INFLUENCE OF DIE CASTING PROCESS PARAMETERS ON THE MECHANICAL PROPERTIES OF CASTINGS

JURAJ RUZBARSKY

Department of Technical Systems Design and Monitoring,
Faculty of Manufacturing Technologies with a seat in
Presov, Technical University of Kosice, Slovakia

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e-mail: juraj.ruzbarsky@tuke.sk

Die casting is a process of injecting molten metal into a metal die under high pressure. The die design, the gating system, venting, and cooling play a crucial role. The quality of the castings is also influenced by pressure, injection speed, and the alloy composition. The experiment studied the impact of die-filling modes on the mechanical properties of castings made from silumin according to CSN 42 4331. Tests were conducted on 180 samples at different positions in the die, temperatures, and injection piston speeds. The chemical composition was analyzed by spectroscopy, and tensile strength (Rm) and microstructure were observed. The results confirmed the importance of proper process parameter settings to achieve optimal mechanical properties and minimize casting defects.

KEYWORDS

die casting, mechanical properties, silumin, die filling, microstructure

1 INTRODUCTION

In the die-casting process, molten metal is injected into a metal die cavity at high speed. This process generates high velocities of molten metal during the filling of the die, which are then converted into pressure and thermal energy. The quality of castings produced by this technology is influenced by a number of interconnected factors. One of the most significant factors is a properly designed and precisely manufactured die construction. A key element is the gating system, which ensures uniform and rapid filling of the die, along with an effective venting system that eliminates gas entrapment during casting. The cooling system of the die, which directly affects the solidification rate of the metal, also influences the mechanical properties of the casting [Sigwort 2020, Hu 2015, Szymczak 2020].

In addition to the structural elements of the die, other technological factors also affect the quality of the castings. A significant role is played by the selection and condition of the die-casting machine, which must allow precise control over technological parameters such as pressure and injection speed. Equally important is the type of material used, specifically the chemical composition of the alloy and its quality of metallurgical processing. It is also necessary to ensure an optimal gas regime in the die to avoid internal defects such as porosity or inhomogeneities [Qin 2019, Ruzbarsky 2019].

To ensure high-quality castings, it is essential to use high-quality equipment, including not only modern die-casting machines but also equipment for melting and modifying the molten metal. Properly designed gating systems, along with precise settings for technological parameters such as temperature, pressure, and injection speed, create ideal conditions for producing quality castings with minimal defects and high accuracy [Szymczak 2020].

For optimal results, it is necessary for the die design to be aligned with correctly set technological conditions, ensuring stable and repeatable production of castings with high quality. These castings will exhibit the required mechanical properties, precise dimensions, surface quality, and long-term reliability.

The pressing mechanism, which is a key element of the die-casting machine, influences the quality and efficiency of casting production. The main task of the pressing mechanism is to deliver the specified amount of molten metal into the die cavity under high pressure. The speed at which the die is filled depends on the flow of metal through the gating system and the geometry of the gating system. Effective control of these parameters is crucial for eliminating defects such as cold shuts, porosity, or surface defects [Bi 2015, Majernik 2016, Do 2017].

Among the basic technological parameters that affect the quality of the casting is the pressing speed. This speed influences the dynamics of the gating process and the flow of metal in the gating system. To properly set the pressing speed, several factors must be considered, such as the type of alloy, the shape and complexity of the casting, wall thickness, and the ratio of the gating system’s area to the overall casting area.

The flow velocity of the metal in the gating system, which ranges from 0.6 $m.s^{-1}$ to 100 $m.s^{-1}$, is critical for the final casting quality. The optimal velocity depends on the shape and wall thickness as well as the length of the casting. At low velocities, laminar flow ensures smooth filling of the die, while at medium velocities, turbulent flow guarantees rapid and uniform die filling. At high velocities, metal flow can cause problems such as gas formation and internal porosity [Iwata 2012, Trudonoshyn 2021, Sadeghi 2012].

