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DESIGN OF CASTING AND GATING SYSTEMS – PRIMARY PREDICTION OF QUALITY OF DIE CASTING COMPONENTS

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TECHNICAL UNIVERSITY
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DESIGN OF CASTING
AND GATING SYSTEMS
– PRIMARY PREDICTION OF QUALITY
OF DIE CASTING COMPONENTS

By

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2021

Key words: *die casting, projection of castings, projection of gating systems, structure of molten metal die casting, quantitative properties of castings*

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Abstract

The monograph points out a current state of knowledge in the sphere of production technology of castings by die casting and in chronological order it describes die casting technology of metals as well as the die casting machines utilized within the frame of the technology. The cornerstone of the monograph is devoted to description of die casting moulds. The authors focused on structure of die casting mouldswith the stress laid on the projection of castings and gating systems. Fundamentals of hydrodynamics of molten metal flow in the mould cavity along with basic and structural parts of the moulds as well as production process and launching the moulds into production are analysed in detail. Emphasize is also put on clarification of regularities and aspects of suitability and of manufacturability of die casting component parts and of projection of gating systems. Based on the results of the selected experiments realized by the team of authors, the analysis of influence of structural modifications of the respective parts of the gating system on quality of castings was carried out with regards to elimination of gas entrapment in the molten metal volume which, as the monograph presents, directly affects the quality of casting properties. The results of the experiments realized under operating conditions as well as of those performed by means of simulation software support and move towards recommendations for industrial practice from the point of view of achieving the maximum level of effectiveness and quality of production of aluminium castings through die casting technology. The monograph is intended mainly for students, postgraduates and pedagogues at technical universities as well as to for broad scientific and expert public and technologists and foundry shop workers.

Contents

Introduction

Die casting represents the method of precise casting and approaches the ideal effort to change basic material into a final product. Castings produced in die casting process are characterized by rather high preciseness, smooth surface, thin walls, and positive mechanical properties. At the same time, the castings produced in die casting process it is possible to pre-cast openings of small dimensions, they require negligible sufficient machining, in several cases they represent final products intended for assembly, they correspond with the requirement for replacement of component parts and low weight offers substantial material saving.

Currently, any engineering industry with series production character successfully uses castings produced in die casting process which contain alloys of zinc, aluminium, magnesium, and brass. Automotive or aviation industry utilizes die casting as a sole method assuring economic die casting of high amount of quality castings.

Mechanical properties of castings are closely related to their inner structure, especially to content and distribution of pores and cavities in the volume of castings and, naturally, to the material structure. The monograph presents this issue as a serious drawback of castings and therefore it contains knowledge verified by industrial practice for the purpose of presentation of methods oriented towards reduction and elimination of defects caused by a design of component parts produced in die casting process. The experimental part presents selected experiments confirming by visual demonstration the knowledge and the recommendations included in the theoretical part. A series of experiments was carried out which point out influence of an ingate and of the sprues on mechanical and structural properties of castings with regards to gas entrapment in the molten metal volume and further distribution to the casting.

Endeavour of the authors is to publish a monograph fully describing the issue of designing and constructing of castings along with appertaining gating systems to assure manufacturability of projected parts and defect-free operation of foundry processes in foundry plants.

Methodical Procedure of Publication

Theoretical foundations in the sphere of die casting are on high level. The WoS and Scopus databases offer several publications dealing with the issue. Prevailing part of publications is devoted to technology as such and revolves around the influence of technological parameters on quality of castings. Therefore, the authors decided to publish this monograph solving the issue of design of castings and gating systems in detail.

The authors of the monograph have been experienced in the field of foundry industry with the focus of activity aimed at die casting for many years. Their research work has been revolving around the issue of influence of technological parameters, design of structural nodes of gating systems and their correlations in relation to final quality of castings. Although the publication specializes in the area of production technology in foundry industry, without proper knowledge and information on technology of foundry process the structure itself would not bring desired result.

The information summed up in the publication reflect the knowledge of designing the die casting parts which the authors gathered when dealing with national and international grants and projects as well as by means of solving production issues in the foundry plants.

1. Technology of Metal Die Casting

Die casting is characterized by replacement of gravitation metalostatic pressure by a plunger force acting upon the melt in the filling chamber of the die casting machine. The aforementioned refers to a mechanical mode of casting in case of which the liquid metal is pressed under pressure into split metal mold by the plunger acting upon the melt in the filling chamber. By means of plunger speed in the order of meter units per second the melt is transferred by the gating system from the filling chamber through the ingate into the mold cavity. The total period of mold cavity filling is very short - ones and tens of milliseconds. This method of mold cavity filling allows production of thin-walled shape-demanding castings with high dimensional accuracy and with an exact surface relief profiling of a mold cavity [6].

The procedure of mold filling is not subjected to gravitation influence as in the case of casting into sand or into cast-iron molds yet it rests in the change of pressure energy into kinetic one. Therefore high speeds occur in the die casting mold in the course of filling and afterward during final filling kinetic energy of the filling system changes into pressure energy. The complexity of the issue of the die casting mold filling rests in the fact that factors such as casting structure and mold heat balance usually determine the actual melt flow. At the same time high speeds of the melt in the ingate complicate the flowing liquid transit as from certain speed probably disperse mold filling occurs when in the flat ingate the melt is divided into the individual interrupted flows up to dispersion of mixture of the air and the melt. The quality of castings cast under pressure is influenced by a number of factors. One of them is a proper structure of the casting mold which includes mainly gating and venting and cooling systems of the mold. The quality of castings is also affected by other factors such as a die casting machine, a type of cast alloy and its metallurgical processing, the quality itself of the produced mold, the set technological parameters, and last but not least, attendance of die casting machine. Optimal structural design of the mold and setting of all technological and metallurgical parameters presuppose production of high quality casting. Therefore in production of castings necessary is to utilize high-quality production equipment including melting, the melt treatment, and die casting machine with properly selected gating system[10][21][22].

Basic technological factors in case of metal die casting include the following:

- pressing speed in the course of casting cycle,
- specific pressure acting upon the melt and increase pressure,
- period of mold cavity filing,
- cast alloy temperature, filling chamber temperature and mold temperature.

These factors influence each other and that represents a complex of reciprocal bonds among alloy character, mold structure, filling period, and efficiency of die casting machine, i.e. comprehending of relations within the entire casting process from the commencement of the mold cavity filling up to the casting solidification in the mold.

The technology has brough several advantages into foundry industry and metal shaping has been provided with new dimension.

Univocally, die casting advantages include the following:

- possibility of production of castings with low dimensional tolerances, quite often without machining,
- smooth surface of castings,
- satisfactory mechanical properties of castings with respect to finegrained structure,
- possibility of production of thin-walled castings,
- low waste production and consequently lower input material costs,
- in case of castings the openings of even small diameters with minor additional machining are possible to be precast,
- possibility of production of complex-shaped components,
- simple application of cast inserts made of other metals or of some non-metal materials.

Despite the mentioned positives, die casting cannot be considered as solely advantageous production method as certain advantages have appeared as well.Yet those are rather irrelevant with respect to overall production effectiveness and returnability, still must be taken into consideration.Therefore the following disadvantages of die casting are necessary to be pointed out:

- high costs related to mould production,
- high investments into machines and other equipment,
- die cast alloys are of lower ductility,

- with respect to danger of formation of surface bubbles the die cast casting is not possible to be used at temperature higher than approximately 350°Cif the temperature is permitted for respective alloys,
- maximum casting size is limited by machine size,
- castings are to certain extent porous yet porosity can be controlled and regulated,
- castings made of aluminium alloys are difficult to be provided with colorful eloxal coat (eloxal coat is grey and black and uneven),
- castings made of brass and partially those made of aluminium alloys dispose after several thousands of operations, sometimes even sooner, of mould cracks (further casting deteriorates the situation and the castings in case of which surface treatment is desired are demanding as to higher costs related to grinding and polishing,
- die casting requires certain working experience and therefore qualified professionals with long-term experience are required.

1.1. Die Casting Machines

Die casting is performed with the die casting machines belonging into the group of hydraulic presses. By their structure the die casting machines must assure the following:

- safe mould locking,
- filling of die casting mold cavity with liquid metal by adjustable speed and pressure,
- casting solidification at set time,
- mould opening,
- extraction of cores,
- casting ejection out of a mould.

Die casting of metals is a process utilizing die casting machines which are classified as per machine technological structure as follows:

<u>1) Hot-chamber die casting machines:</u>

a) with metal pressed by a plunger,
b) with metal pressed by air.

