INFLUENCE OF DIE CASTING SPEED ON PROPERTIES OF CASTING BASED ON AL-SI ALLOYS

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The paper focuses on the research of the influence of chosen technological parameters of die casting on the selected mechanical properties of castings based on Al-Si alloys. The experiments conducted within the frame of the practical part examined the plunger pressing speed in the mould cavity influencing the mechanical properties of a casting which were represented by ultimate tensile strength and percentage share of porosity of Al-Si castings. Plunger pressing speed is closely related to mould cavity filling mode which affected the final porosity of casting. In the case of increased percentage porosity share, the ultimate tensile strength decrease was detected due to the reduction of the cross-section area of the casting. The increase in percentage porosity share in the casting was caused by the increase in plunger pressing speed. To achieve the desired quality of castings, higher production efficiency, and reduced occurrence of faulty pieces during production, an optimal set of technological parameters of die casting is inevitable.

KEYWORDS

quality, die casting, technological parameters, Al-Si alloys, mechanical properties, pressing speed, porosity, ultimate tensile strength

1 INTRODUCTION

The technology of die casting of non-ferrous metals and their alloys under the conditions of high-pressure ranks among the youngest ones in the founding industry. During a relatively short period, the technology has become widely used in bulk series production of castings. It is a specific method used especially in the case of the production of smaller, lighter, thin-walled products with more complicated shapes and with a strictly dimensioned number of pieces in the individual series. Particular attention is paid to surface quality which is usually smooth. These castings are mostly produced from non-ferrous metal alloys with average die casting temperature. An increase in the share of castings in modern designs requires a range of knowledge related to foundry processes and their targeted application [Szymczak 2020a, Blondheim 2021].

Die casting technology of metals represents the method of precise casting production approaching the ideal effort to change basic material into a final version. It is the means of casting production in the case which the molten metal is injected into a permanent mould at a high speed of 10-100 m.s^{-1} that the metal reaches the ingate under the influence of high pressure (the melt is being cast with the pressure of up to 500 MPa). Throughout solidification, the metal remains under the pressure, i.e., the process is referred to as multiplication. High filling speed and high pressure allow the casting of thin-walled and rather fragmented castings, which in many cases do not require further machining other than the removal of sprues and fins [Caceres 1996, Ruzbarsky 2019a].

Die casting technology allows producing of castings with high complexity and surface quality approaching the final shapes and dimensions. Right the properties and quality of castings are influenced by several factors that affect the entire die casting process. The factors include a correct mould design, a gating system, the venting, and cooling systems, a type of casting alloy, the quality of produced mould, a die casting machine with attendance, and adequate setting of all technological and metallurgical parameters of the technology [Lumley 2011, Gaspar 2019, Trudonoshyn 2021]. A complex of all the aforementioned factors and parameters determines a precondition to produce high-quality castings. Technological parameters significantly influencing mechanical properties involve casting pressure (holding pressure), mould cavity filling time, and thermal conditions of the die casting process [Ruzbarsky 2014, Zhang 2020a].

1.1 Pressing Speed

The melt pressing speed in the die casting process relates to mould filling time. It determines the metal speed in the gating system and in the ingate of the mould which can be expressed using the continuity equation as follows [Ragan 2006 and 2007]:

$$v.S_p = v_1.S_f \tag{1}$$

where:

v – pressing speed in the filling chamber [m.s^{-1}],
v_1 – metal flow speed in the ingate [m.s^{-1}],
S_p – cross section area of the pressing plunger [m^2],
S_f – cross section area of the ingate [m^2].

The theoretically calculated flow speed of the alloy in the ingate differs from the actual one. Measuring the flow speed in the ingate has proved that the actual speed is only 30 to 50% of the calculated theoretical speed [Ruzbarsky 2014]. In the mould cavity the values of metal flow speed range from 5 to 15% of the theoretically calculated flow speed of alloy [Ragan 2007, Ruzbarsky 2019b]. The actual molten metal flow speed is affected mainly by the following [Majernik 2016]:

- viscosity of alloy depending also on its temperature,
- losses caused by friction in the gating system and a mould cavity,
- losses caused by the change of the melt flow direction in the gating system and the mould cavity,
- pressure of air and vapours in the mould cavity moving against the molten metal flow.

The speed of the melt flow also affects the mechanical properties of the casting and the inner and surface quality of castings. Selection of the right speed of the mould cavity filling depends on the alloy type, the casting complexity, the wall thickness, and the ratio of the gate area and the area of casting. The dependence of optimal speed in the ingate on the wall thickness and on the length of casting is shown in Figure 1 [Majernik 2016, Silmbroth 2020].

The character of the melt flow in the mould cavity depends on input melt speed into the mould cavity, mutual relation of the ingate thickness and the casting or their areas, viscosity and surface tension of the melt, and thermal conditions which are formed due to reciprocal influence between the melt and the mould.

In general, three input speed types can be distinguished with three methods of mould cavity filling.

1. low speed – laminar filling (up to 0.3 m.s^{-1})
2. medium speed – continuous turbulent filling (0.5 – 15 m.s^{-1})

3. high speed – disperse filling (25 – 30 m.s^{-1}).

