www.czasopisma.pan.pl PAN www.journals.pan.pl

ARCHIVES of FOUNDRY ENGINEERING

DOI: 10.1515/afe-2016-0105

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (2299-2944)
Volume 16
Issue 4/2016

175 – 180

Effect of Casting Die Cooling on Solidification Process and Microstructure of Hypereutectic Al-Si Alloy

R. Władysiak [a], *, A. Kozuń [b], T. Pacyniak [a]

[a] Department of Materials Engineering and Production Systems, Lodz University of Technology, 1/15 Stefanowskiego Street, 90-924 Lodz, Poland

[b] PhD Student, Faculty of Mechanical Engineering, Lodz University of Technology, 1/15 Stefanowskiego Street, 90-924 Lodz, Poland

*Corresponding author. E-mail address: ryszard.wladysiak@p.lodz.pl

Received 31.03.2016; accepted in revised form 23.06.2016

Abstract

The work is a continuation of research concerning the influence of intensive cooling of permanent mold in order to increase the casting efficiency of aluminium alloys using the multipoint water mist cooling system. The paper presents results of investigation of crystallization process and microstructure of synthetic hypereutectic alloys: AlSi15 and AlSi19. Casts were made in permanent mold cooled with water mist stream. The study was conducted for unmodified silumins on the research station allowing the cooling of the special permanent probe using a program of computer control. Furthermore the study used a thermal imaging camera to analyze the solidification process of hypereutectic silumins. The study demonstrated that the use of mold cooled with water mist stream allows in wide range the formation of the microstructure of hypereutectic silumins. It leads to higher homogeneity of microstructure and refinement of crystallizing phases and also it increases subsequently the mechanical properties of casting.

Keywords: Innovative foundry technologies and materials, Casting die cooling, Water mist, Hypereutectic silumin

1. Introduction

The ongoing work is a part of studies on the application of water mist system for multipoint sequential cooling of casting die to produce silumin castings [1-5].

The essence of the research is the efficient cooling mist of water through evaporation of water droplets on a hot surface of the casting die. An analysis of earlier studies indicate that the cooling of mold with the water mist stream enables the shaping of microstructure and achieving high quality casts made of AlSi11 alloy with improved properties. Efficiency of heat transfer process is largely determined by the characteristics of the generated stream, optimization of air and water amount in the mist stream and adequate spraying of water.

The aim of the study was to investigate the effect of water mist cooling on microstructure of hypereutectic synthetic unmodified silumin. Castings made of aluminium alloys are used for heavy-duty pistons for combustion engines. They have good casting properties, corrosion resistance, good mechanical properties at elevated temperatures, abrasion resistance, low coefficient of abrasion and thermal expansion [6-8].

The paper presents also the possibility of implementing thermal imaging camera for analyzing of silumins solidification process by Thermal and Derivative Analysis (TDA) method [9].

2. Description of the work methodology, materials for research, experiments

The study was conducted on a research station (shown in Figure 1) using the metallic probe and infrared camera located in the thermographic stand (10). The water mist was produced in the device (1, 2) that dosed the appropriate amount of water and its dispersion in air by centrifugal spraying of water in a stream of compressed air (3). The probe was cooled with water mist delivered by hose of cooling circuit (9). At the end the water mist stream is emitted by cylindrical nozzle towards the external surface of probe. This probe was optionally made of aluminium alloy, of cast iron or bronze. Its cone-like shape ensures symmetrical cooling and testing solidification process of Al-alloys with use very small test pieces which weight average is 0,012 kg.

The stream of water mist was controlled using a computerized control system cooling, developed by Z-Tech. The software system includes a set of functions and procedures to monitor and control the course of generating water mist cooling system multicircuited using pre-drafted program.

In the probe were casted the test pieces with use the synthetic hypereutectic silumins AlSi15 and AlSi19 that chemical composition was shown in Table 1.

The test results of solidification process (Fig. 2) were recorded by infrared camera PI OPTRIS 160. Computer software of the camera enables based on the measured signal the development of static thermograms and dynamic thermal cooling curves of objects under study. These modern cameras work with a high resolution matrix and with advanced methods of reading and amplification of infrared signal. Features of used camera enable for measurement and recording the temperature in real time with good thermal sensitivity (from 80 mK), high-resolution field (120 x 160 pixel) and with high frequency of measurements (10^2 Hz) [9].