2) Cold-chamber die casting machines:

a) with vertical pressing mechanism,
b) with horizontal pressing mechanism.

1.1.1. Hot-Chamber Die Casting

With the hot-chamber machines the metal is forced into the mould by a plunger moving inside the filling chamber (Fig. 1) or the metal is pressed by compressed air at pressure from 2 up to 7 MPa.The machines are used for die casting of metals with low melting point such as alloys of copper, lead, zinc and magnesium.

In both cases the chamber gets narrower in the gooseneck with the nozzle at the end which is prior to metal pressing pushed against the gate opening of the fixed part of a mould. In its upper, starting position the plunger does not overlap the gate opening and thus the molten metal flows out of the melting pot directly into the chamber. When the plunger moves inside the chamber, the gate opening gets overlapped by means of which spontaneous and excessive flow of molten metal into the chamber is prevented. The plunger forces the molten metal through the nozzle into the mould cavity. Consequently, during holding period lasting several seconds the metal solidifies in the mould and the casting is formed. When the holding period ends, the plunger acts backwards and the gate opening of the chamber opens again. The chamber is filled with further dose of the molten metal and simultaneously the liquid metal flows out of the gooseneck back to the chamber. At the same time the active part of the mould opens which carries along the casting. The casting is released in the ejector and grasped by tongs or any device and transferred to the palette. Consequently, in its open position the mould cavity is sprayed with greasing solution. The mould is then locked, and the device returns to initial state and the entire cycle is repeated. [28].

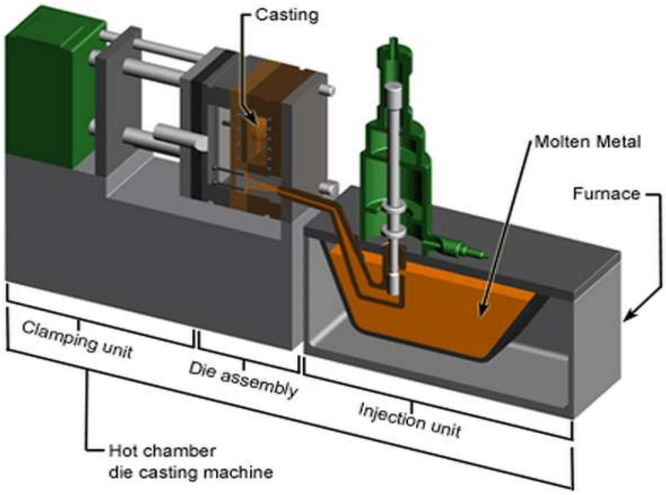


Fig.1 Hot-chamber die casting machine [8]

1.1.2. Cold-Chamber Die Casting

Cold-chamber die casting machines are used for casting of high-melting alloys of aluminium, magnesium, brass, and iron. The holding furnace with the melting pot containing molten metal is not part of the cold-chamber machines. The furnace is built separately, and the molten metal is fed to the chamber of the machine prior to each pressing [15][27].

Vertical Cold-Chamber Die Casting Machines

The vertical cold-chamber die casting machines consist of a vertically positioned cylinder, the nozzle, the pressing plunger, and the lower plunger with a spring. In its initial position the plunger is pushed above the chamber with the liquid metal being poured into it. Acting downwards the plunger affects the molten metal and presses the lower one by means of which the nozzle is exposed. The molten metal is forced to the mould cavity through the nozzle. During holding period, the metal solidifies in the mould cavity and then the pressing plunger returns to its initial position. The force of the spring located below the lower plunger forces the plunger to act, trims the metal tablet which was formed during solidification of the metal in the chamber and removes it out of the mould. Then the mould opens, the casting is ejected, and the mould is sprayed with greasing solution. The mould is locked, and the cycle is repeated [27].

Horizontal Cold-Chamber Die Casting Machines

The operating principle of the horizontal cold-chamber die casting machines (Fig. 2) is as follows: horizontally positioned chamber disposes of the pouring hole intended for molten metal to be fed in. The plunger moves inside the chamber. The inner opening of the filling chamber must pass through the fixed part of the mould unless it reaches the dividing plane. In metal casting the plunger is situated in the backward position to assure release of the pouring hole. Forward movement of the plunger forces the metal to the mould cavity. The pressing and the holding period are followed by the mould opening and the plunger forces the metal tablet out of the filling chamber. After opening, the plunger returns to its backward position. Then the mould opens, the casting is ejected, and the mould cavity is sprayed with greasing solution. Consequently, the mould is locked, and the cycle is repeated [27].

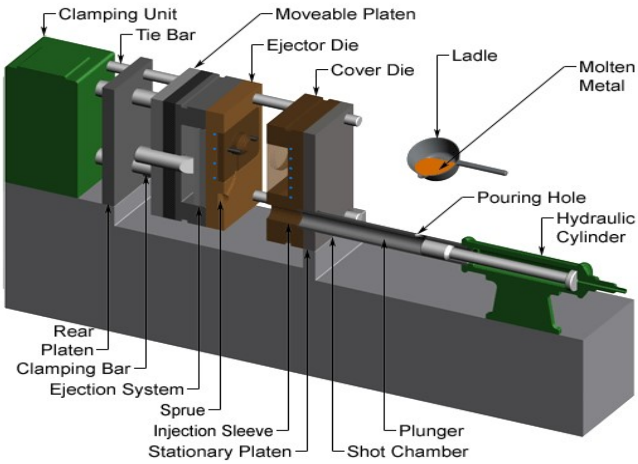


Fig. 2 Horizontal Cold-chamber die casting machine [8]

1.2. Technological Parameters of Metal Die Casting

The quality of diecast parts is influenced by a number of factors. From the point of view of structure of considerable influence are correct design, gating system, venting system, tempering system, and selection of a suitable moulding press. Important is to mention the influence of type of casting alloy and of its metallurgical processing along with maintenance and the state and greasing of the mould quality. Of a considerable impact is the machine attendance. A separate group of factors includes technological parameters related to die casting[23][25].

Those can be categorized as follows:

- moulding press parameters,
- temperature parameters of die casting process,
- parameters following from the melt properties.

1.2.1. Pressing Mechanism Parameters

The main task of the pressing mechanism is to transfer and to press the molten metal to the mould cavity in accordance with prescribed technological parameters and to assure continuous and consistent mould cavity filling.

The entire pressing process can be classified as follows: (Fig.3 – Fig.5):

Ist phase – pre-filling of the filling chamber (segment $x_0 - x_1$)

After filling of the chamber by the molten metal the pressing plunger starts to move. The plunger moves at rather low speed v_1 and with low pressure value p_1 in the course of rather long period of approximately 300 ms until the plunger passes through the gooseneck. In this phase turbulence of the molten metal and air intake must be prevented.

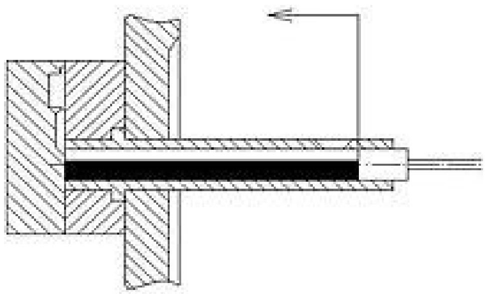


Fig. 2 Istpressing phase [25]

IInd phase – mould filling (segment $x_1 - x_2$)

When the molten metal reaches the ingate, the filling is commenced, in the segment from $x_1$to x_2 rapid acceleration can be observed from speed v_1 to pre-set speed v_2 with higher pressure value p_2 which is needed to overcome the resistance of this phase, The gating system and mould cavity are filled with the molten metal at shorter time (40 - 50ms). Clearance between the pressing plunger and chamber drilling is used to discharge the gasses above the molten metal surface.

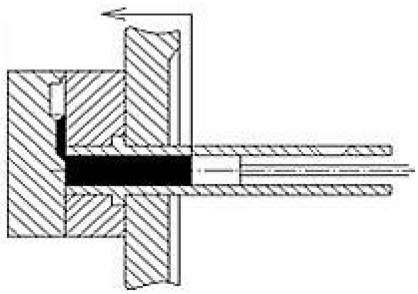


Fig. 3 IInd pressing phase [25]

<u>IIIrd phase – pressure (segment $x_2 – x_3$)</u>

When the pressing plunger halts, pressure p rapidly increases up to operating pressure p_{operp} and by means of a multiplier it reaches the values of holding pressure p_{holdp} and then pressing commences. Time of pressure increase moves up to the value of approximately 7ms and must be lower than 20 ms to prevent solidification of metal in the ingate. Consequently, melt solidification in the mould cavity can be observed which lasts for about 6 – 10 seconds.