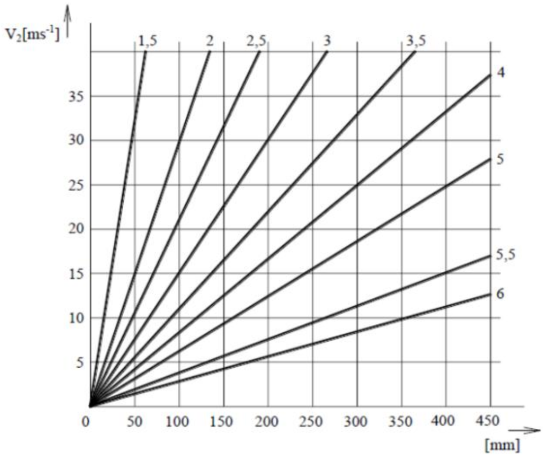

Figure 1. Dependence of alloy speed v2 in the ingate on the wall thickness of casting and on the maximal distance of the mould cavity from the ingate [Majernik 2016]

Based on the aforementioned point of view of the final quality of casting, the speed of mould cavity filling determined the filling mode and the casting temperature influences the thermal model of the mould and the casting [Ruzbarsky 2017, Cho 2014].

1.2 Mould Cavity Filling Time

Mould cavity filling time ranks among the main technological parameters which is a high degree of influence quality of castings. It affects especially the surface quality and the inner structure of the casting. Short filling time prevents the gases and the vapours from escaping the mould cavity to a necessary extent. They entrap in the casting walls and although the surface quality remains satisfactory, the inner structure is disturbed. The long filling time of the mould cavity allows the gases to escape through a venting system when the melt front proceeds in the cavity. In this case, the inner structure is satisfactory, however, due to alloy temperature reduction in the flow front, a perfect blending of the melt in all locations as absent and dry joints and cold laps emerge [Kang 2021]. These defects represent a risk in the case of such castings, which are under dynamic and cyclic stress. Therefore, the optimal filling time is a compromise between the long and short time of the mould cavity filling and must be shorter than the time of the casting solidification in the mould. Theoretically, the mould cavity filling time can be calculated as follows [Pasko 2014, Gaspar 2016a,b]:

$$\tau = \frac{V_F}{S_f . v_1} \tag{2}$$

where:
τ – mould cavity filling time [s],
V_F – mould cavity volume [m^3],
S_f – cross section area of the ingate [m^2],
v_1 – metal flow speed in the ingate [m.s^{-1}].
Start-up time, which should be shorter than the mould cavity filling time, can be theoretically expressed by the following relation:

$$t_1 = \frac{l_0\frac{S_f}{S_p} - l_1\sqrt{\frac{S_f}{S_p}} - l_2}{v_p} . 2.944 \tag{3}$$

where:
t_1 - start-up time [s],
v_p - pressing speed in the filling chamber [m.s^{-1}],
l_0 - total trajectory length of the pressing plunger [m],
l_1 – melt trajectory length in the gating system before the ingate [m],
l_2 - melt trajectory length in the ingate [m],
S_p - cross section area of a plunger [m^2].
In the case of constant thermal and physical characteristics, it has been proved in the experiments that filling time depends on the casting wall thickness and is independent of its dimensions as it is shown in Figure 2 [Caceres 1996, Cao 2017, Ragan 2006]. Optimal mould cavity filling time about the casting wall thickness can be expressed by the following empirical relation [Majernik 2016]:

$$\tau = 1.6.10^{-2}.s^{1.984} \tag{4}$$

where:
s – casting wall thickness.

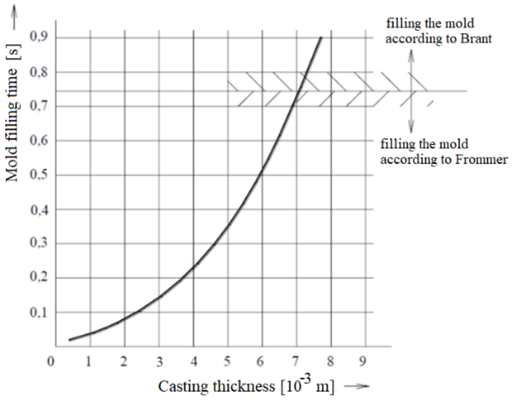

Figure 2. Dependence of optimal mould cavity filling time on the casting wall thickness [Ragan 2006]

Fluids following Newton´s Law are referred to as Newtonian fluids (Figure 3) and the other fluids not following Newton´s Law are referred to as non-Newtonian ones. Non-Newtonian fluids include Bingham fluids following the Bingham Law (Figure 4) [Pasko 2014]. The following relation is applicable for the fluids following Newton´s Law [Ruzbarsky 2017]:

$$\tau = \eta\frac{dv}{dx} \tag{5}$$

where:
τ – tangential stress of the flowing fluid layer in dependence on distance x from the edge [Pa]
η – coefficient of dynamic viscosity of the flowing fluid [Pa.s]
v – speed of the flowing fluid layer in distance x from the edge [m.s^{-1}]
x – distance from the edge in the direction perpendicular to the fluid flow direction [m].

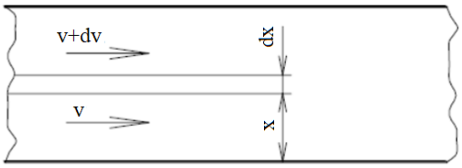

Figure 3. Scheme of the flowing fluid layers according to Newton´s Law [Ragan 2006]

The following is applicable for the fluids following the Bingham Law [Ruzbarsky 2017]:

$$\tau = \eta_p\frac{dv}{dx} + \tau_0 \tag{6}$$

where:
τ – tangential stress of the flowing fluid layer in dependence on distance x from the edge [Pa]

η_p – plastic viscosity [Nm^{-2}.s]
τ_0 – initial stress to be overcome by fluid movement [Pa].