Another important factor is the hydrodynamic pressure acting on the alloy. This pressure affects the compaction of the material and minimizes the occurrence of internal defects. The pressure is generated as the molten metal flows through narrow channels in the gating system and around the shaping cores. Ideally, if there are no resistance factors, the pressure determines the counterpressure of gases and air in the die cavity, with effective venting being crucial for the casting quality [Zhang 2020, Pagone 2020, Ragan 2007].

The kinetic energy of the flowing metal is decisive for the precision of copying the die's relief and the final surface roughness of the casting. Based on this, the hydrodynamic pressure, which affects the casting quality, is calculated. This pressure is transmitted through the pressing piston and the gating channel into the die cavity. It is important for the gating channel not to solidify too quickly to ensure that the pressure acts long enough to improve the casting quality [Ruzbarsky 2017, Konopka 2015, Qin 2021].

In die casting, it is also crucial to ensure optimal filling time for the die cavity. This time must be short enough to prevent premature solidification of the metal but long enough to allow gases to be effectively vented from the die. The proper filling time depends on the wall thickness of the casting, and it is important to avoid filling that is either too long or too short.

The entire casting process occurs in three phases: pre-filling the injection chamber, filling the die, and the pressure phase. In each phase, the molten metal must flow at the correct speed and pressure. After the die is filled, solidification occurs, which is key to achieving the desired geometry and mechanical properties of the casting [Gaspar 2019, Choi 2002, Ruzbarsky 2019].

These parameters, such as the temperature of the molten metal, pressure, and filling speed, are decisive for achieving high-quality results and minimizing manufacturing defects. It is important to set the correct technological conditions to achieve high-quality and accurate castings in die casting [Lumley 2011, Ruzbarsky 2023].

2 METHODS AND MATERIALS USED

To monitor the effect of different filling regimes on the basic mechanical properties of castings, a special die was used, designed for casting test rods measuring 6 x 30 mm according to the CSN 42 0315 standards, as shown in Figure 1.

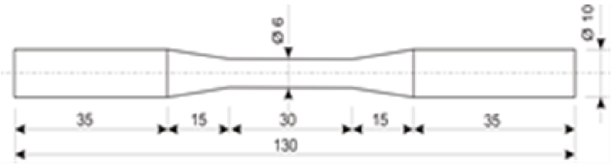

Figure 1. Test bar 6x30 [CSN 420315 1980]

These rods serve as test samples for investigating the mechanical properties of the resulting castings depending on various parameters of the die-casting process. The placement of the rods within the die and the design of the gating system are important aspects that influence the quality and uniformity of the final castings. A diagram of the rod placement and gating configuration is shown in Figure 2.

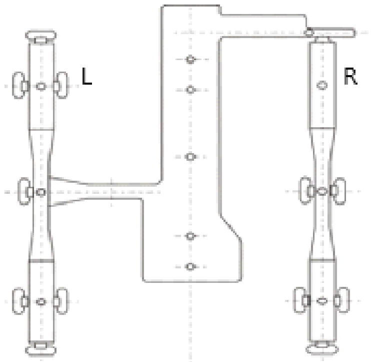

Figure 2. Placement of the rods in the die

This placement method was designed to enable efficient and uniform filling of the die with molten metal, thereby minimizing potential defects such as air bubbles or irregularities in the casting structure. This approach ensures a consistent metal flow into each test rod, which is crucial for obtaining accurate and comparable results when measuring mechanical properties.

In this experimental methodology, different arrangements of gating and notch designs in the die are applied, resulting in distinct filling regimes for the right and left test rods. The goal of the experiment was to investigate the impact of these different filling regimes on the degree of inhomogeneity in the mechanical properties, specifically the tensile strength (Rm), of the aluminum-silicon alloy casting with a chemical composition corresponding to CSN 42 4331 [CSN 424331 1987].