Table 1.
Chemical composition of researched Al-Si alloy

Name	Elements, weight %								
	Si	Mg	Cu	Mn	Fe	Ti	P	Sr	Al
AlSi15	15,57	0,011	0,012	0,012	0,186	0,006	<0,001	<0,001	rest
AlSi19	19,36	0,012	0,010	0,005	0,159	0,007	<0,001	<0,001	rest

The effect of water mist cooling on the crystallization and resulting microstructure of silumins was evaluated by using a Nikon microscope MA200.

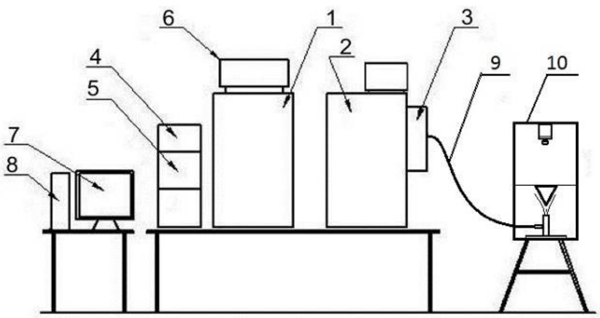


Fig. 1. The scheme of the research station: modules: 1, 2 – air and water dosing, 3 – mixing of components, 4, 5 – supplying of air and water solenoid valves, 6 – computer cooling control, 7, 8 – PC, 9 – cooling circuit, 10 – thermographic analysis stand

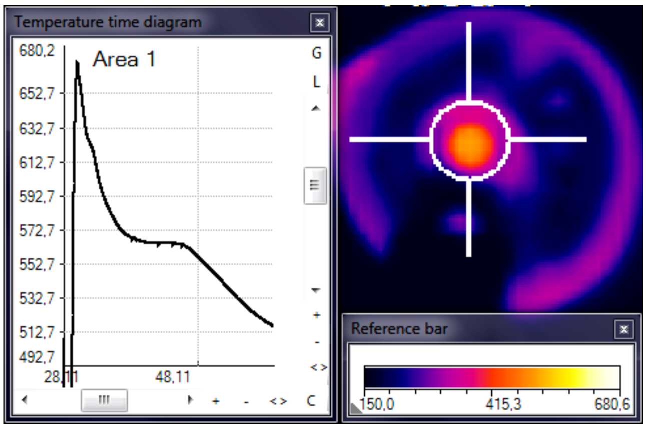


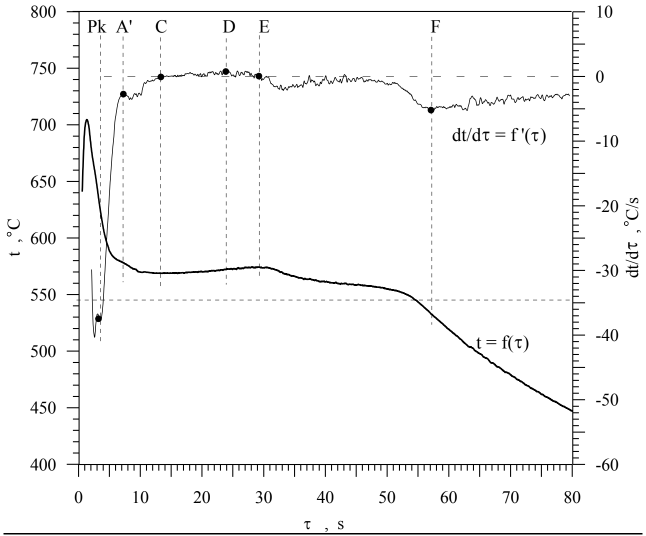
Fig. 2. Thermographic test results of Al-Si alloy during the solidification process

3. Research results and analysis

In the paper was presented the influence of cooling of casts made of synthetic unmodified silumins AlSi15 and AlSi19 on morphology of crystallizing phases. Tests of crystallization process were made in the aluminium probe. The melting process of researched silumins was conducted in the same conditions in a resistance furnace.

3.1. Effect of cooling on solidification process of hypereutectic Al-Si alloy

In Figures 3-6 have shown, respectively, representative curves - thermal and derivative (TDA) of hypereutectic silumins AlSi15 (Fig. 3, Fig. 4) and AlSi19 (Fig. 5, Fig. 6) obtained by thermographic method. Analysis of silumins solidification was conducted without cooling of metallic probe, what was shown in Figures 3 and 5 and with cooling of probe by the water mist stream (Fig. 4, Fig. 6).