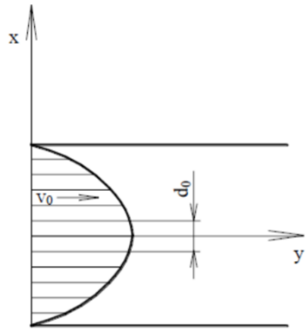

Figure 4. Fluid flow according to the Bingham Law [Ragan 2007]

Bingham fluids are alloys in the interval of crystallization and of suspension, for instance, fluid grease for the mould treatment in the case in which solid particles float in a fluid diluent of a concentrate. Not until the release of crystallization germs right above the fluid and the crystals of the solid phase between the liquid and the solid, do the alloys follow Newton´s Law. In the case of a mixture of solid particles floating in the fluid phase, the alloys follow the Bingham Law [Majernik 2016, Ruzbarsky 2019a].

In the interval of alloy crystallization, it is the case of two properties – viscosity and initial stress [Miglierini 2004]. The following relation is applicable for the initial stress of alloy in the interval of crystallization [Ruzbarsky 2020]:

$$\tau_0 = c_1 \Delta T^{a} . k^{b \Delta T d} \qquad (7)$$

where:
τ_0 – initial stress of alloy in the interval of crystallization [Pa]
ΔT– reduction of temperature contrary to the temperature at the beginning of the formation of crystallization germs [°C]
c_1 – constant [Pa.°C^{-a}]
d – constant [Pa.°C^{-d}]
k – constant
a,d – exponent.

The following relation is applicable for viscosity in the interval of crystallization [Ruzbarsky 2017]:

$$\eta_p = \eta \left[1 + c_1 \left(\frac{V}{V_0} \right) + c_2 \left(\frac{V}{V_0} \right)^2 \right] \qquad (8)$$

where:
η_p – plastic viscosity [Nm^{-2}.s]
η – dynamic viscosity of fluid alloy [Nm^{-2}.s]
c_1, c_2– constants
V – volume of solid particles [m^3]
V_0 – total volume [m^3].

Within the frame of the research, it is desired to detect the relationship between the pressing speed of die casting about the selected properties of aluminium alloy which are represented by ultimate tensile strength and by the porosity of castings [Majernik 2016, Szymczak 2020b, Blondheim 2021, Trudonoshyn 2021].

1.3 Foundry Alloys Al-Si

Aluminium alloys characterized by low specific weight, good machinability, and castability currently rank among the most widespread materials in the foundry field. The production volume of castings manufactured in the die casting process from aluminium alloys increases annually by approximately 12%. The technology still represents one of the progressive production methods of castings [Ruzbarsky 2020, Zhang 2020a].

Rapid development and utilization in the economic sphere can be observed in the case of silumin which is an aluminium alloy based on an aluminium–silicon system. Silumin is characterized by low specific weight (2650 kg.m^{-3}), high corrosion resistance, low tendency to seize, good running-in capacity in die casting, low tendency to shrinkage (0.5%), and cracking. Their machinability is slightly worse contrary to other aluminium alloys. Alloys of Al-Si type are applied especially in case of requirements for good castability and corrosion resistance [Diler 2021, Qi 2021].

The selection of suitable aluminium alloy for the production of the casting is conditioned by design and foundry properties. Design properties include especially mechanical properties at standard or low or high temperatures, extraordinary density-strength ratio, corrosion resistance, weldability, and machinability. These properties can be adjusted. Foundry properties relate mainly to running-in capacity, low tendency to shrink, low inclination to crack, and clink formation [Turtelli 2006, Diler 2021, Qin 2021].

According to the Al-Si equilibrium diagram, aluminium and silicon form a eutectic system with limited solubility of silicon in aluminium. The phase structure of binary alloys is characterized by Al-Si binary diagram in Figure 5 [Majernik 2016].

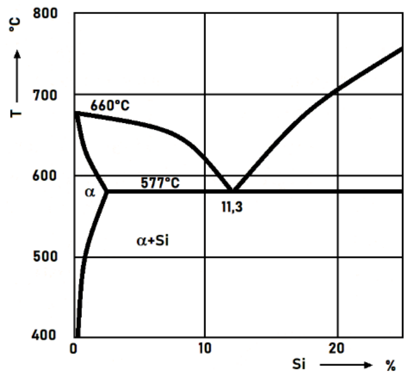

Figure 5. Binary diagram Al-Si [Majernik 2016]

Aluminium as a basic element is characterized by low melting temperature (660°C), low specific weight, and very good electric and thermal conductivity. Aluminium is also characterized by rather high ductility and relatively low strength properties. Silicon is brittle with a high melting temperature (1430°C) and with low specific weight and it crystallizes in a centered cubic lattice of a diamond type [Majernik 2016, Bolat 2022].

Aluminium and silicon form binary eutectic α+Si. The eutectic point is defined by a temperature of 577°C and a silicon concentration of 11.3% (scientific literature states values of 11.7% and 12.5 %).

The-α phase refers to the substitution solid solution of silicon in aluminium with a maximum solubility of 1.65% of silicon at eutectic temperature and 0.05 up to 0.1% of silicon at 200 °C. In binary systems, the eutectic represents a mixture of substitution solid solution α and almost pure silicon. Metalographically, it is a two-phase structure containing dark grey silicon particles located in a light matrix of the α-phase [Majernik 2016, Pasko 2014, Yuan 2021].