To determine the impact on mechanical properties, three main factors were examined:

- position of the casting in the mold – specifically, a comparison of results between the right (P) and left (L) test rods
- pouring temperature – the measured temperatures included t1 = 620°C, t2 = 640°C, and t3 = 660°C
- piston filling speed – the speeds tested ranged from v1 = 0.2 m.s^{-1} to v6 = 1.2 m.s^{-1}, creating different filling regimes from laminar to dispersed filling

In addition to these factors, which were examined in the experimental research, other factors were maintained at constant levels to eliminate their impact on the results:

- the degree of filling in the filling chamber, which was constantly monitored to ensure the same conditions for all tested samples
- the speed and method of piston ramp-up to the required pressure, which had to be controlled according to specified parameters
- the applied back pressure, which was set to the same value for all experiments

The mold temperature (with a tolerance of ± 20 ºC), is aimed to ensure stable conditions for casting.

The pouring temperatures were set by commonly used temperatures in pressure die-casting foundries. The piston filling speeds were set over a wide range to simulate various filling regimes, from laminar flow, through continuous turbulent flow, to dispersed filling. Experimentally, it was determined that at speeds less than 0.25 m.s^{-1}, the mold would not fill properly, meaning the molten metal could not sufficiently fill the mold. On the other hand, at speeds greater than 1.2 m.s^{-1}, issues such as leakage in the mold parting line occurred, caused by partial mold opening due to the impact of the molten metal flow.

To obtain reliable and representative data, each measurement was repeated 5 times, resulting in a set of 180 test samples. This repetition range and number of test samples allowed for detailed analysis and provided valuable information about the impact of various filling regimes on the quality and mechanical properties of aluminum-silicon alloy castings.

The chemical composition of the alloy was determined in the laboratory at a temperature of 22ºC and 50% relative humidity using a SPECTROCAST spectrometer (SPECTRO Company). Static pressure testing (permanent deformation) was measured using a TIRAtest 28200 device (TIRA Company).

2.1 *Analysis of the chemical composition of the melt*

During the experiment, a total of five melts were performed, each of which was carefully analyzed in terms of its chemical composition. These melts represent different variations of the alloy, which were cast according to the prescribed parameters and conditions of the experiment. For proper interpretation of the results and assessment of the influence of the chemical composition on the mechanical properties of the castings, it was essential to subject each melt to a detailed chemical analysis.

Table 1 provides an overview of the chemical composition of each melt, as well as a comparison with the official alloy composition according to CSN 42 4331. The alloy according to CSN 42 4331 is intended for specific applications and must meet precisely defined requirements regarding the content of various chemical elements. For each melt, the amounts of the main components as well as the presence of trace elements, which may affect the properties of the alloy during casting and subsequent cooling, were analyzed [CSN 424331 1987].

As part of these melts, the percentage of individual elements was carefully monitored to ensure that the chemical composition met the requirements set for the specific alloy. An important aspect was also tracking any deviations from the desired values, which could affect the final mechanical properties of the castings, such as tensile strength, hardness, and other factors.

These analyses were conducted to obtain detailed information about the stability of the chemical composition during the experiment and to compare these values with the CSN 42 4331 standards, which allowed for the evaluation of the impact of different melting conditions on the final properties of the melt and the castings [CSN 424331 1987].

Table 1. Chemical Composition of Experimental Melts of the Used Alloy [CSN 424331 1987]

Heat number	% content of elements							
	Al	Si	Mg	Mn	Fe	Cu	Zn	Ca
1	89.08	9.86	0.333	0.16	0.31	0.028	0.029	0.010
2	89.13	9.94	0.327	0.15	0.31	0.027	0.030	0.010
3	89.31	9.77	0.324	0.15	0.30	0.025	0.028	0.010
4	89.37	9.72	0.313	0.14	0.31	0.024	0.027	0.010
5	89.13	9.93	0.321	0.16	0.31			0.010
According to CSN 42 4331								
remainder		9 - 10.5	0.2 - 0.5	0.1 - 0.4	up to 1.5	up to 0.2	up to 0.3	-

3 RESULTS

As part of the experiment, the tensile strength limit Rm was measured on test bars, serving as a key parameter for evaluating the quality of the casting. This parameter is one of the most important indicators, providing information about a material’s resistance to tensile stress and, consequently, its ability to withstand deformation under external forces.