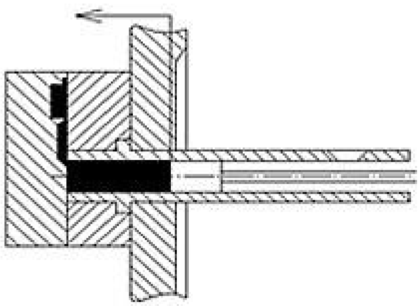


Fig. 4 IIIrd pressing phase[25]

Fig. 6 shows development of technological parameters of the pressing system in dependence on position of the pressing plunger in the filling chamber.

Holding pressure should replace gravity feeding of the melt to blank areas in the cast and supress clustering and expansion of gas bubbles during crystallization of the cast (a condition to be met is sufficient hydraulic connection of the mould with the gating system). To reach higher holding pressure the multiplier is used which represents a part of a diecasting machine. Modern die casting machines allow regulation of distribution of pressing plunger motion and speed according to mode of mould cavity filling in relation to the cast shape, the gate structure, the ingate area and the alloy used.

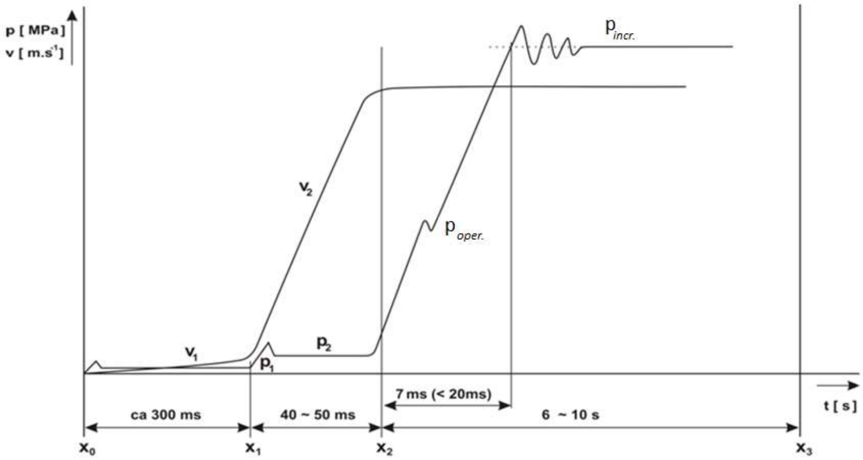


Fig. 5 Development of technological parameters in individual pressing phases [27]

The interpretation of the effect of individual casting conditions or their interaction concurrence upon the quality of the casting is issued from the conception of a mold cavity filling. This conception results in useful conclusions about the appropriate shape of the gating system, position of ingates and direction of the melt flow towards the ingate shape. Complexity of the issues on filling the die casting mold is the fact that factors such as the casting structure and thermal balance of a mold generally determine the actual melt flow. Also, high melt speeds in the ingate aggravate the concept of fluid since the dispersion filling starts at a certain speed. It is implicit that basic parameters of die casting are a mold cavity filling time and the melt speed in the ingate. Filling time must ensure the complete filling of a mold cavity before the effects of solidification could adversely affect it. Solidification starts simultaneously with the filling, which makes the filling more difficult, because the viscosity of the liquid metal is constantly increasing and the fluidity is reducing. Energy of motion is supported by pressing force induced by a pressing plunger in the filling chamber. It can be assumed that there is not any contact between the melt and a mold face occurred because before the melt drops on a mold wall a surface layer on the molten metal is managed to be created. Under the condition of castings production made of the alloy of the same chemical composition the structural parameters are affected by the cooling speed and the pressure. Cooling speed is primarily controlled by temperature of the cast mold and heat content of the cast alloy (casting temperature). Under the condition of the same mold temperature the structural parameters shall be affected only by the casting temperature and the pressure determining the melt speed in a mold. The melt speed depends on its temperature since as the temperature is increasing the viscosity of the melt is reducing which causes the increase of its mobility when exposed to the same pressure. The melt speed is determined by the filling mode, i.e. a degree of melt turbulence in a mold by which it contributes, with a certain share, to the cooling speed of the casting because the change of turbulence degree results at the time in the change of melt volumes meeting a mold face. Turbulence degree significantly affects the internal soundness of the casting, i.e. the type and extent of internal defects. The mutual interrelatedness, conditionality and complexity of effects occurring in a mold cavity during the die casting are implicit[25][28].

Plunger Pressing Speed during Casting Cycle

Pressing speed of a plunger is a determining factor of the mould cavity filling mode. It influences melt speed in the ingate. Selection of suitable pressing speed depends on several factors, mainly on type of casting alloy and on cast dimensions.

Measuring the flow speed in the ingate has proved that the actual speed is only 30 to 50% of the calculated theoretical speed and only 5 to 15% in a mold cavity thereafter. Actual speed is affected by viscosity of alloy, flow friction losses in the ingate and a mold cavity, losses caused by changing the flow direction.

Speed of the alloy flow in the ingate affects mechanical properties of the casting and thus acts on the internal and surface quality of castings.It is important to determine the optimal value of such speed, e.g. its increase above the optimal value recorded a strength decrease due to adhering of the alloy in the ingate. This can be explained by the fact that increasing the alloy flow speed caused a gradual washing off the initially formed crust on a mold wall. A further speed increase in the ingate can completely wash off the crust and the parallel of dry friction occurs between the alloy flow and a mold material. As a result, there is a rapid temperature increase on the surface of a mold cavity and an accelerated diffusion of the alloy element into the hot mold surface. After solidification it is manifested as intense adhering of the alloy in the ingate areas [21][27][30].

Fig. 7 shows dependence of optimal speed in the ingate on prevailing thickness and length of the casting.

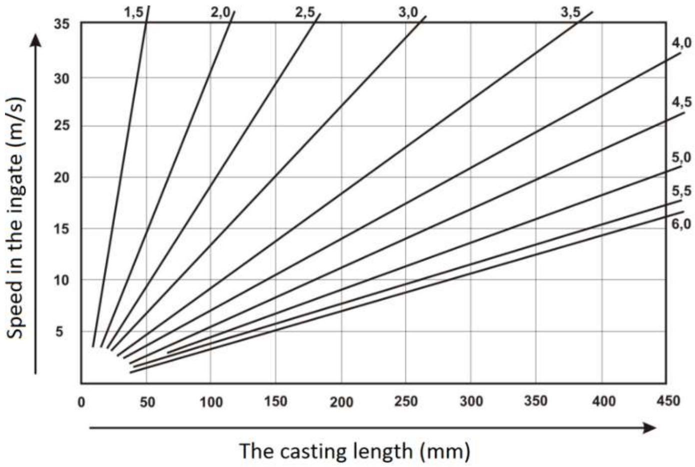


Fig. 6 Dependence of optimal speed in the ingate on the characteristic dimensions of the cast [27]

This dependence was devised on the basis of recognizing the nature of the metal flow in a mold at different filling speeds. The following is distinguished:

- low filling speeds from 0.6 to 1 m.s-1 providing solid laminar filling,
- medium filling speeds from 1 to 15 m.s-1 providing solid turbulent filling,
- high filling speeds above 25 m.s-1 inducing distribution of the solid flow and emergence of the dispersion flowing.
-

Specific Pressure Acting upon Alloy in Casting Cycle

From the physical point of view, the specific pressure can be defined as hydrodynamic pressure. Hydrodynamic pressure acts in the liquid metal flow in the process of the die casting mold filling. It arises as a result of resistance during the metal motion passing through the thin mold cavities and during the cores bypass, reversals, the flow reduction and expansion. In the absence of such resistances the value of the hydrodynamic pressure in the flow is determined by air and gases back pressure the removal of which is obstructed due to venting system. Accuracy of the relief molding and the casting surface roughness depend on kinetic energy of the flow.

To overcome the resistance of solidifying metal mass in thin cross sections of a mould cavity and also the resistance of gases remaining in the casting a large hydrostatic pressure is inevitable. It is transmitted from a pressing plunger through the gating system.The process of transferring the hydrostatic pressure into a mould cavity is called holding pressure.

The process of hydrostatic pressure transfer to mould cavity is referred to as holding pressure.