The amount, shape, size, and distribution of free silicon are connected with the mechanical properties of binary alloys Al-Si. The α-phase is soft and ductile and represents a coherent structural component of the eutectic. Eutectic is solid, soft, and sufficiently ductile as it contains approximately 90% of the α-phase and about 10% of silicon. The relatively high content of eutectic (40 up to 75%) in Al-Si alloys provides them with excellent running-in capacity and at the same time, it reduces their linear shrinkage and tendency to crack under the effects of heat and inclination to microporosity formation.

Al-Si based alloys are classified according to the Si content as follows:

- sub-eutectic (below 11.3 % of Si),
- eutectic (about 11.3 % of Si),
- supra-eutectic (over 11.3 % of Si) [Ragan 2006, Qi 2020].

Variable solubility of silicon in aluminium in dependence on temperature resulted in the effort made to increase the strength properties of binary alloys by hardening. From the point of view of the possibility of hardening by heat treatment, the Al-Si based alloys (silumin) can be classified as follows:

a) non-hardenable alloys

They contain from 5 to 20% of Si as well as other admixtures out of which Mn appears to be the most important one as it eliminates the negative effect of Fe upon draw ability, ductility, and foundry properties of silumin. The Cu admixture can increase endurance strength even though corrosion resistance gets slightly worse. The best foundry properties are typical for eutectic silumin containing from 10 up to 13 % of Si. The strength of such alloys (influenced by admixture content) ranges from 200 MPa up to 300 MPa and even more. They are highly resistant to corrosion and especially to water.

b) hardenable alloys

Apart from Si, they contain also Mg or Cu. Hardenability is assured by the existence of the Mg2Si or Al2Cu phase. The alloys in the injected and modified condition can reach ultimate tensile strength of over 300 MPs and they might be mechanically stressed at temperatures ranging from 250 up to 275°C [Ruzbarsky 2019a, Szymczak 2020b].

1.4 Physical and Mechanical Properties of Aluminium Alloys

Table 1 presents an overview of basic physical properties. The presence of impurities and material conditions can considerably change some of the values. Most values are informative only.

Table 1. Basic physical properties of aluminium alloys [Munoz-Ibanez 2019]

Thermal conductivity (W.m^{-1}°K^{-1})	96.2 – 142
Coefficient of thermal expansion (µm.m^{-1} °K^{-1})	18 – 24.1
Melting range (°C)	549 – 603
Electrical conductivity (%IACS)	22 – 37
Density (g. cm^{-3})	2.6 – 2.85

The mechanical properties of Al-Si-based alloys are better in a liquid state than in the moulded one. They resist atmosphere effects well and their corrosion resistance approaches the resistance of pure aluminium. Alloys are subjected to heat treatment.

Informative values of mechanical properties of Al-Si-based alloys are present in Table 2. Improvement of mechanical properties of Al-Si alloys is achieved through injection, modification, the addition of alloying agents, heat treatment, and other non-conventional methods [Munoz-Ibanez 2019].

Table 2. Informative values of mechanical properties of Al-Si alloys [Munoz-Ibanez 2019]

Young modulus (GPa)	71 – 82
Ultimate tensile strength (MPa)	228 – 330
Yield strength (Mpa)	97 – 250
Elongation (%/51 mm)	2.5 - 9
Hardness (BHN)	65 – 120
Shear strength (MPa)	130 - 200
Fatigue strength (MPa)	120 - 145

2 METHODS AND MATERIALS

Alloy AlSi9Cu3 was used in the experiment the chemical composition of which under the DIN EN 1706 standard is present in Table 3. Figure 6 shows a particular casting used in the automotive industry which was also the subject of the research.

Table 3. Chemical composition of alloy AlSi9Cu3 under DIN EN 1706 standard

Chemical composition in weight %											
Al	Si	Cu	Mg	Mn	Fe	Zn	Ni	Sn	Cr	Ti	Pb
residual	8.5 – 10.0	2.0 – 3.5	0.1 – 0.5	0.1 – 0.4	max. 1	max. 0.3	max. 0.3	max. 0.1	max. 0.05	max. 0.15	max. 0.2

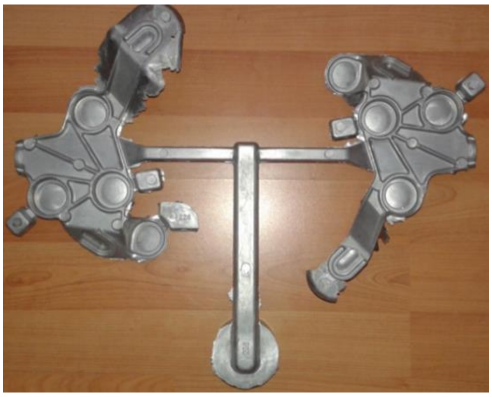

Figure 6. Non-machined casting with a gating system

The automotive industry employs a dominant sub-eutectic alloy of the Al-Si-Cu type which is used for the production of castings such as engine blocks, gear cases, etc. The Cu element increases machinability and allows automatic hardening after fast cooling in water. Fast cooling results in the occurrence of supersaturated solution α (Al), which splits apart, and afterward a precipitate is formed with subsequent structure hardening. Alloys with soluble admixture elements in the solid solution containing hardening phases released out of the solid solution can be hardened. This alloy also contains a specific amount of Mg present in the hardening phase, which improves casting properties. The procedure is applied in serial production in the case of which cooling castings in water is advantageous for less complicated separation of the gating system from the casting. Consequent natural hardening – referred to as aging – is a process that considerably influences further machining of the casting. Achieving optimal machining conditions requires observation of the time lag between casting and processing procedures. In machining of the casting in a liquid state, the material adheres to a tool and its service life noticeably shortens. If machining is performed with a specific time lag, the machining conditions considerably improve. Table 4 presents the physical properties of casting material and Table 5 presents the mechanical properties of casting used in experiments.

