperquenching: 6 hours at 540°C / water 20°C; aging: 8 hours at 175°C / air)

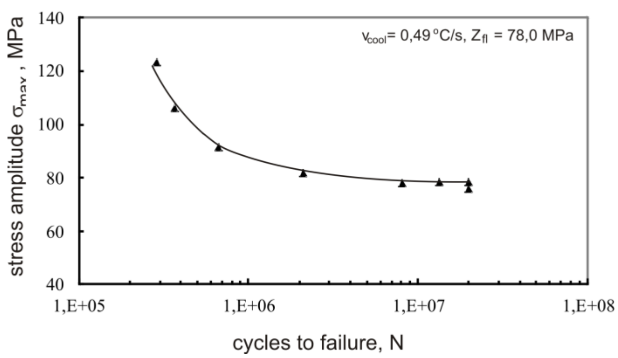

Fig. 6. Wöhler diagrams for specimens of AlSi7Mg alloy subject to Process III and heat treatment (hyperquenching: 6 hours at 540°C / water 20°C; aging: 8 hours at 175°C / air)

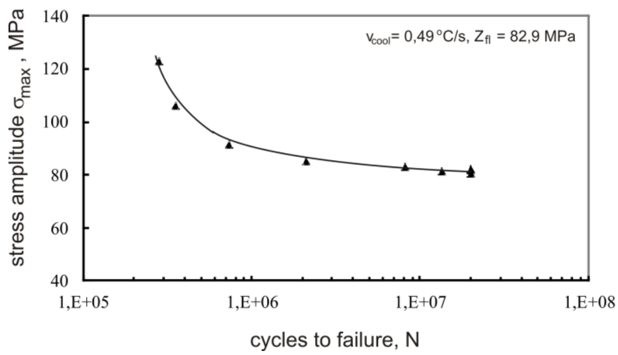

Fig. 7. Wöhler diagrams for specimens of AlSi7Mg alloy subject to Process IV and heat treatment (hyperquenching: 6 hours at 540°C / water 20°C; aging: 8 hours at 175°C / air)

Figure 8 presents photos of example AlSi7Mg alloy specimen fatigue fractures.

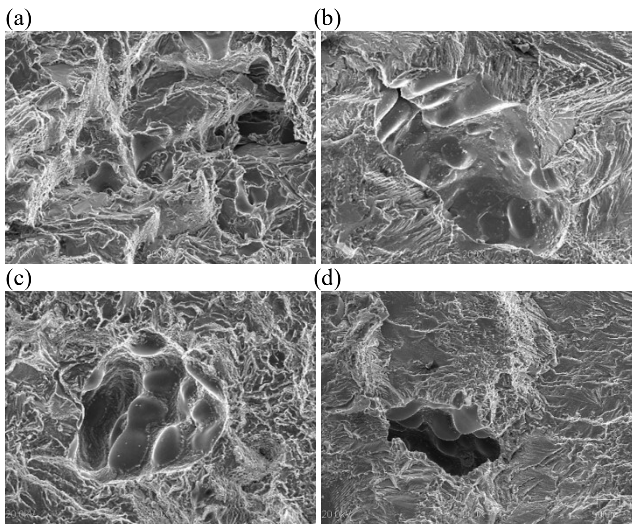

Fig. 8. Fatigue fracture surfaces of heat-treated (hyperquenching: 6 h at 540°C / water 20°C; aging: 175°C / 8 h / air) specimens of AlSi7Mg alloy subject to: (a) Process I; (b) Process II; (c) Process III; (d) Process IV

The present study indicates that application of modification with titanium and boron and with sodium or strontium has an effect consisting in refinement of α(Al) phase dendrites (decrease of SDAS parameter value) and refinement of silicon in eutectic (decrease of value of parameter λ_E) in case of all the examined alloy variants. On the other hand, the application of modification with sodium (Process II) resulted in an increase of the porosity ratio value compared to the alloy refined with hexachloroethane (Process I). In case of those alloy variants which underwent parallel purging with argon with the use of the spinning rotor method and modification by adding titanium salts, boron salts, and either metallic strontium or sodium salts (Processes III and IV), significant reduction of the porosity index value was observed in comparison with the alloy refined only with hexachloroethane (Process I). Application of refining and modification Ti and B accompanied by modification with either Na or Sr resulted in an increase of values of the fatigue limit of the examined alloy variants. In case of Process II, despite an increase of the porosity ratio value, the fatigue limit value increase can be explained by significant refinement of silicon in eutectic (λ_E parameter value decrease). In case of variants of the alloy corresponding to Processes III and IV, further increase of the fatigue strength value was an effect of significant decrease of values of the porosity ratio, the parameter SDAS, and the parameter λ_E. The highest value of the fatigue strength was demonstrated by the alloy subjected to Process IV, i.e. simultaneous refining by purging with argon and modification by an addition of titanium, boron, and sodium salts. The value, equaling 82.9 MPa, seems to be satisfactory when compared to results reported by other authors. In [24], the fatigue limit value for A356 alloy at SDAS value equaling 57 µm, was found to be 65 MPa. In that case, the rotary bending fatigue test was used with R = –1, frequency 60 Hz, and number of cycles $N = 10^7$. Unfortunately, the authors did not specify in which way the liquid metal was improved. In case of A357 after T6 heat treatment, for SDAS = 22–62 µm, the fatigue limit value of specimens cast to a metal mold was 82 MPa (test at R = –1, f = 20 Hz), but the number of cycles was less by a half ($N = 10^7$) compared to the fatigue resistance test performed in this paper [25]. The fatigue limit value reported in [26] for SDAS = 45 µm was 83.3 MPa. The specimens were cut out from a V8 engine block low-pressure cast of an Al-Si-Cu-Mg alloy subjected then to T6 heat treatment. The liquid metal was degassed with nitrogen and modified with titanium, boron, and strontium (test at R = –1, f = 70 Hz). Also in that case, the number of cycles was less by a half ($N = 10^7$) compared to the fatigue resistance test performed in this paper.