At present, the holding pressure represents one of the most discussed factors of die casting. On the one hand, its high value reduces service life of moulds and prolongs idle time of die casting machines, however, on the other hand it increases filling-up of the casting and diminishes the air volume entrapped in the casting volume through which the quality of castings increases. Magnitude of holding pressure value (of specific pressure in the mould cavity) is in úractice determined individually according to the cast type of casting and alloy.In case of castings upon which high strength and tightness requirements are laid, the holding pressure of approximately 60 - 100MPa is used [25].

Mould Cavity Filling Time

Mould cavity filling time has a significant effect upon the quality of the casting surface as well as its internal soundness.Short filling time does not allow the gases and vapors to escape from a mould cavity in a necessary extent. They entrap in the casting walls and its internal soundness is thereby reduced, although the surface quality is satisfactory. Long filling time of the cavity allows the gases prior to the proceeding alloy front in a mould cavity to be delivered through a mould venting system. In this case, the internal soundness of the casting is satisfactory, however, due to alloy temperature reduction in the flow fronts during long filling a complete interconnection shall not occur in all locations where the alloy flow meet, but dry joints and internal cold laps emerge. These defects are particularly dangerous in parts which are stressed by a dynamic cyclic stress because dry joints have notch effect. Therefore, the optimal filling time is a compromise between the long and short time of a mould cavity filling. Such time must be shorter than time of the casting solidification in a mould. Influence of filling time on the cast quality is shown in the graph in Fig. 8.

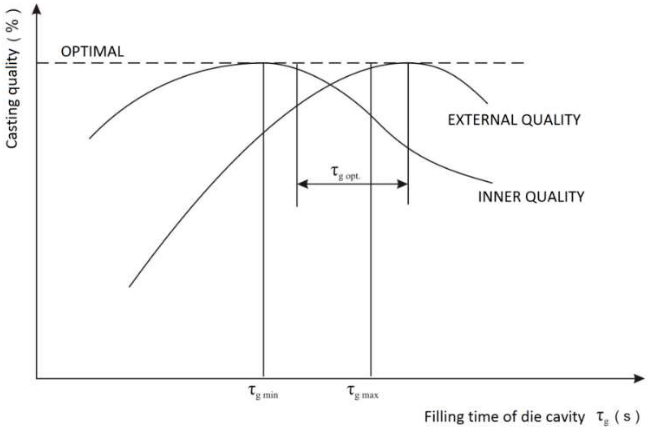


Fig. 7 Influence of filling time on cast quality [27]

Calculations and experiments show that under the condition of constant thermal and physical characteristics the filling time depends solely on cast wall thickness, not on its dimensions. Optimal filling time of mould cavity is given by the diagram in Fig. 9[25].

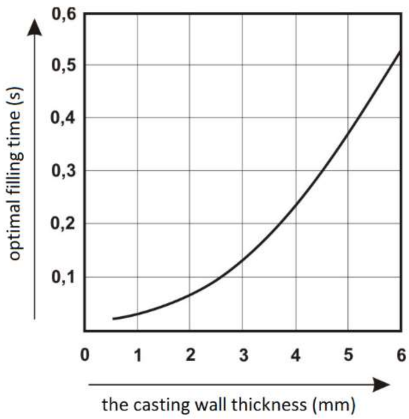


Fig. 8 Filling time dependence on the casting wall thickness

1.2.2. Thermal Parameters of Die Casting

Temperature parameters influence behaviour of the melt in the mould press from the period of dosing to removal of the solidified diecast part out of a mould cavity. The parameters include especially the following:

- molten alloy temperarture,
- loading chamber temperature,
- mould temperature.

Important assumption for the production of quality castings is observing an optimum temperature of individual parts of a mold cavity surface. This depends on the material temperature, the amount of metal, the cooling method of the casting mold, thermal conductivity of a mold material and dwell time of the casting in a mold. Casting of excessively hot material into the cold mold with insufficient surface insulation due to a suitable lubricating agent causes enormous stress to surface layers of the casting mold material. When casting the alloy into a mold with insufficient temperature of a mold cavity surface a premature temperature reduction of the alloy occurs. The castings have dry joints, cold laps emerge on the casting surface and even the seemingly satisfactory castings lack the necessary quality because enormous internal strains in material structure occur due to major undercooling. In some cases this is reflected by fine surface cracks. It is well known that a mold temperature after casting the melt into a mold is non-constant. The first casting usually contains defects such as dry joints and surface cracks. Main cause of these defects is a non-constant mold temperature that is being stabilized due to heat exchange, mold – casting, after at least seven cast castings. A mold temperature is closely related to the filling chamber temperature. The chamber should be preheated before casting in order not to decrease the cast alloy temperature before filling a mold cavity. The hot chamber determines a structure or more precisely a machine type, and it applies maximum use in casting the castings of lower weight category with a lower alloy melting point. Observing the optimum temperatures of a mold face is necessary in close range to achieve proper dimensional tolerances of the castings. Proper temperature of the die casting mold during a cycle of the casting solidification and cooling is ensured by so-called tempering system. Heat transfer from the casting into a mold depends on the temperature of the cast metal, a mold material, the treatment of mold cavity active parts, the casting wall thickness, but also on duration of the melt contact with a mold. The presence of extra fine crystals in the casting zone beside a mold face is typical for die castings, which is documented in Fig. 10.

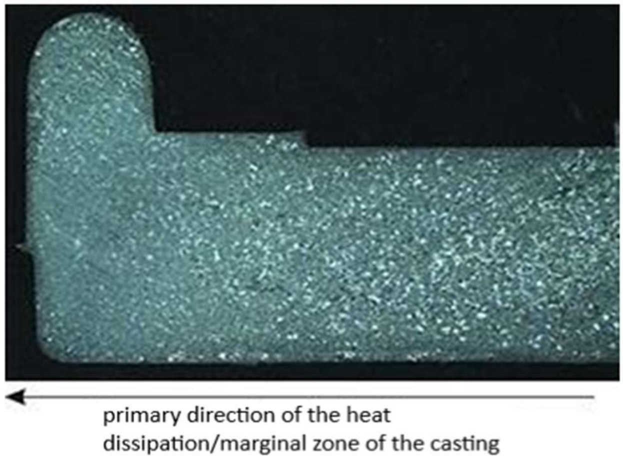


Fig.9 Microstructure of a peripheral part of alloy sample Al-Si[15]

Thickness of this zone is different, ranging from a few µm up to 1 mm. The zone transition of fine crystals into a thicker structure is smooth. Emergence of the fine structure zone is related to a degree of undercooling beside a mold face which depends on a mold temperature as well as the ingate location and manner of a mold filling. In the process of casting the alloy into a mold with a high temperature of a mold cavity surface a diffusion of an alloy element into the overheated mold surface occurs. After solidification it is manifested by an intense adhering of the alloy on a mold and the range of bubbles and porosity increases. Increased speed of cooling castings in the metal mold compared to the sand mold causes the increase of thermal gradients in the casting. As a result, the solidification speed is increasing. Increased thermal gradients reduce the zone of crystallizing alloy in the temperatures range. Despite this fact, an intense heat exchange between the casting and the metal mold adversely acts on fluidity which increases the risk of uncast and dry joints especially in thin-walled castings. One of the basic questions concerning thermal regime of metal molds is the calculation of solidification and cooling time of the casting in a mold. Labor productivity and accuracy of calculations in designing the casting machines depends on precision of this calculation [15].

1.2.3. Parameters Stemming from the Melt Properties

The properties of the melt and method of its preparation considerably influence the quality of a diecast part. Basic technological parameters following from the melt properties include the following:

- tendency to gasification,
- tendency to formation of contractions.

Tendency to gasification is characterized by the ability to dissolve in the melt. The alloys used in die casting technology should be melted only to minimal temperature, which is sufficient for casting. The precaution is based on the fact that the overheating of the melt results in increase of its tendency to gasification. Low temperature decreases absorption of gases to a minimal acceptable degree and provides the metal with higher strength and tensibility. Generally accepted is the statement that amount of gas absorbed by the melt is directly proportional to the formation of bubbles in the walls of a diecast part. Tendency to formation of contractions is represented by decline in metal during the period of its solidification. Casting of the alloy extremely prone to formation of contractions results in structural incompactness of the diecast part [6].