Table 4. Physical properties of casting

Density [g.cm^{-3}]	2700
Solid temperature [°C]	525
Liquid temperature [°C]	610

Table 5. Mechanical properties of casting

Ultimate tensile strength	min. 240 MPa
Yield point Rp 0.2	min. 140 MPa
Drawability A5	min. < 1
Brinell hardness test HB	min. 80

The experiments were performed with the die casting machine CLV 250 (Fig. 7) in the company dealing with the production of castings for the automotive industry.

Figure 7. Die casting machine CLV 250

The basic parameters of production equipment designed for the production of castings are shown in Table 6.

Table 6. Operation parameters of die casting machine designed for the production of castings CLV 250

Dimensions	2 x 3,2 x 8,7 m
Weight	27 t
Engine performance	37 kW
Locking force	600 t
Injection force	65 t
Ejection force	35 t
Min./max. mould height	400-900 mm
Max. weight of Al-Si casting	12 kg

2.1 *The setting of Technological Parameters of Die Casting*

Constantly setup speed of the plunger during chamber and gating system filling is 0.15 m.s^{-1} and the plunger speed, from the point when the chamber is filled and mould cavity filling starts, is 4.5 m.s^{-1}. Values of the melt temperature (660 °C) and the mould temperature were set up to constant values during experiments. The casting solidification time from the point when the mould is filled up to its opening is set to 30 seconds. The standardly set pressure or holding pressure value in the filling chamber is 28 MPa.

Within the frame of research aimed at the achievement of diverse homogeneity of castings, the experimental values of the melt flow speed were selected so that laminar and turbulent modes of mould filling are assured. The experimental speed values of the plunger were defined as follows: 3.5 – 4,5* – 5.5 m.s^{-1} (*value of 4.5 m.s^{-1} is a standardly set up value in the production of castings).

2.2 *Tensile Test – Strength Limit*

Research of the mechanical properties of materials is inevitable for their utilization under operation conditions. It is important to acquire knowledge of the structure and properties of produced components as well as of their behaviour in case of stress. To determine mechanical properties, a tensile test with testing specimens is used based on which it is possible to define ultimate tensile strength under respective ISO 6892-1:2009 standards. Consequently, the relation between ultimate tensile strength and pressing speed change with constantly set pressure–holding pressure values was examined. A universal TIRAtest machine was used as testing equipment.

2.3 *Preparation of Metallographic Specimens for Porosity Detection*

In general, aluminium alloys represent the most harmful gasses such as water vapour, hydrogen, and oxygen. The solubility of hydrogen in liquid aluminium is significant and increases with temperature. During crystallization, hydrogen is released in the form of pores and bubbles. Water vapour also leads to the formation of hydrogen bubbles and therefore porosity of the casting was examined as it is directly influenced by the change in the melt temperature [Gaspar 2019, Silmbroth 2020]. To detect porosity, the parts of the casting were used which were identified as the spots of the possible occurrence of increased porosity with regards to changing pressing speed considered to be the technological parameter of die casting.

The circular saw MIKRON with the alternative of water cooling was used for the cutting of the casting. The technological parameters of cutting were selected for cutting material. The compressive force of a cutting wheel was set to the lowest value of a loading scale and rotations of the cutting wheel were set to maximum, i.e., 3000 rev./min^{-1}. These precautions were taken to achieve the highest quality of the cutting. Consequently, the specimens were cast-in with dentacryl resin (Fig.8).

Figure 8. Specimens intended for grinding and polishing for optic microscopy

To examine porosity with a microscope, the examined specimens must be well prepared. Consequent preparation of the specimens included mechanical grinding with water and polishing with a diamond paste was performed with the use of a semi-automatic polishing machine Struers LaboPol-5.

Technological parameters of grinding:

- sandpaper with a grading of 1200,
- revolutions of the grinding wheel are 300 rev./min^{-1},
- compressive force of the grinding wheel acting upon specimens was selected in dependence on surface irregularities,
- grinding time depended on the surface quality of the specimen a single grinding cycle lasted for 3 minutes and the specimens were sufficiently ground after two grinding cycles (2x3 min.).

Further preparation of ground specimens included polishing with the same machine, yet the grinding wheel was replaced by the polishing one. All of the diamond pastes with diverse grading dispose of special polishing wheels which had to be replaced with polishing paste, i.e., firstly, diamond paste with lubricating component DiaDuo with the grading of 3 micrometers and then diamond paste with the grading of 1 micrometer. The first dosing of the polishing paste was performed manually by estimation and consequently, in the course of polishing, the machine indicated the amount of polishing paste to add dropwise onto the polishing wheel.