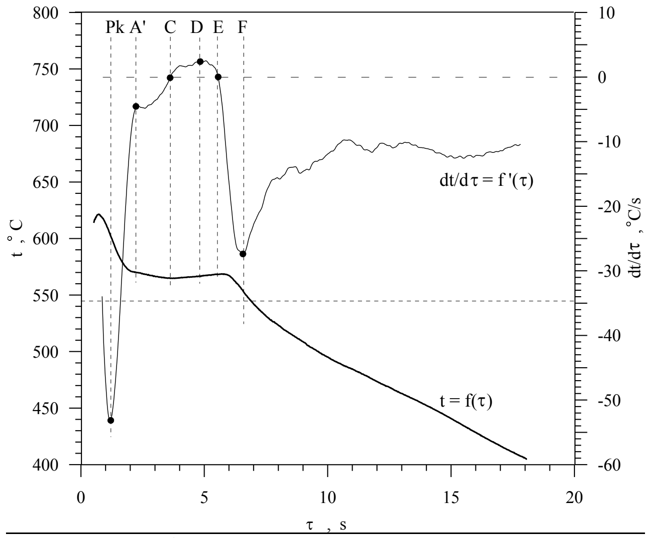


	Pk	A'	C	D	E	F
τ, s	3,54	6,84	13,12	23,92	29,88	57,16
t , C	624,0	579,2	568,9	572,4	573,8	533
dt/dτ, C/s	-41,8	-1,5	0	3,8	0	-7,2

Fig. 3. TDA curves of solidification process of AlSi15 alloy without cooling obtained by thermographic method

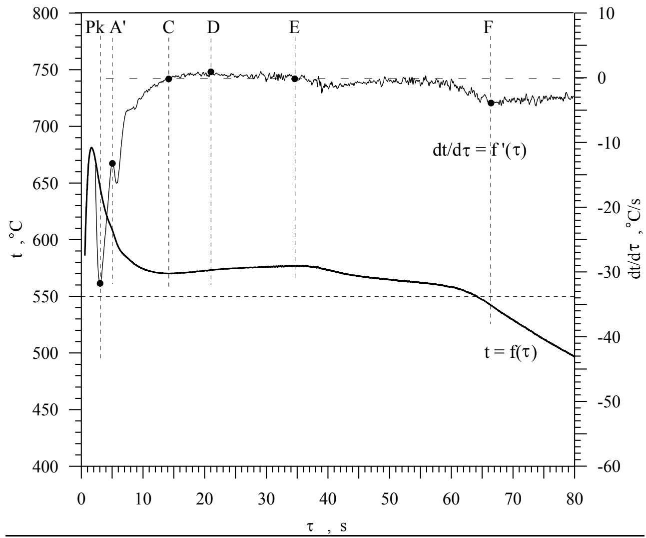
The crystallization of researched silumins starts at the point Pk. from the initial crystallization of silicon crystals. The temperature of AlSi15 is t_{Pk} = 624 C. This point is a local minimum value in derivative curve dt/dτ = -41.8 C/s. It follows that emitted heat of crystallization of pre-eutectic crystals Si (Fig. 7a) (β phase) causes the heating up of the alloy from Pk to A'and decrease of cooling rate to dt/dτ =-1.5 C/s.

The concentration of silicon in the liquid around the large crystals of β decreases creating favorable conditions for nucleation of α phase on the existing silicon crystals. On the crystallization curve it manifests probably with the peak of heat from the crystallization of α phase dendrites. Farther lowering the temperature causes that the silumin enter into a zone of eutectic coupled growth and in terms of irregular eutectic CDEF crystallized lamellar α + β (Al + Si) at the temperature $t_{C\text{-}E}$ = 569÷572 C.



	Pk	A'	C	D	E	F
τ, s	1,24	2,12	3,62	4,84	5,44	6,50
t , C	600,4	570,5	564,8	566,7	568,3	555,5
dt/dτ, C/s	-56,7	-3,3	0	3,3	0	-31,5

Fig. 4. TDA curves of solidification process of AlSi15 alloy with water mist cooling obtained by thermographic method