Effect of Gases Molten in Alloys

Processes of air, gases and vapors abstraction out of lubricating agents during mold filling with the alloy affect the castings quality. It is assumed that approximately 90% of pressing mechanisms force in die casting machines is used to overcome the gas back pressure contained in a mold during working cavity filling with the alloy. Experimentally and theoretically it is proved that the maximum pressure of gases in a mold during filling with the alloy is ≤ 0.5 MPa. Observing this variable is essential because it is influential for casting pressure efficiency which helps to increase the castings quality. With all the melts containing gases, there is a significant decrease of their solubility in the alloy during self-solidification. During fast solidification of the alloy there remains higher amount of dissolved gas in it and even in the solid form as during slow solidification. Therefore, at low gassing during melting and thin walls of the casting a risk of porosity caused by gas content in the melt is smaller than in thicker walls and slow solidification. As soon as conditions are favorable for the gas elimination, i.e. if the melt contains higher amount of gas, the casting wall is thicker or it cools more slowly due to inconvenient removal of certain mold location, the gas inside the casting wall has enough time to be excluded. This increases the porosity and tension of external solidified layers and reduces their shrinkage. A danger of non-tightness and cracks shall thus be increased. Therefore, it is generally considered that in alloys intended for die casting it is necessary to check the gassing carefully. It is particularly important in aluminium alloys. Aluminium has a high affinity for oxygen and ability to dissolve gases, especially hydrogen. Chemical affinity of aluminium for oxygen is well known which causes the formation of oxide inclusions which, together with the hydrogen solubility, present an important cause of rejects and losses in production. Aluminium alloys should be heated only at the lowest temperature required for casting, as with overheating there is a rising tendency towards gassing. On one hand, low temperature restricts the absorption of gases to a minimum but also provides the metal with a better strength and ductility[21].

Lubricant Effect upon Gas Mode of a Mould

The amount of gas in a mold depends on lubrication mode of a mold and a mold venting system. Air volume in a mold cavity and gases being formed during thermo-destruction of lubricating agents and also the gas volume from the pressing chamber during casting with the cold horizontal chamber affects the formation of gassing porosity in the casting. In the operation of die casting plants we come across the following use of lubricants:

- treatment of molds surface, pressing plungers and filling chambers where the lubricant effect is insulating,
- greasing of moving parts of moulds and machinery, reduction of friction effects.

Proper lubricants must include the following characteristics:

- it must coat the surface with a fine, tight adhering layer protecting mould working surfaces from attacking by cast metal,
- it must insulate a molud surface from thermal shock of molten metal,
- lubricant must have proper greasing characteristics at a mould operating temperatures necessary for greasing of a mould moving parts,
- burnt lubricant must not form any undesired residues that could reduce the casting quality,
- must not have any chemical influence that would be manifested by etching,
- when applied to a mould surface, the chambers with a plunger can produce a minimum amount of gas that must not be harmful to health,
- it must not colorize the casting surface.

Lubricants development is characterized by the transition from paste preparations based on oil products towards water-soluble preparations based on water emulsions and mineral oils. These have brought improvement in terms of hygiene and work safety. The most important lubricants ingredient for aluminium alloys in order to improve greasing effects is molybdenum disulfide MoS_2 and the graphite whereby the graphite has higher working temperatures. As for zinc alloys, water emulsions are used for greasing in regard to lower casting temperatures. Casting temperatures for brass alloys are relatively high (above 900°C), so the lubricants demands are high as well. Lubricating agents containing a higher proportion of the graphite are recommended here. A lubricating agent for lubricating material of paste consistency is essentially considered a fine dispersion of colloidal graphite in mineral oil or fat containing 8% of the graphite. Gradually, with regard to work hygiene and human health, graphite-free lubricant has been developed [21].

2. Moulds Designed for Die Casting of Metals

The main role of the mould is to form the processed material into desired shape and cool it down to the temperature at which the diecast part is solid enough to be removed from the mould. The moulds must be resistant to high pressure, to produce items of precise dimensions and to allow removal of the diecast part.
Fig.11 shows the mould with its individual parts.

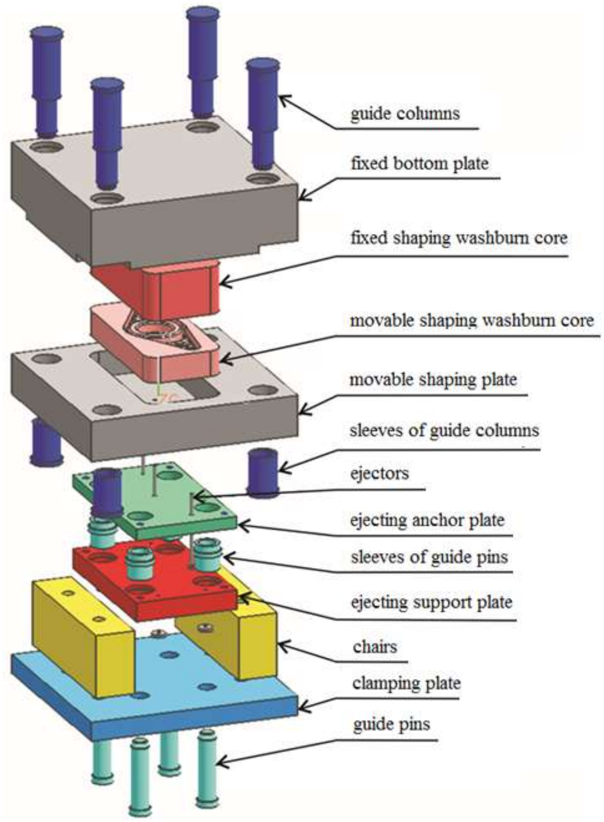


Fig. 10 Scheme of die casting mould [8]

2.1. Basic Mould Parts Designed for Die Casting

The mould structure is of high significance for castings produced in the die casting process. The mould, in general, consists of a fixed and of a moving part.

Basic mould parts include the following:

- parts limiting the shaping mould cavity,
- cooling or tempering system,
- gating system,
- ejecting system,
- venting system,
- clamping and guide elements.

In fact, the basic mould parts can be classified as the structural and functional ones. The structural parts assure correct operation of a tool and the functional parts are in a contact with the processed material which is provided with a desired shape.

2.1.1. Shaping Cavity of a Mould

Shaping cavity is the most important for the mould function. As to shape it is identical with a desired diecast part, yet its dimensions must be bigger by the value of material contraction. Material cools down in the cavity. With regards to the properties more preferable would be the identical speed of cooling in all areas of a diecast part, which requires assurance of homogeneity of a cavity thermal field. Uneven cooling leads premature solidification of the mass in the cooler spots, at which a thicker surface layer of the solidified mass is formed. Thus the section, through which the melt flows to other cavity parts, becomes smaller. Consequently, the mould is loaded at diverse spots under different technological conditions, which causes variability of properties of a diecast part at those spots. The final outcome of uneven cooling is occurrence of internal strain leading to disturbances of a diecast part[8].

2.1.2. Tempering System

The term tempering system covers a system of sprues and cavities through which the cooling medium flows. The system preserves the desired value of the mould temperature.

The tempering system is divided into partial circuits designed both according to the method of shaping of the diecast part in the mould and position of a dividing plane. When designing the distribution of tempering sprues and their dimensions, it is inevitable to take into consideration the overall design of the mould. Desired is to achieve even solidification of the diecast part within the frame of entire

volume. The section of the sprues is generally of a round shape, yet sprues with rectangle section are used as well.
The mould temperature and temperature balance of the die casting mould considerably influences the quality of diecast parts and prolongation of the mould service life. The cooling system of the mould must be designed to prevent occurrence of errors caused by wrong temperature. The sprues are drilled into the mould in case of tempering system. The diameter of channels depends on the thickness of the diecast part wall. Frequently selected values are shown in Table 1.[8].

Tab. 1
Dependence of cooling sprue diameter on the wall thickness of diecast part.[15]

Thickness of diecast wall [mm]	Sprue diameter [mm]
< 2	8 - 10
2 – 4	10 - 12
4 – 6	12 - 15

2.1.3. Gating System

Gating system consists of more simple or complicated sprues connecting the shaping mould cavity with the loading chamber. The system must assure correct loading of the mould cavity, simple separating or detaching of residual sprue. The gating system is designed according to number of shaping cavities and on the basis of their distribution. Since the sprue prolongs the trajectory of flowing of the molten metal into the mould, its negative influence causes decrease of temperature and working pressure. Therefore the mould structure requires taking into consideration the fact that the sprues should be as short as possible and the sections should reach maximum size. The gating system must be designed in order to achieve the following:

- correct mould cavity loading,
- such direction of metal flowing so that premature wear of the walls is avoided,
- limitation of local increase of temperature that could possibly lead to extreme wear and deterioration of surface purity of the diecast part,
- minimum occurrence of whirls in the melt jet that could possibly lead to closure of gases in the diecast part volume,
- desired shape and surface quality of the diecast part.