Technological parameters of polishing:

- revolutions of the wheel - 150 rev./min^{-1},

- period of a single polishing cycle was 3 minutes, and all of the specimens were subjected to two polishing cycles, i.e. 2 x 3 min in the case of diamond paste with the grading of 3 micrometers and one cycle, i.e., 1 x 3 minutes in case of diamond paste with the grading of 1 micrometer,
- compressive force of the polishing when set in dependence on the quality of a particular scratch pattern.

The final quality of the polished specimens was checked with the microscope 2303 Intraco Micro with a trinocular head. When all three specimens had been examined, it was determined which of them met the required quality standards and which of them had to be re-polished.

The porosity of the casting was evaluated by the optical microscope (microscope 2303 Intraco Micro) with a subsequent image import of the specimen scratch pattern to a camera interface to have the final image produced.

The final images of the individual specimens were processed using image analysis with the software Stream Motion by the Olympus company. The selected parts of the specimens for evaluation of porosity must be perfectly polished as each scratch or other dents or cracks of the specimens could be evaluated as the pores by the software and the results of porosity measurement would be thus misrepresented. Probably, it would be the case of a higher percentage of porosity occurrence contrary to the actual situation. Porosity is evaluated by graphic filters in the program Stream Motion. The filters find a colour in the evaluated image to which they are set. Each of the filters disposes of defined sensitivity which prevents the intervention into the detection zone of another filter. Before measurement, the filters must be set to adequate sensitivity so that just the pores are evaluated. The setting is followed by the analysis of the objects in the images which differ in colour from their environment and meet all the required conditions. The program saves the results of all specimen values in the tables.

3 RESULTS

One of the many options used for the production of castings is die-casting technology. The technology of metal dies casting ranks among the prime technologies. In the die casting process, the metal is pressed at high speed into the mould cavity. The principle rests in a change of kinetic energy to compressive energy. The entire process of die casting is influenced by different factors. The factors with a dominant effect on the quality of final castings include mainly die pressing speed, specific pressure acting upon the melt, holding pressure, mould cavity filling time, casting alloy temperature, and filling chamber temperature. Secondary factors must also be taken into consideration as they influence the entire process of die casting and the quality of produced castings such as the design of the casting and of the mould, and the effectivity of the machine in die casting, which all represents a complex of mutual bonds.

The conducted experiments serve for assessment of the influence of the set up technological parameters of die casting machines, especially of plunger speed during mould cavity filling on physical and mechanical properties of castings produced in the die casting process which are represented by ultimate tensile strength and by the porosity of castings.

3.1 Evaluation of ultimate tensile strength

Ultimate tensile strength ranks among basic quantities for the evaluation of the mechanical properties of castings. The final ultimate strength of the individual testing specimens was evaluated independence on change of plunger speed during mould cavity filling which was on the levels of 3.5; 4.5 and 5.5 m.s^{-1} with standardly pre-set pressure or holding pressure value of 28 MPa. The measured values of ultimate tensile strength about the change of pressing speed in the mould cavity are shown in Table 7.

Table 7. Ultimate tensile strength values Rm depending on the change in pressing speed

Sample No.	Plunger speed v_p [m.s^{-1}]	Pressure [MPa]	Ultimate tensile strength R_m [MPa]	Average tensile strength R_{mp} [MPa]
1.1	3.5	28	175	176.3
1.2			184	
1.3			170	
2.1	4.5		159	149
2.2			147	
2.3			141	
3.1	5.5		115	119.6
3.2			123	
3.3			121	

The course of the measured values of ultimate strength as a function of the change of pressing speed in the mould cavity is in Figure 9.

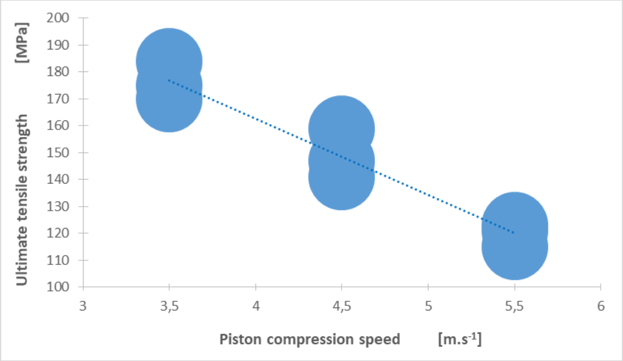

Figure 9. Dependence of ultimate tensile strength on change of piston compression speed

Figure 9 shows a comparison of values of ultimate tensile strength about a change in pressing speed and holding pressure. At higher speed values, detected was the slight mould opening with consequent injection in the dividing plane in the course of the forcing-in process. In dependence on the cross-section of the gating system, the speed was increased in the course of filling. About diverse mould cavity filling speed values, various types of filling could occur such as laminar filling, turbulent filling, or their mutual combination.

3.2 Evaluation of casting porosity

Completion of evaluation tests of ultimate tensile strength independence on change of piston compression speed in the mould cavity was followed by an examination of the inner structure and porosity of the castings with the application of testing bars. Apart from the aforementioned, the specimens were taken also from other parts of the castings which were identified as the point of the possible increase of porosity occurrence.

The porosity of the casting was evaluated by the optical microscope with a subsequent image import to have it analyzed and processed by the software Stream Motion (Fig. 10). The porosity of the casting is evaluated with the use of graphic filters in the program Stream Motion. Each of the filters disposes of defined sensitivity which prevents the intervention into the detection zone of another filter. Before measurement, the filters must be set to adequate sensitivity so that just the pores are evaluated. The setting is followed by the analysis of the objects in the images which differ in colour from their environment and meet all the required conditions. The program saved the results of all specimen values in the tables out of which the individual graphical dependences were generated.