For castings made of cast iron CSN 42 4331, the standard prescribes a tensile strength limit Rm of 196 MPa. However, in the conducted experiments, the measured values of the tensile strength limit on individual casting samples ranged from 151.9 MPa to 291.1 MPa. This wide range of values indicates variability in properties, which can be influenced by various factors during the casting and cooling processes.

Table 2 presents the dependence of the average tensile strength limit Rm values for the left test bars on the filling speed and casting temperature. Each value in the table represents the arithmetic mean of five measurements taken on castings produced under identical conditions. Additionally, the table displays the average values of samples analyzed according to casting temperature (T) and filling speed (V).

Table 2. Average Rm Values [MPa] for Left Test Bars Based on Filling Speed and Casting Temperature

Rm	v1	v2	v3	v4	v5	v6	T
t1	211.4	233.2	232.2	256.2	244.2	225.2	**233.7**
t2	230.4	213.9	229.9	223.7	238.1	236.2	**228.7**
t3	232.7	233.1	233.4	238.4	247.1	237.1	**237.0**
V	**224.8**	**226.7**	**231.8**	**239.4**	**243.1**	**232.8**	

Table 2 clearly shows that the tensile strength limit Rm values vary at different casting temperatures and filling speeds. For example, at a casting temperature of t10 (620°C) and different filling speeds (from v1 to v6), the Rm values range from 211.4 MPa to 256.2 MPa, while at a temperature of t2 (640°C), they range from 213.9 MPa to 238.4 MPa. This indicates that casting temperature and filling speed significantly influence the final mechanical properties of the castings.

Table 3, structured similarly to Table 2, presents the average tensile strength limit Rm values for the right test bars. This dataset allows for a comparison with the results f0.028or the left test bars and illustrates the same dependenci0.028es while considering different parameters and conditions during the casting of the right bars.

Table 3. Average Rm Values [MPa] for Right Test Bars Based on Filling Speed and Casting Temperature

Rm	v1	v2	v3	v4	v5	v6	T
t1	182.2	191.3	186.9	205.4	209.6	183.4	**193.1**
t2	203.3	192.5	187.4	205.9	213.7	211.4	**202.4**
t3	196.1	193.5	204.8	200.9	213.3	193.5	**200.4**
V	**193.9**	**192.4**	**193.0**	**204.1**	**212.2**	**196.1**	

The results in Table 3 show that at a casting temperature of t1 (620°C), the tensile strength limit Rm values for the right test bars range from 182.2 MPa to 209.6 MPa, while at a temperature of t2 (640°C), they range from 187.4 MPa to 213.7 MPa. This range is comparable to the values measured for the left test bars, with slight differences that may be caused by various factors during the casting process.

This pattern is illustrated in Figure 3, which shows the dependence of the average tensile strength limit Rm values on the filling speed for both right and left test bars, and in Figure 4, which depicts how the average tensile strength limit values change depending on the casting temperature for both right and left test bars.

The overall analysis of these results shows that the tensile strength limit Rm is influenced by several factors, such as casting temperature and filling speed. These factors can have a significant impact on the final quality of the casting, and therefore, they need to be carefully optimized when producing castings with high strength requirements.