The main channel of the gating system connects the filling chamber with the ingate. Diameter of the main feed channel is to decrease evenly along with the direction from the filling chamber towards the ingate to provide even increase of the melt speed in the course of the passing through the main channel. Not before the last quarter of the direction close to the ingate the cross section starts decreasing faster that means increasing of the melt speed by which reduction in difference between the optimal melt speed inside the ingate and the speed of the last part of the main channel is achieved. Sudden enlargement of the cross section of main channel and consequent diminishing to the original one results in enclosure of the bubbles in the liquid metal and their transfer to a mould cavity which is tried to be prevented in practice [8].

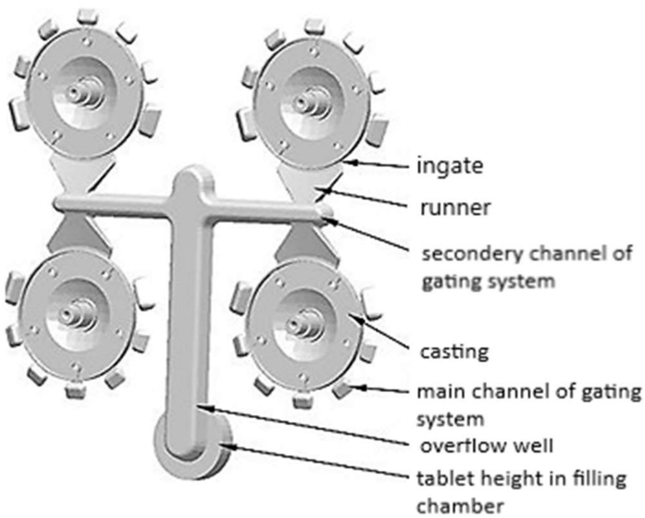


Fig. 11 Structural solution of gating system [15]

2.1.4. Ejection System

Since the casting shrinks during cooling, it remains attached to the shaping parts of the mould cavity and therefore the mould must be provided with the ejection system. Frequently, mechanical systems are used yet rather common are the hydraulic and the pneumatic ones. The individual solutions of ejection are often combined.

Ejection forces are calculated through derivation from specific pressure between the mould and the casting, from thermal relation of friction coefficient between both halves of the mould, and from the casting dimensions.

Ejectors usually dispose of circular section which is convenient as for production and offers possibility of the use of standard ejection systems. Their diameter reaches over 1.5 mm and hardly ever it exceeds 16 mm. It is dimensioned according to anticipated resistance of the casting in the point of the ejector location. The ejectors must be situated close to those casting parts which keep the casting in the moving part of the mould. Thus, the production of the casting with correct shape is assured. At the same time, positioning of the ejectors must assure the utmost admissibility of ejectors' prints.

In case of die casting the mould gets shortened by approximately 0.3 mm due to action of machine locking force and of mould elastic deformation. The length of ejectors is thus by 0.3 mm shorter to prevent sinkage into the casting [15][32].

2.1.5. Venting System

To vent the shaping mould cavity is rather important. Since moulding period is short and moulding itself is accompanied by high speed and high pressure, the air present in the mould cavity could not be released. That would lead to incomplete mould cavity loading and to critical increase of cavity pressure. Therefore it is inevitable to assure intensive evacuation of fair by fixing a system of venting channels. Yet, those must not be the cause of a fin occurrence in the diecast part.

In a high degree mould ventilation influences the surface quality and inner structure of the casting with the air being the main cause of the casting porosity. Gases are also produced by the lubricant of active mould parts in its thermal destruction in contact with the melt that is necessary to be removed by the venting system. The venting system must be effective especially at the points of mould cavity which are situated the furthest from the ingate. Several ventilation channels might be cut in the parting line of the die casting mould so that excess of air can escape to the points not forming the final casting volume. These channels are open to the air, i.e. air venting system or they are connected to vacuum systems.

The air inside the cavity is necessary to be displaced to other mould parts in which the final casting volume is not present in order to negate the correct and required mould cavity shape. Out of the aforementioned the time aspect of a mould cavity filling results and that significantly influences the period of filling under the air influence inside the cavity with the atmospheric pressure value when the plunger begins to move. Predominantly at the end of a mould cavity filling, during which the air is compressed, it substantially slows down the period of mould cavity filling under the effect of alloy flow braking in the cavity. If the air is not completely exhausted out of the final casting volume so at the end of the metal liquid phase pressing into a mould cavity it remains enclosed and compressed in the casting by means of which exogenous and endogenous bubbliness is caused. The up-to-date metal die casting technology applies the vacuum systems designed for the air exhaustion out of the working parts of the machine and mould cavity yet comparing to natural venting system these systems are economically more demanding. With the use of high pressure in the casting process certain amounts of air leaks through the gaps of a die casting mould components such as ejector pins, and the highest amount of bubbles in the casting escape through the parting line of a die casting mould. Many studies have proved that the air volume which must be displaced out of the casting is far higher comparing to mould cavity volume. In case of coldchamber machines the liquid metal volume represents less than 40% which means that the overall air volume is 60%. This air volume along with the air volume from the filling chamber must be shifted beyond the boundaries of the final contours of the casting. The objective is to design a venting system to provide escape of the air prior to the flowing alloy approximately at the sound speed in the air. The venting hole cross section size should range from 10 to 20% of the ingate cross section size.

2.1.6. Clamping and Guide Elements

Those are the structural parts of a machine assuring and determining functional mobility and precise installation of the mould parts.

2.2. Mould Production Material

Production of moulds and of their shaping inserts requires selection of materials capable of resisting to forces induced by high pressure and by speed of the melt jet and at the same time with high tolerance to rapid and considerable temperature changes occurring during pressing process [14].

2.2.1. Service Life of Moulds

Die casting moulds of non-ferrous metals represent permanent moulds made of steel. The active parts (being in contact with molten parts) are made of high alloy steel intended for hot work. Die casting moulds are rather complicated and expensie tools therefore a long service life is expected. Long service life represents one of the most significant issues in the sphere of die casting.

Under operating conditions, the mould is exposed to high alternating mechanical and heat stress which increases with the increasing of melting temperature of casting alloy. Furthermore, the mould cavity is exposed to chemical effect of casting material. The alternating mechanical and heat stress permanently influences the quality of mould cavity being in contact with molten metal. After certain operation period tiny cracks occur which gradually expand. The cracks leave distinct markings on the casting surface in the form of veins. The cores forming diverse holes and cavities in the casting are stressed during casting ejection by forces which occur due to its shrinkage. Dividing plane of the mould is also stressed when maximal locking force si generated and the individual sections show signs of wear due to the moving parts. Service life of moudl is influenced by variety of factors related to its operation – regularity, smoothness of operation, type of casting alloy, casting temperature of alloy, structural arrangement of the mould, speed and specific pressure forcing the metal into the mould and type of machine. Based on the presented facts it is clear that different parts of moulds are exposed to intensive stress and therefore assurance of particular service life requires high alloyed material the quality of which guarantees these expectations.

Criterion of service life of mould is number of break outs which can be reached unlessthe mould is put out of operation. Putting the mould out of operation appeats to be inevitable when the cracks in the mould cause considerable difficulties in continuous castng or in case of cracks damaging the casting surface to high degree, i.e., the casting lacks required quality.

Factors acting upon the mould during operation can be classified as follows:

- alternating mechanical stress caused by casting machine, i.e., gripping and pressing the molten metal under high pressure and stressing the mould parts, mainly the cores during ejecton of castings;
- alternating heat and mechanical stress of surface layer of the mould cavity;
- physical and chemical effects of the injected metal.

Heat and mechanical stress of surface layer of the mould represents the most serious issue for causing hairline cracks which extend and grow in the course of operation. The stress extent of the surface layer of the mould is influenced by thermal expansion and thermal gradient. All of the circumstances significantly influence selection of steel [14][32].

2.2.2. Requirements for Mould Production Material

Steel intended for die casting of metals must meet lot of requirements. Unfortunately, up to present no suitable material has been found which would match the criteria. The material in question must dispose of the following properties:

- high temperature stability and tempering resistance;
- high tensile strength under high temperatures;
- good thermal conductivity;
- low coefficient of thermal expansion;
- dimensional stability under temperature change and during thermal treatment;
- resistance to thermal shocks which is a function of the properties mentioned above;
- resistance to erosive effects of flowing metal;
- good machinability;
- good forgeability.