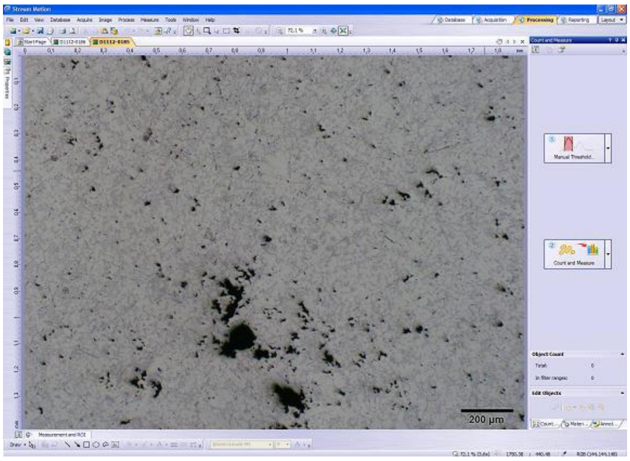

Figure 10. Evaluation of porosity in the Stream Motion

Figure 11 shows photographs that were used for the casting porosity analysis. In the case of each specimen, three independent spots were selected in which measurement and evaluation of porosity were conducted. The selected spots had to be perfectly polished as each scratch or other dent or crack of the specimens could be evaluated as the pores by the software and the results of porosity measurement would be thus misrepresented. Probably, it would be the case of a higher percentage of porosity occurrence contrary to the actual situation.

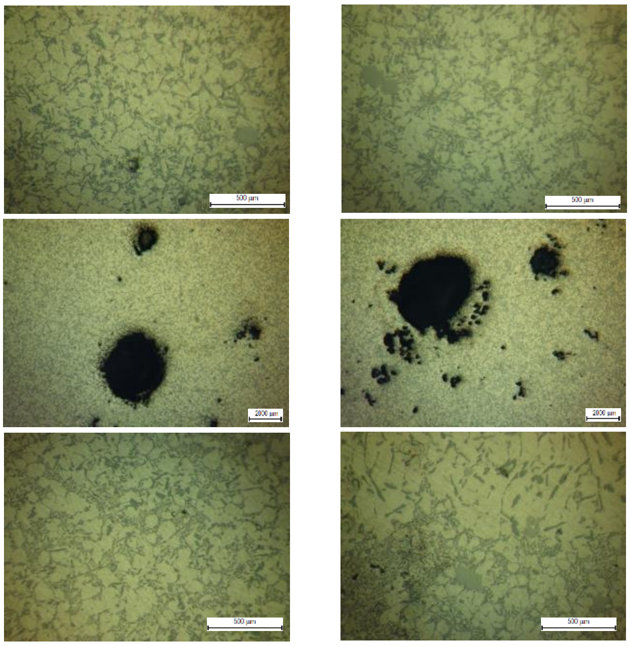

Figure 11. Metallographic photographs of specimens examined by the optical microscope

The measured values of porosity about the change of pressing speed in the mould cavity are shown in Table 8. The course of the measured values of ultimate strength as a function of the change of pressing speed in the mould cavity is in Figure 12. The measured porosity values of the examined samples pointed out the influence of the change in the pressing speed of the piston on the inner structure of the casting. As the compression speed of the piston increases, we can observe in Figure 12 increasing the porosity values of the casting. Since different types of mould cavity filling occur at different press piston speeds, we can state that the porosity is dependent on the mould cavity filling mode.

Table 8. The porosity depends on the change in pressing speed

Sample No.	Pressing speed v_p [m.s^{-1}]	Pressure [MPa]	Porosity P [%]	Average porosity P_p [%]
1.1	3.5	28	2.15	2.49
1.2			2.74	
1.3			2.59	
2.1	4.5		2.89	3.29
2.2			3.78	
2.3			3.21	
3.1	5.5		4.58	4.22
3.2			4.12	
3.3			3.98	

The measured values of the porosity of the examined samples indicate the influence of the change of the pressing speed of the piston on the internal structure of the casting, ie. porosity. As the compression speed of the piston increases, we can observe in Figure 12 increasing the porosity values of the casting, which is very undesirable in castings. As the filling cavity of the mould cavity increases, a turbulent flow of melt into the mould occurs and at the same time, the melt turns into a dispersive mass, which results in an increase in porosity in the resulting casting. To reduce the porosity, it is necessary to select such filling speeds of the piston which do not promote the formation of dispersion and cause exclusively laminar flow of the melt into the mould. During the laminar flow of the melt into the mould, no disperse mass is formed from the melt, which is a guarantee of low pore formation in the castings. Since different types of mould cavities fill at different press piston speeds, we can state that the porosity depends on the melt filling mode of the mould cavity.