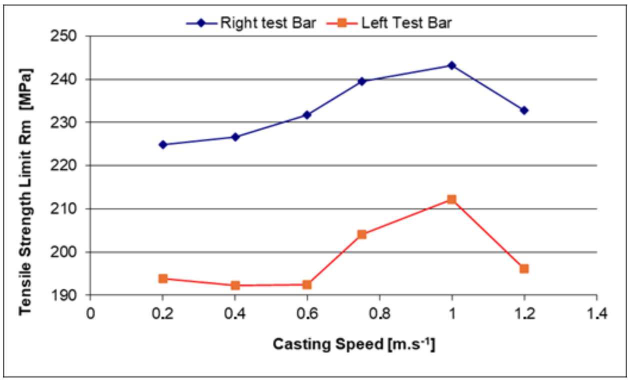

Figure 3. Dependence of Average Tensile Strength Limit Values on Casting Speed

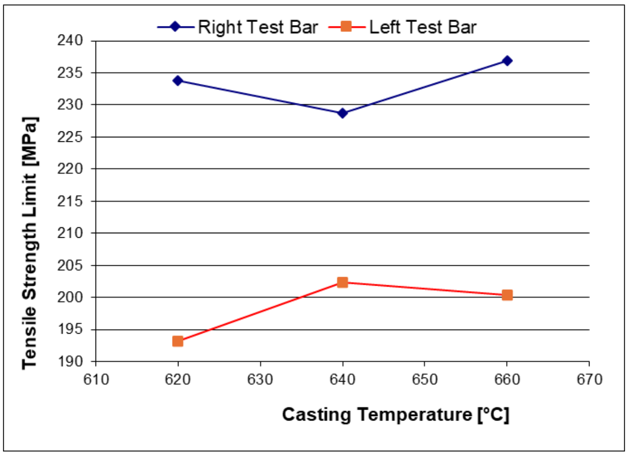

Figure 4. Dependence of Average Tensile Strength Limit Values on Casting Temperature

4 CONCLUSION

In the experiment, we aimed to identify the optimal conditions under which the best mechanical properties of casting are achieved in the die-casting process. By focusing on factors such as filling speed and casting temperature, we obtained important information about their impact on casting quality [Cleary 2014].

- Analysis of the results showed that the final quality of the castings varies depending on whether it is a left or right test bar. This difference is due to the different conditions present during casting in these two areas of the die. Additionally, filling speed has a significant impact on casting quality. The optimal filling speed range is between 0.75 – 1.2 m/s, with the best results, particularly in terms of tensile strength, achieved at a filling speed of 1 m/s. This effect is noticeable on both sides, although it should be noted that other factors may also contribute to the overall casting quality.
- In the experiments, we also studied casting temperature, which affects the mechanical properties of the castings. Castings made at different temperatures (620 °C, 640 °C, 660 °C) showed differences in tensile strength, indicating that casting temperature plays a key role in meeting material quality requirements. The results showed that the optimal combination of temperature and filling speed can significantly improve the mechanical properties of the castings.
- Average tensile strength values Rm differed depending on the location of the test bars in the mold. For the left test bars, the average values ranged from 211.4 MPa to 247.1 MPa, while for the right test bars, the values ranged from 182.2 MPa to 213.7 MPa. These differences indicate that factors such as position in the mold, filling speed, and casting temperature have a significant impact on the final quality of the castings.
- Based on repeated experiments that demonstrated the high reliability of the results, we can conclude that the optimal filling conditions occur at a casting speed of 1 m/s. These conditions lead to the highest tensile strength values, indicating that castings made at this speed have the best mechanical resistance.

The results obtained from repeated experiments confirm the importance of filling speed and casting temperature in optimizing the mechanical properties of castings. For the best results, it is essential to control not only the filling speed but also other factors such as mold temperature and the speed of the filling plunger [Cai 2021, Ruzbarsky 2014].

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REFERENCES

[Bi 2015] Bi, C., Guo, Z., Xiong, S. Modelling and simulation for die casting mold filling process using Cartesian cut cell approach. Int. J. Cast Met. Res., 2015, Vol. 28, pp. 234-241.

[Cai 2021] Cai, Q., Mendis, Ch. L., Chang, I.T.H., Fan, Z. Microstructure and mechanical properties of new die-cast quaternary Al-Cu-Si-Mg alloys. Materials Science and Engineering A, 2021, Vol. 800, 140357. https://doi.org/10.1016/j.msea.2020.140357.