Metallurgical works endeavour to achieve such properties by appropriate selection and ratio of additives. Yet, properties or resistance of steel in the operation process are not conditioned solely by its chemical composition. Metalurgical processing such as forging is of high significance. Two pieces of steel of the identical chemical compositon yet from different suppliers can dispose of diverse service life. This fact is especially important in case of big moulds and therefore each delivery of steel must be checked. Big foundry plants or tool shops utilize fast and precise ultrasound to detect internal cracks.

Further relevant factor influencing the service life of mould during operation is correct selection of machining additive, i.e., selection of rough dimensions of material used for the mould production.

In case of steel an ideal surface of the machined part is assured only when machining additive, prescribed by the standard is taken into consideration during selection of thickness or diameter. A steel manufacturer usually leaves cracks and other surface defects unremoved. If moulds are produced from flat steel it is

inevitable to be particular about removing sufficient amount of material to eliminate all surface defects.
At the beginning of die casting method, alloys of tin, lead and zinc were cast by hot-chamber die casting machines. With regards to rather low die casting temperature of the metals and low pressure, the requirements for mould material were not strict. Low alloy or chromium-vanadium steel was used for production. At present, hot-chamber die casting machines are utilized mainly for casting of zinc alloys. Demands related to steel properties intended for mould production have increased, especially in case of service life.
Much higher demands are laid upon steel applied in die casting with cold-chamber machines in case of which mainly alloys of aluminium, magnesium and copper are cast. These alloys are characteristic for considerably higher melting temperature contrary to zinc and therefore steel with higher content of alloying elements must be used to reach desired service life [15][32].

2.2.3. Development Trends of Mould Production Materials

Significant factor is steel quality as per composition and purity. It refers mainly to low content of sulphur and phosphorus as well as of inclusions, their fineness and regular distribution. Cavities always reduce resistance to crack occurrence. Vacuum remelting of steel is rather important as well. Increase of endurance of mould material can be achieved by change of content of chromium, molybdenum, wolfram, and vanadium. Thus secondary hardness with the lowest content of these elements along with the highest possible thermal conductivity might be reached, too.

Further improvement can be achieved through hardness reduction after tempering. In case of large series of castings made of zinc alloys, the material selection for mould production moves towards chromium-molybdenum steel used for casting of aluminium alloys. Similar trend might occur in case of other casting alloys.

Molybdenum appears to be perspective material for die casting moulds. Molybdenum is characterized by high heat conductivity and low coefficient of thermal expansion, so even in case of extensive modulus of elasticity, high tension is absent. Hardness and strength at high temperature are considerable. At intervals of low temperature, molybdenum acts as a fragile element and then cracking can be observed. If the mould face is not covered with any protection layer, for instance the nitriding one, sublimation occurs during coating. Molybdenum is difficult to be machined and therefore powder metallurgy is recommended to be used for production of the moulds.

Moulds made of composite materials appear to be perspective. Composite materials are characterized by considerable resistance to erosion. Applicability of composite materials hardened by titanium particles for structural design of pressing chambers of die casting machine was studied in the USA. Resistance to reaction effects in the contact area with aluminium alloy thus increased. Mechanical properties and machinability matched the requirements for pressing chamber properties [21][22][27].

2.3. Process of a New Mould Designing and Manufacturing

The quality and productivity of diecast production is closely related to inevitable tools, especially to die casting moulds. Final design depends on communication ability between design engineers of the individual parts, of the diecast part and of the mould and technologists of a foundry plant and of a tool shop. The methodology of design and manufacturing of a new die casting mould can be divided into the following stages:

- completion of solution of technical, price, and date requests from part of a customer the result of which, besides other, is a drawing or a 3D model of a diecast part that apart from dimensions and their tolerances contains further technical requirements;
- as long as the required diecast parts are intended for further machining, it is inevitable to prepare documentation for both a diecast part and final product;
- a design concept of a mould and tools for further machining, a project plant, and assurance of material for a mould production;
- suitable mould structure, processing of a plan related to mould clamping during the first test, structure of other tools and construction jigs;
- production of a mould of such quality so that the mould does not need to be repeatedly tested;
- the first mould test, setting and temporary support of technological parameters of die casting control of used alloy, of dimensions, and other parameters;
- optimization of a mould according to a design after being consulted with the mould design engineer, with the foundry plant and with the tool shop;
- preparation of basic documents for zero series;

- the second mould test or production of zero series, verification of structural operations, preparation related to dispatch of the samples with the enclosed protocol to a customer and preparation for serial production of diecast parts.

The mould concept is prepared during consideration of the customer´s requirements and influenced by the following factors out of which are subjected to discussion with a customer:

- - total and yearly production of diecast parts;
- type of die casting alloy;
- required dimensional preciseness of a diecast part, thickness of walls, chamfers, roundness, placement of marking and further technical requirements;
- multiplicity of a mould;
- shaping of a diecast part, selection of the dividing planes;
- directions of movement of mobile cores, backing of a diecast part during core removal;
- mode of a diecast part ejection, placement of ejectors and position of marks left by ejectors;
- size of a die casting machine with respect to needed locking force and injection pressure, size of a mould and distribution of core removers;
- selection of diameter of a loading chamber, arrangement of the gating system;
- positioning, orientation, and cross section of the ingate;
- mode of ventilation or vacuuming of the mould;
- cooling or tempering of the mould with regards to inner quality of the diecast part;
- installation and in-building of possible compactors;
- mode of mould treatment and application of a parting jigs;
- mode of diecast part removal out of the mould, selection of material for processing of shaping parts of the mould with regards to required service life;
- demand factor of cleaning, maintenance, and fast replacement of respective parts of the mould.

According to the character and shape of the alloy a variety of not always conventional solutions is used when the mould is designed:

- considering the requirement related to higher preciseness it is uncertain if the preciseness can be observed in practice. On the basis of practice it may be stated that in case of so-called fixed or by the mould connected dimensions the tolerance lower by a half can be observed and reached contrary to the tolerance prescribed by STN 421431 standard. In case of perpendicular and with the mould not connected dimensions the tolerance specified by the STN standard can be decreased only by a third. Precondition to reach such decreased tolerances stems in sufficient implasticity, locking force, purity of the mould, etc.;

- during running in of the movable cores the stops should be located the furthest from the diecast part shape, i.e. in the mould frame. This structural design is applied to avoid forcing-in of metal or sinking of the fin into the area of a stop;
- to assure the dragging of the diecast part by its ejection part it is possible, additionally, to change the chamfer angle of the shape, to adjust retentivity by allowing shorter movement of the fixed cores through a down of their header in a stem or to force the diecast part out of the fixed mould part by using springs or hydraulically or pneumatically;
- during ejection, as needed, rubbing off the cores and consequent ejecting of the diecast part from the mould cavity are combined. Return pins assure observance of the conditions for allowed ejector lines and prevent possible damaging of the mould when the connection between the ejecting plates and a hydraulic ejector of a machine is interrupted;
- turbulent flowing of the metal in the sprue and air closure in the metal volume is avoided when the passages are rounded. The cross section of the sprues should approach the round or trapezoidal shape in which the metal temperature decreases least. Arrangement of the gating system and distribution of cavities of a multicavity mould must be designed to assure the identical length of metal trajectory towards all cavities which thus allows concurrent commencement of loading of the shaping cavities;
- placement and directing of the sprue in a high degree determines appropriate loading of the mould cavity or adhering of the metal to the cavity walls. Inside the mould the metal should not hit the wall in a perpendicular manner, yet in a few cases the hit can be used for correct filling of the thicker shapes;
- concurrently with the utilization of a common system of the mould venting, the application of the wavy venting inserts and vacuum treatment of the moulds is used. The wavy inserts are made of bronze or steel. Bronze inserts are better heat conductors and the melt solidifies faster in them, however, contrary to the steel ones they are more vulnerable to erosion caused by the melt jet. The wavy inserts are also used in case of vacuum treatment of the moulds as replacement for high-priced valve, yet the effectiveness is considerably lower. Vacuum treatment brings into die casting technology

higher quality of diecast parts, prolongation of service life of moulds and its broader application in operation results in economic efficiency;
- tempering of moulds by oil or water with higher pressure is used in operations as standard. Less frequently employed elements of a tempering system are copper bars or warm-water tubes applied in the cores and serving for their cooling;
- dividing agent is sprayed onto the mould which is harshly cooled and subjected to thermal stressed. Suitable is application of wax vapours into the moulds and their consequent condensation on the surface of the mould cavity. Due to absence of water and water vapour the quality of diecast part considerably increases along with prolongation of the mould service life, yet design of a suitable mould cooling is required.