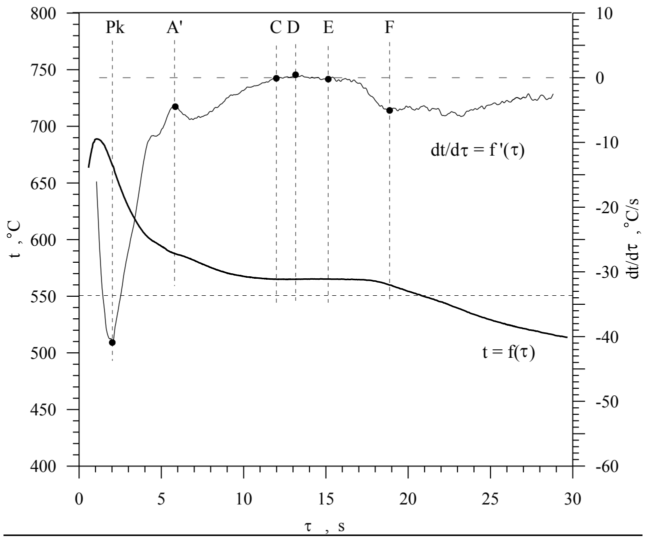
	Pk	A'	C	D	E	F
τ, s	3,12	5,22	14	21,02	34,86	66,4
t , C	664,5	605,4	570,2	573,1	575,6	540
dt/dτ, C/s	-32,8	-13,2	0	1,7	0	-4,3

Fig. 5. TDA curves of solidification process of AlSi19 alloy without cooling obtained by thermographic method

The water mist cooling of probe with AlSi15 (Fig. 4) causes that the liquid silumin cools down many times faster (dt/dτ =-56.7 C/s) than the alloy tested without the cooling. The cooling rate causes strong overcooling the liquid and the nucleation of Si crystals starts only at the temperature t_{Pk} = 600,4 C. This time the

Al+Si eutectic crystallizes at the range of temperature $t_{C\text{-}E}$ = 565÷568 C. The duration of whole solidification process of silumin AlSi15 with use of cooling is τ = 5.26 s. It is about 10 times shorter than uncooled AlSi15 alloy solidification.

In the case of AlSi19 (Fig. 5, Fig. 6) alloy was observed similar changes in the process of solidification as a result of application the water mist cooling of the probe. The liquid metal is more overcooled because the cooling rate increased from dt/dτ = -32.8 C/s to dt/dτ = -41.2 C/s. Temperature of crystallization of Si crystals decreases from $t_{A'}$ = 605 C to $t_{A'}$ = 587 C. The temperature of eutectic crystallization decreases from $t_{C\text{-}E}$ = 570÷576 C to $t_{C\text{-}E}$ = 565÷565 C for cooling probe with AlSi19 alloy.



	Pk	A’	C	D	E	F
τ, s	2,24	6,02	12,08	13,26	15,22	19,24
t , C	648,7	587	564,8	565,2	565,4	557
dt/dτ, C/s	-41,2	-4,2	0	0,6	0	-5,5

Fig. 6. TDA curves of solidification process of AlSi19 alloy with water mist cooling obtained by thermographic method

3.2. Effect of cooling on microstructure of hypereutectic Al-Si alloy

In Figures 7 and 8 have shown a representative microstructure of specimens of silumins AlSi15 and AlSi19 obtained in casting test probe adequately of cooling naturally at elevated temperature (Fig. 7a, Fig. 8a) and with use of cooling of probe by water mist stream (Fig. 7b, Fig. 8b).

Microstructure of all silumins contains crystals of silicon (Si), grains of lamellar eutectic α+β (Al+Si) and also aluminium dendrites (α phase).

Changing the morphology of crystallizing phases is probably the result of concentration super cooling. It is caused by a high cooling rate of silumin, which prevents crystallization of the case and it makes difficult to align the concentration of the chemical composition of the melt. Under such conditions, a rapid enrichment of liquid crystallization front dendrites Si (β) of aluminum (α) which locates in the spaces between the branches of dendrite Si.