Analysis of fracture patterns after fatigue tests indicates that the alloy prepared in line with Process I is characterized with a mixed brittle-ductile fracture. In such case, initiation and propagation of fatigue cracks proceeds very fast in view of presence of porosity and low plasticity of the alloy. The alloys prepared with the use of Processes II–IV are characterized with a predominance of the ductile fracture pattern. In such case, initiation and propagation of fatigue cracks occurs, despite presence of porosity, much later in view of higher plasticity of the alloy.

4. Conclusions

- The Application of modification with titanium and boron and with sodium resulted in decrease of SDAS parameter value by about 15% and decrease of λ_E parameter value by about 45% compared to the allot refined traditionally. Further decrease of SDAS parameter value by about 17% and λ_E parameter value by about 51% was obtained in case of applying refining by argon purging with the use of the spinning rotor method and parallel modification with titanium and boron salts and with metallic strontium. The most favorable values of microstructure parameters SDAS and λ_E were demonstrated by the alloy for which the liquid metal was subject to purging with argon and parallel modification with titanium, boron, and sodium salts (Process IV), for which the value of SDAS parameter decreased by about 19% and this of λ_E parameter decreased by about 53%, in comparison with the alloy refined with the use of traditional methods.
- Application of modification with sodium resulted in an increase of the porosity ratio by about 14% compared to the alloy refined as per the traditional method. On the other hand, application of refining by argon purging with the use of the spinning rotor method and parallel modification with titanium and boron salts and with metallic strontium resulted in reduction of the porosity ratio by about 8%, and in case of the alloy obtained after refining by argon purging with the use of the spinning rotor method and parallel modification with titanium and boron salts and sodium salts, value of the porosity ratio decreased by about 37%.
- The effect of refining and comprehensive modification with titanium and boron and with sodium or strontium consisted in an improvement of the fatigue life of the alloy samples, despite an increase of the porosity ratio value in case of Process II used to treat the liquid metal. Application of refining by argon purging with the use of the spinning rotor method and parallel modification with titanium and boron salts and sodium salts resulted in the highest increase of fatigue strength of the alloy which was found to be about 34%.
- It has been found that in the fatigue cracking process observed in all the four variants of the alloy, the crucial role in initiation of fatigue cracks was played by the porosity. Application of refining by argon purging with the use of the spinning rotor method and parallel modification with titanium and boron salts and sodium salts allowed to refine the microstructure and reduce significantly the porosity of the alloy extending thus the time of initiation and propagation of fatigue cracks.
- Simultaneous refining by argon purging and comprehensive modification with salts of titanium, boron, and sodium is used to fabricate articles cast of AlSi7Mg alloy for applications where high tightness is required in conditions characterized with variable loads.

References

[1] Wang, Q.G., Apelian, D. & Lados, D.A. (2001). Fatigue behavior of A356/357 aluminum cast alloys. Part II - Effect of microstructural constituents. *Journal of Light Metals.* 1, 85-97.

[2] Wang, Q.G., Cáceres, C. H. & Griffith J.R. (1998). Cracking of Fe-rich inter-metallics and eutectic Si particles in an Al-7Si-0.7Mg casting alloy. *AFS Transactions.* 32, 131-136.

[3] Liu, Y., Jie, W., Gao, Z., Zheng, Y., Luo, H. & Song, W. (2015). Rotary bending fatigue behavior of A356 T6 aluminum alloys by vacuum pressurizing casting. *China Foundry.* 12(5), 326-332.

[4] Zheng, X., Cui, H. Engler-Pinto Jr., C.C., Sub, X. & Wen, W. (2013). Statistical relationship between fatigue crack initiator size and fatigue life for a cast aluminum alloy. *Materials Science and Engineering: A*. 580, 15 September, 71-76. DOI: 10.1016/j.msea.2013.05.045.

[5] Zhang, B., Chen, W. & Poirier, D.R. (2000). Effect of solidification cooling rate on the fatigue life A356.2-T6 cast aluminium alloy. *Fatigue & Fracture of Engineering Materials & Structures.* 23, 417-423.

[6] Siegfanz, S., Giertler, A., Michels, W. & Krupp, U. (2013). Influence of the microstructure on the fatigue damage behaviour of the aluminium cast alloy AlSi7Mg0.3. *Materials Science and Engineering A.* 565, 10 March, 21-26. DOI: 10.1016/j.msea.2012.12.047.