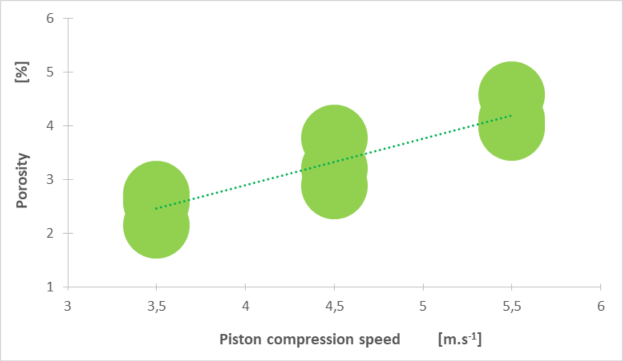

Figure 12. Dependence of porosity of the casting on change of piston compression speed

4 CONCLUSIONS

The conducted experiments serve for assessment of the influence of technological parameters such as plunger speed on mechanical and utility properties of castings being produced in the die casting process. When the results had been evaluated, it could be assumed that ultimate tensile strength decreased, and porosity occurrence increased in case of an increase in the pressing speed of the plunger. In the case of lower values of plunger pressing speed, the share of porosity occurrence was lower which pointed out the laminar development of mould cavity filling with the melt. The results of the individual tests and measurements confirm, from a scientific point of view, the theoretical premises of the influence of the pressing speed of the plunger on the change of ultimate tensile strength and porosity of castings [Pasko 2014, Majernik 2016].

When examining the influence of the pressing speed of the plunger on ultimate tensile strength, the measured values of ultimate tensile strength tended to decrease in dependence on the increase in pressing speed of the plunger. Contrary to a single moment during which a considerable increase of ultimate tensile strength was detected at the highest pressing speed of the plunger, the entire development of dependence was similar to one of the values mentioned by the authors [Pasko 2014, Majernik 2016, Zhang 2020b, Cai 2021]. About the aforementioned facts, it has been proved and confirmed that mechanical properties are considerably influenced by mould cavity filling mode and thus lower values of castings speed of plunger are recommended to be opted for.

The measured and evaluated values of the individual examined properties proved that the selected technological parameters, to a high degree, influenced both the final properties and the quality of castings produced in the die casting process. The technological parameter under monitoring – pressing speed of plunger or mould cavity filling speed along with mould cavity filling mode rank among the basic factors influencing final casting quality most. Naturally, several other parameters such as melt temperature and cooling influenced the final properties of castings as well. These parameters in the form of cooling speed and of mould temperature remained constant. Structural parameters were influenced only by the melt temperature which is related to mould cavity filling speed. Melt speed depends on temperature because increasing temperature results in a decrease in the melt viscosity which causes an increase in its mobility under the action of the same pressure. As the melting speed is also determined by the mould cavity filling, it influences the melt cooling speed, too, due to the melt volume change in the course of the time when being in the contact with the mould surface following which the phenomena occurring in the mould cavity are mutually related and final properties of casting are influenced.

At the same time, the research proved the connection between the mechanical properties of the casting and the inner structure. Based on the results, a higher concentration of pores and cavities causes a considerable decline in strength in case of which a higher percentage porosity share led to a lower ultimate tensile strength value at the same pressing speed of the plunger. Contrary to the aforementioned, lower porosity share led to a higher ultimate tensile strength value at the same speed, too.

A higher porosity value at a higher mould cavity filling speed points out a lower degree of mould cavity filling which is caused by dispersed melt flow. Lower porosity values occur at lower mould cavity filling speed in the case of laminar melt flow. From the point of view of mould cavity filling speed, higher ultimate tensile strength, and lower porosity it is desired to opt for a lower pressing speed of plunger or of mould cavity filling with the melt.

Regarding the comparison of the conducted research, a conclusion is possible to be drawn – the influence of ideal input conditions of the production process on the final quality of castings cannot be ambiguously and generally determined. The measured and evaluated data can be considered to be specific and valid for the particular combination of the selected technological parameters in both cases. The final quality and the examined quality properties depend on several other criteria such as melt and mould temperature, melt composition, the complexity of casting, and parameters of production equipment. etc. In an evaluation of results, it is inevitable to take into consideration testing conditions and the possible occurrence of faults.

From the point of view of acquiring the required quality of castings, increasing the production effectivity, and decreasing the occurrence of faulty pieces in production, the optimal setting of technological parameters of die casting is rather significant which has also been unambiguously confirmed by the research. To prevent a decrease in the final quality of castings, in the future it is desired to conduct research in different operation plants producing castings. In cases in which the companies use a higher amount of returnable material, it is recommended to plan the checks of properties of castings at particular intervals to prevent undesired changes in the melt composition and the final quality of the casting. Companies with the increasing trend of customers´ complaints or of occurrence of defects or faults of produced components should implement into the production process the check aimed at testing mechanical properties and of inner structure about applied input technological parameters influencing the final quality of castings. Even though activities related to checks and additional testing influence the costs which thus increase, it is a good investment for the companies to assure the increase of quality and to satisfy the demands of customers.

From the point of view of science, the achieved results of experimental measurement confirm the theoretical premises of dependence of ultimate tensile strength and porosity of castings on change of plunger speed. At the same time, the achieved results will serve as a ground for the technical preparation of the production of castings. In case of requirement for optimization of properties and the final quality of castings, the values of the examined technological parameters will be used as the starting point from the point of view of quality demands for the individual qualitative types of produced castings. The achieved results proved that it is inevitable to take particular precautions in case of the optimization of input technological parameters in the process of die casting such as decreasing plunger speed so that laminar melt flow in the mould cavity is achieved. About the adjustment of the values of the selected technological parameter, the increase of ultimate tensile strength is achieved along with the decrease in the percentage share of porosity occurrence in the castings. Knowledge describing the mutual bond and relation between technological parameters of die casting and the final properties of castings represents a significant aspect from the point of view of technological practice which influences the required final quality of castings and increases the effectivity of the entire production process.

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