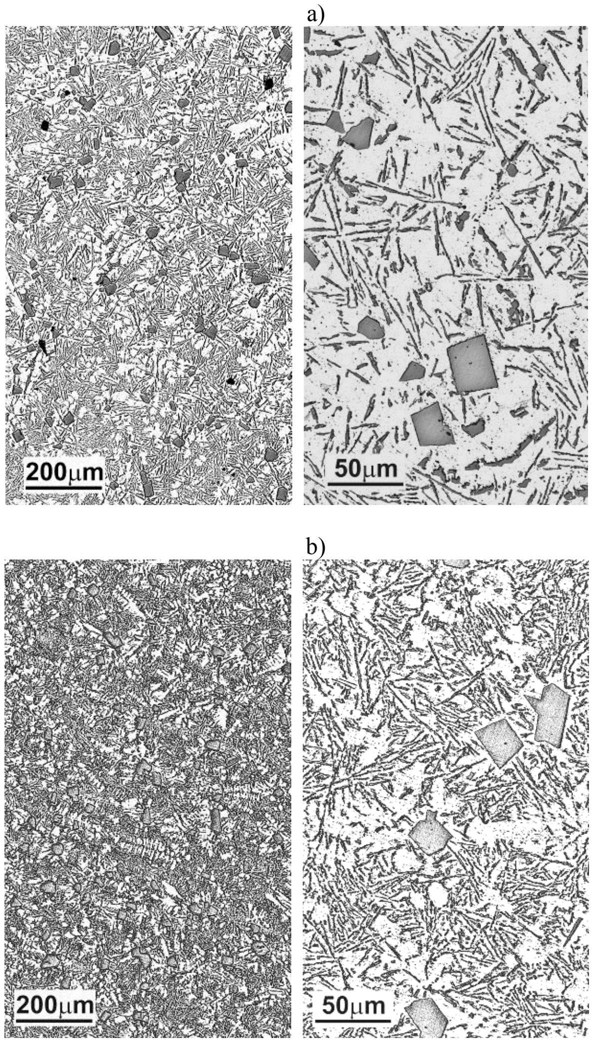


Fig. 7. Microstructure of AlSi15 alloy poured without cooling of probe (a) and with water mist cooling of metallic probe (b). Phase β (Si), lamellar eutectic α+β (Al+Si)

In silumin that was cooled the silicon crystals are smaller (20 ÷ 40 um) and have a compact longwall. The use of cooling with water mist caused their 2-fold fragmentation and reduction of the share of this phase in the silumin microstructure.

Comparing the specimens shows that the casting from cooled probe have the refinement of microstructure which is much more for the eutectic grain of AlSi19 than AlSi15 alloy. This is probably due to an increase in crystallization rate due to the increased cooling rate in the melt solidification temperature range.

The use of probe cooling with water mist resulted in a further increase in the average cooling rate silumin to about 6.0 K/s. As shown in Figures 7, the microstructure of the cast, in addition to the increase in refinement of the crystallizing phases of a change in crystal morphology of particle pre-eutectic silicon and eutectic grains.

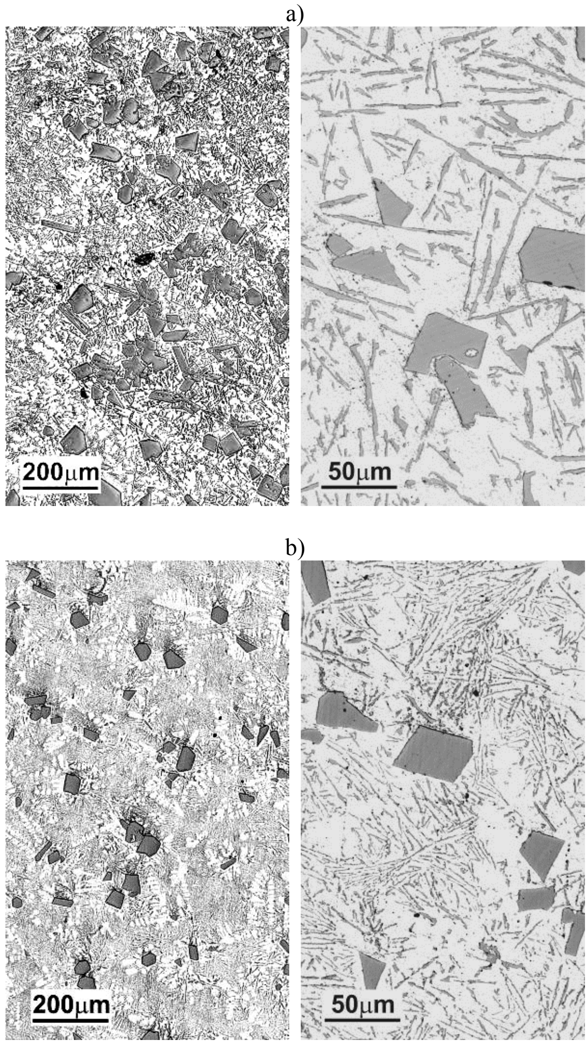


Fig. 8. Microstructure of AlSi19 alloy poured without cooling of probe (a) and with water mist cooling of metalic probe (b). Phase β (Si), lamellar eutectic α+β (Al+Si)

The microstructure of the cast is characterized pre-eutectic probably crystallized silicon dendrites [8]. They are built with thick branches of the first order, which grow from the nucleus in almost perpendicular directions, and have much thinner edge parallel branches of the second row. The microstructure is also present and the lamellar eutectic dendritic.
From a comparison of microstructure (Fig. 7) that the probe cooling with water mist comminuted silicon primary crystals and much more the eutectic grains hypereutectic silumin lamellar.