[Choi 2002] Choi, J.C., Kwon, T.H., Park, J.H., Kim, J.H., Kim, C.H. A Study on Development of a Die Design System for Diecasting. Int. J. Adv. Manuf. Technol., 2002, Vol. 20, pp. 1-8.

[Cleary 2014] Cleary, P.W., Savage, G., Ha, J., Prakash, M. Flow analysis and validation of numerical modeling for a thin-walled high pressure die casting using SPH. Comput. Part. Mech., 2014, Vol. 1, pp. 229-243.

[CSN 420315 1980] CSN 420315 Testing of metals. Cylindrical test specimens with smooth cylindrical heads for tensile testing (Zkouseni kovu. Zkusebni tyce valcove s hladkymi valcovymi hlavami pro zkousku tahem). Prague: Office for Standards, Metrology and Testing, 1987, 4 p. (in Czech)

[CSN 424331 1987] CSN 42 4331 Aluminium alloy for castings 42 4331 AlSi10MgMn (Slitina hliniku na odlitky 42 4331 AlSi10MgMn). Prague: Office for Standards, Metrology and Testing, 1987, 8 p. (in Czech)

[Do 2017] Do, T.A. and Tran, V.T. Optimization of Precision Die Design on High-Pressure Die Casting of AlSi9Cu3. Lecture Notes in Mechanical Engineering, 2017, pp. 759-771.

[Gaspar 2019] Gaspar, S. and Pasko, J. Plunger pressing speed like the main factor influencing the mechanical properties of die casting. MM Science Journal, 2019, No. December, pp. 3490-3493. https://doi.org/10.17973/MMSJ.2019_12_2019029.

[Hu 2015] Hu, Z.-Q., Zhang, X.-J., Wu, S.-S. Microstructure, Mechanical Properties and Die-Filling Behavior of High-Performance Die-Cast Al–Mg–Si–Mn Alloy. Acta Metall. Sin. Eng., 2015, Vol. 28, pp. 1344-1353.

[Iwata 2012] Iwata, Y., Dong, S., Sugiyama, Y., Iwahori, H. Compression Behavior of Entrapped Gas in High-Pressure Diecasting. Mater. Trans., 2012, Vol. 53, pp. 483-488.

[Konopka 2015] Konopka, Z., Zyska, A., Lagiewka, M., Nadolski, M. The Influence of Pressure Die Casting Parameters on the Castability of AlSi11-SiCp Composites. Arch. Foundry Eng., 2015, Vol. 15, pp. 29-34.

[Lumley 2011] Lumley, R., Deeva, N., Gershenzon, M. An Evaluation of Quality Parameters for High-Pressure Die Castings. Inter Metalcast, 2011, Vol. 5, No. 3, pp. 37-56. https://doi.org/10.1007/BF0335551.

[Majernik 2016] Majernik, R., Ruzbarsky, J. The impact of technological parameters of dies casting to casting porosity. MM Science Journal, 2016, Vol. October, pp. 1047-1050. https://doi.org/10.17973/MMSJ.2016_10_201623.

[Pagone 2020] Pagone, E., Papanikolaou, M., Salonitis, K., Jolly, M. Multi-criteria decision-making for the life cycle of sustainable high pressure die casting products. Int. J. Sustain. Manuf., 2020, Vol. 4, 101.

[Qin 2019] Qin, X.-Y., Su, Y., Chen, J., Liu, L.-J. Finite element analysis for die casting parameters in high-pressure die casting process. China Foundry, 2019, Vol. 16, pp. 272-276.

[Qin 2021] Qin, P.F., Yang, Q., He, YY., et al. Microstructure and mechanical properties of high-strength high-pressure die-cast Mg–4Al–3La–1Ca–0.3Mn alloy. Rare Met., 2021, Vol. 40, pp. 2956-2963. https://doi.org/10.1007/s12598-020-01661-5.