[7] Fuoco, R., Correa, E.R. & de Andrade Bastos, M. (1998). Effect of grain refinement on feeding mechanisms in A356 aluminum alloy. *AFS Transactions.* 78, 401-409.

[8] Easton, M.A. & StJohn, D.H. (2000). The effect of grain refinement on the formation of casting defects in alloy 356 castings. *International Journal of Cast Metals Research*. 12, 393-408.

[9] Kim, W.B., Lee, W.-S., Ye, B.J. & Loper, C.R. Jr. (2000). Effect of casting conditions and grain refinement on hot-tearing behavior in A356 Al alloy. *AFS Transactions.* 38, 541-546.

[10] Alan Najafabadi, M.A., Ourdjini, A. & Elliot, R. (1994). Impurity modification of aluminum-silicon eutectic alloys. *Cast Metals*. 8(1), 43-50.

[11] Alan Najafabadi, M.A., Khan, S., Ourdjini, A. & Elliot, R. (1994). The flake-fibre transition in aluminum-silicon eutectic alloys. *Cast Metals.* 8(1), 35-42.

[12] Liu, L., Samuel, A.M. & Samuel, F.H. (2002). Role of strontium oxide on porosity formation in Al-Si casting alloy. *AFS Transactions*. 139, 1-14.

[13] Fuoco, R., Correa, E.R. & Goldenstein, H. (1996). Effect of modification treatment on microporosity formation in 356 Al Alloy, Part I: Interdendritic feeding evaluation. *AFS Transactions*. 160, 1151-1157.

[14] Boileau, J. & Allison, J.E. (2003). The effect of solidification time and heat treatment on the fatigue properties of a cast 319 aluminum alloy. *Metallurgical and Materials Transactions A.* 34A, June, 1807-1820.

[15] Yi, J.Z., Gao, Y.X., Lee, P.D., Flower, H.M. & Lindley, T.C. (2003). Scatter in fatigue life due to effects of porosity in cast A356-T6 aluminum-silicon alloys. *Metallurgical and Materials Transactions A.* 34A, September, 2003, 1879-1890.

[16] Orłowicz, A.W., Tupaj, M. & Mróz, M. (2008). Effect of cooling rate on the λ_{2D} - parameter with sodium modified AlSi7Mg alloy. *Archives of Foundry Engineering*. 8(1), 245-248.

[17] Orłowicz, A., Tupaj, M. & Mróz, M. (2008). Mechanical properties of AlSi7Mg alloy modified with sodium. *Archives of Foundry Engineering*. 8(spec.1), 241-244. (in Polish).

[18] Orłowicz, A.W., Tupaj, M. & Mróz, M. (2006). Selecting of heat treatment parameters for AlSi7Mg0,3 alloy. *Archives of Foundry.* 6(22), 350-356. (in Polish).

[19] Orłowicz, A., Tupaj, M. & Mróz, M. (2000). Effect of cooling rate on the structure of hypoeutectic silumin after sodium modification. *Rudy i Metale Nieżelazne.* 53(7), 425-429. (in Polish).

[20] Cáceres, C.H. & Wang, Q.G. (1996). Dendrite cell size and ductility of Al-Si-Mg casting alloys: Spear and Gardner revisited. *International Journal of Cast Metals Research.* 9, 157-162.

[21] Spear, R.E. & Gardner, G.R. (1963). Dendrite cell size. *AFS Transactions*. 71, 209-215.

[22] Rontó, V. & Roósz, A. (2001). The effect of cooling rate and composition and com-position on the secondary dendrite arm spacing during solidification Part I: Al-Cu-Si alloy. *International Journal of Cast Metals Research.* 13, 337-342.

[23] Mróz, M., Orłowicz, A., Tupaj, M. & Trytek, A. (2010). Fatigue of strength of MAR-M509 alloy with structure refined by rapid crystallization. *Archives of Foundry Engineering*. 10(3), 119-122.

[24] Tajiri, A., Nozaki, T., Uematsu, Y., Kakiuchi, T., Nakajima M., Nakamura, Y. & Tanaka, H. (2014). Fatigue limit prediction of large scale cast aluminum alloy A356. 20th European Conference on Fracture (ECF20). *Procedia Materials Science.* 3, 924 – 929. DOI: 10.1016/j.mspro.2014.06.150.

[25] Brochu, M., Verreman, Y., Ajersch, F. & Bouchard, D. (2010). High cycle fatigue strength of permanent mold and rheocast aluminum 357 alloy. *International Journal of Fatigue*. 32(8), 1233-1242. DOI: 10.1016/j.ijfatigue.2010.01.001.

[26] González, R., González, A., Talamantes-Silva, J., Valtierra, S., Mercado-Solís, R.D., Garza-Montes-de-Oca, N.F. & Colás, R. (2013). Fatigue of an aluminium cast alloy used in the manufacture of automotive engine blocks. *International Journal of Fatigue*. 54, 118-126. DOI: 10.1016/j.ijfatigue.2013.03.018.