Silicon crystals are rather small (20 ÷ 40 µm) and have a compact longwall shape. The use of probe cooling water mist caused their double fragmentation and reduction of the share of this phase in the microstructure of silumin. From a comparison of cast microstructure (Fig. 7b, Fig. 8b) that the mold cooling water mist reduces size of the lamellar eutectic grains much more than the primary crystals of hypereutectic silumins.

Variety of microstructure morphology is probably the result of changes in the solidification process caused by the intensive cooling of the melt at a rate of 50 C/s.
The super cooling of alloy caused by the cooling of probe will start pre-eutectic crystallization of silicon at a much lower temperature than the alloy uncooled. Further cooling of the silumin causes that the liquid metal is super cooled below the eutectic temperature and then, in accordance with the metastable diagram of Al-Si, crystallized aluminum dendrites and the remaining liquid having a higher concentration of silicon, crystallizes as a eutectic Al + Si.

The research shows that increased as a result of mold cooling water mist cooling rate increases refinement of pre-eutectic long-wall silicon crystals of silumin. Heat treatment of these castings also causes rounding of the edges, reducing lamella length and spheroidization of eutectic silicon lamellas. These changes are much larger in castings obtained from intensively cooled mold in compare to castings cooled down naturally, in which the primary silicon crystals are larger and do not exhibit the reducing of the lamellas length and edge rounding.

In summary, the studies show that the use the mold cooling with water mist makes possible to shape the different types of microstructures of hypereutectic silumins. A wide range of solidification temperature of hypereutectic silumins increases the potential impact of the change of cooling rate on the size, number and morphology of the crystallizing phases.

4. Conclusions

The study shows that the use of thermographic method and cooling of probe with water mist:

- provides a quantitative analysis of kinetics the cooling and solidification process,
- proved that the duration time of entire solidification process of cooled silumin AlSi15 is about 10 times shorter than uncooled,
- water mist cooling of probe increases cooling rate of liquid alloy from $dt/d\tau = -32.8$ C/s to $dt/d\tau = -56.7$ C/s,
- allows in a wide range the formation of the microstructure of hypereutectic silumins,
- in hypereutectic silumin unmodified reduces size of lamellar eutectic grains and it allows to obtain fine-grained crystals of silicon,
- causes high refinement of the microstructure despite increasing silicon content between alloys AlSi15 and AlSi19.

References

[1] Władysiak, R. (2007). Effective Intensification Method of Die Casting Process of Silumins. *Archives of Metallurgy and Materials*. 52(3), 529-534.

[2] Władysiak, R. (2008). Water Mist Effect on Cooling Range and Efficiency of Casting Die. *Archives of Foundry Engineering*. 8(4), 213-218.

[3] Władysiak, R. (2010). Effect of Water Mist on Cooling Process of Casting Die and Microstructure of AlSi11 Alloy. *Archives of Metallurgy and Materials*. 55(3), 939-946.

[4] Władysiak, R. (2013). Computer Control the Cooling Process in Permanent Mold Casting of Al-Si Alloy. *Archives of Metallurgy and Materials*. 58(3), 977-980.

[5] Fraś, E. (1992). *Crystallization of Metals and Alloys*. PWN, Warsaw (Polish).

[6] Rapiejko, C., Pisarek, B. & Pacyniak, T. (2014). Effect of Cr and V Alloy Additions on the Microstructure and Mechanical Properties of AM60 Magnesium Alloy. *Archives of Metallurgy and Materials*. 59(2), 771-775.

[7] Rapiejko, C., Pisarek, B. & Pacyniak, T. (2014). Analysis of AM60 and AZ91 Alloy Crystallisation in Ceramic Moulds by Thermal Derivative Analysis (TDA). *Archives of Metallurgy and Materials*. 59(4), 1449-1455.

[8] Rapiejko, C., Pisarek, B., Czekaj, E. & Pacyniak, T. (2014). Analysis of the Crystallization of AZ91 Alloy by Thermal and Derivative Analysis Method Intensively Cooled in Ceramic Shell. *Archives of Foundry Engineering*. 14(1), 97-102.

[9] Władysiak, R. (2013). Examining the Possibilities of Analyzing the Solidification Process of Al-Si Alloy with the Infrared Camera. *Archives of Foundry Engineering*. 16(1), 89-94.