[Ragan 2007] Ragan, E., et al. Die Casting of Metals (Liatie kovov pod tlakom). FMT TUKE: Presov, Slovakia, 2007, 383 p. ISBN 978-80-8073-979-9. (in Slovak)

[Ruzbarsky 2014] Ruzbarsky, J., Pasko, J., Gaspar, S. Techniques of Die Casting, 1st ed. RAM-Verlag: Ludenscheid, Germany, 2014, 199 p. ISBN 978-3-942303-29-3.

[Ruzbarsky 2017] Ruzbarsky, J. and Majernik, R. Theoretical Regulation of Delimitation of Metal Level Decrease in the Furnace in Case of Pneumatic Dosing Device of Metal. Manufacturing Technology Journal, 2017 Vol. 17, No. 1, pp. 84-86. https://doi.org/10.21062/ujep/x.2017/a/1213-2489/MT/17/1/84.

[Ruzbarsky 2019] Ruzbarsky, J. Al-Si Alloys Casts by Die Casting – A case Study, 1st ed. Springer: Cham, Switzerland, 2019, 71 p. https://doi.org/10.1007/978-3-030-25150-5.

[Ruzbarsky 2019] Ruzbarsky, J. and Sitko, J. Possibilities of Pressure Die Casting of Iron Alloys. Management Systems in Production Engineering, 2019, Vol. 27, No. 4, pp. 199-204. https://doi.org/10.1515/mspe-2019-0031.

[Ruzbarsky 2023] Ruzbarsky, J., Gaspar, S. Analysis of Selected Production Parameters for the Quality of Pressure Castings as a Tool to Increase Competitiveness. Applied Sciences, 2023, Vol. 13, No. 14, 8098. https://doi.org/10.3390/app13148098.

[Sadeghi 2012] Sadeghi, M. and Mahmoudi, J. Experimental and Theoretical Studies on the Effect of Die Temperature on the Quality of the Products in High-Pressure Die-Casting Process. Adv. Mater. Sci. Eng., 2012, 434605.

[Sigwort 2020] Sigworth, G.K. and Donahue, R.J. The Metallurgy of Aluminum Alloys for Structural High-Pressure Die Castings. Inter Metalcast, 2020. https://doi.org/10.1007/s40962-020-00535-X.

[Szymczak 2020] Szymczak, T., Gumienny, G., Klimek, L., Goly, M., Pacyniak, T. Microstructural Characteristics of AlSi9Cu3(Fe) Alloy with High Melting Point Elements. Metals, 2020, Vol. 10, 1278. https://doi.org/10.3390/met10101278.

[Szymczak 2020] Szymczak, T., et al. Characteristics of Al-Si Alloys with High Melting Point Elements for High Pressure Die Casting. Materials, 2020, Vol. 13, 4861. https://doi.org/10.3390/ma13214861.

[Trudonoshyn 2021] Trudonoshyn, O., Randelzhofer, P., Korner, C. Heat treatment of high-pressure die casting Al-Mg-Si-Mn-Zn alloys. Journal of Alloys and Compounds, 2021, Vol. 872, 159692. https://doi.org/10.1016/j.jallcom.2021.159692.

[Zhang 2020] Zhang, J.Y., et al. Effect of thermal exposure on microstructure and mechanical properties of Al−Si−Cu−Ni−Mg alloy produced by different casting technologies. Transactions of Nonferrous Metals Society of China, 2020, Vol. 30, No. 7, pp. 1717-1730. https://doi.org/10.1016/S1003-6326(20)65333-X.

CONTACTS:

Juraj Ruzbarsky
Department of Technical Systems Design and Monitoring
Faculty of Manufacturing Technologies with a seat in Presov
Technical University of Kosice
Sturova 31, 080 01 Presov, Slovakia
tel.: +421 55 602 6458
e-mail: juraj.ruzbarsky@tuke.sk