In cooperation with the supply companies the mould production is related to purchase or to production of some parts such as frames, standardized ejectors, sleeves or cores with special chemical and thermal treatment of the surface resistant to galling and sticking of metal. Production of shaping inserts of the mould is the most demanding as to time. Fast production run with preserving shaping tolerances of inserts is allowed by state-of-the-art CNC machining centres. Computer processing of 3D model of the insert is applicable in a designing process and consequently in program preparation. The machining is also used for production even more complicated sprues of gating systems including roundness. In general, the mould cavity surfaces are not polished. To achieve thorough inflow of metal into the mould cavity and high quality of diecast part surfaces the method of fine jetting is employed. The mould quality is checked after each operation by a 3D measuring appliance. To check fitting of a large mould it is inevitable to use a fitting press[8].

3. Designing of Moulds

Failure free operation and positive economic results of die casting depends to a great extent on correct structure of moulds, on selection of suitable material and its thermal processing. Inherent structural arrangement of moulds rests on character of the casting and entire amount of castings intended to be cast. In case of mould design, both the casting and the mould construction technology must be taken into consideration. With complicated moulds different operating procedures exist which are typical solely for this tool branch. When determining tolerances of diverse mould parts, it is necessary to take into consideration the fact that the tools are heat working tools. The precision requirement related to various detailsshould not be extreme in cases in which increased precision is not well-founded to prevent complications and higher costs of production. However, active cavity of the mould (negative casting shape in the mould) must be dimensioned thoroughly and precisely including the shrinkage additives. The entire mould design must be elaborated with regards to maximum use of standardized components.

Two types of moulds are used: moulds produced form a single piece of special steel or inserted moulds in case of which the inserts with negative casting shape are located inside the sleeve made of suitable steel.

The moulds produced from a single piece are applied in case of delicate castings of smaller dimensions as well as in case of complicated castings requiring a few side cores. The inserted moulds appear to be useful with the moulds in case of which long operating period is required. The arrangement allows replacement of inserts with active cavities after long operating period when the inserts show signs of wear and castings do not meet standards of surface quality. Inherent mould structure remains unchanged.

Each mould consists of two main parts – the moving one and the fixed one. The moving parts usually contains fitting pins. The fixed part is attached to a strap of a pressing system of die casting machine. The moving part includes half of the mould and a bench with the ejector. It is attached to a mould carrier. In case of obsolete machines, the moulds are tightened with screws and threaded openings situated in the fixed part of the mould and on the bench. In case of modern machines, the moulds are tightened with clamps and T-slots.

During operation the moulds are exposed to extensive specific pressure and thus the moulds produced from a single piece or the inserted moulds must be sufficiently dimensioned. The inserts must be of sufficient size to assure the strength and long service life.

Processing of structural design of moulds must be focused on achieving smooth operation of the produced mould and highest quality of castings requiring the kowest machining costs.

General instructions and rules are necessary to be followed when designing castings. Abidence of directives and guidelines assures quality castings with minimal difficulties occurring in the course of die casting process.

Each part can be modified to make the mould as well as the casting simpler. However, on the other hand, every single facilitation means considerable increase of overall economic efficiency and therefore it is inevitable to devote the entire attention to endeavour to simplify the casting and thus accelerate and rationalize the production. Yet, prior to each casting modification the shape of parts must be thoroughly analysed and modifications can be carried out after verification of their influence upon overall function of individual parts [15][29].

The rules for designing and modifying of castings can be summed up as follows:

- Shapes must be as simple as possible according to the circumstances. It is necessary to avoid high offsets and use them only upon requirement of structural design and if no other suitable structural arrangement exists.
- In accordance with structural design alternatives and requirements laid upon mechanical properties of the casting, the weight of part must as low as possible and the external dimensions must be as small as possible.
- The casting walls must be strong and thin (according to recommended wall thickness). Required casting strength can be achieved by correct ribbing.
- Cross sections of the casting must dispose of identical thickness. In case of varying cross sections it is necessary to use stepping to avoid concentration of stress.
- Light arch of the casting is more advantageous than large flat area. It is applicable especially in case of castings demanding of surface quality since surface defects would spoil the overall appearance.
- Incomplete inner shapes of castings must be avoided as mould production costs increase and installing and removing diverse shaping inserts in and from the mould decelerates the production speed to high degree. Such randomly installed inserts should either save costs or bring any other advantages,

otherwise it isbetter not to use them and change structural desing of the casting.

- Inner corners of the castings must be rounded and sharp external corners must be avoided.
- The holes and walls of the casting must dispose of respective bevels allowing safe ejecting of the casting out of the mould without deformation.
- To determine the holes and shouldering so that the entire design of the casting results in material and cost saving without negative impact on mould price increase.
- To design the castings to assure simple removal of cores without using complicated structures and operations.
- Without economic reasoning it is not advisable to pre-cast small holes in the casting. Thin core is vulnerable to abruption which causes higher costs of mould maintenance and reduction production speed.
- Design of core shapes must be as simple as possible and in accordance with casting functional requirements.
- Position of ejectors must always be taken into consideration. If ejectors are not positioned adequately, it can result in disturbance of casting surface or deformation of casting for forces acting intensively or in insufficiently reinforced areas.
- If the casting is inteneded to be polished, it must be designed to make the surface accessible. Sharp corners and various shoulderings increase finishing costs.
- The castings are designed to assure the simplest removal of sprues and fins and the lowest costs.
- If the casting requires machining, excessive application of machining additives must be avoided.
- If it is possible, the clamping device in case of potential machining must be taken into consideration.
- Inject element are designed with regards to their uncomplicated location in the mould. The inject elements are treated by appropriate embedding in the casting.
- If the casting influences final appearance of the product, its aesthetic shape must be taken into consideration. In such case the casting must be in harmony with overall product design.
- The widest permissibe limits are applied and requirements for confined tolerances of castings should not be exceeded.

3.1. Designing of Die Casting Parts

Two fundamental requirements must be met when designing the casting. It is the utmost utilization of material and assurance of the maximum production speed with the aid of structural design of casting which fully complies with foundry conditions.

Undoubtedly, design engineers endeavour to make the castings as light as possible and to save basic material. The savings can be rather high, especially in case of mass production and should be taken into consideration by all design engineers. However, strength requirements for final casting must be taken into account. Extensive continuous areas of the casting must be ribbed and arranged to assure the best mode of mould cavity filling with metal. In case of castings being cast in die casting process the strength is increased by appropriately located ribs with the thickness approximately identical with the one of the walls which they are led to. Extreme accumulation of material in some parts of the casting must be avoided as it can result in formation of contractions, inhomogeneity and locat overheating. Thus welding of metal onto the mould occurs and under such circumstances pace of work must be slowed down to achieve sufficiend solidification of the casting prior to its ejection out of the mould. Naturally, this circumstance decreases die casting speed. The inconvenient spots occurring on the casting can be eliminated by suitable structural modification although with the risk of having the mould structure complicated.

Castings under the threat of possible deformation during their removal from the mould must be equipped with sufficient amount of suitably located auxiliary feeder heads for ejectors. It is convenient to use higher number of the auxiliary feeder heads to increase the number of ejectors by means of which more balanced ejection of the casting out of the mould is achieved, jeopardy of casting deformation during ejection is eliminated, stress of the individual ejectors is reduced and thus their service life is prolonged. Idle time caused by break of the ejectors and their removal is eliminated as well, Furthermore, the ejectors with circular cross section leave traces on the castings which during longer operation of the mould change into fins and this fact is relevant when designing the casting. Removing the fins from the area which should be used as the functional one after casting includes certain costs. It is possible to avoid such inconveniences when the areas of possible location of these ejectors are taken into consideration. These areas or areas with auxiliary feeder heads will be diminished by 1 up to 2 mm in comparison to functional area.

The backs of ribs, diverse offsets and feeder heads must be always designed with maximum roundness. When designing the castings, it must be taken into consideration that the walls perpendicular to dividing plane and all cavities should have maximum bevel. This way the core extraction and casting ejection will be less complicated.

Requirements for castings produced in die casting process have been constantly increasing and their structure and applicability have been gradually used in all types of machinery industry. Therefore, designing of new castings intended for die casting must take into consideration those requriments for structural solution which are demanded by this method of casting. Mainly the alternative of simple moulding comes into question which in particular details differs from moulding into sand and cast-iron mould. It is always advisable and sometimes even inevitable to have a design engineer consult the suitability of the proposed solution with the foundry plant professionals. Mutual cooperation will result in elimination of many difficulties and in creation of conditions for smooth die casting operation. If the principles mentioned above are ignored in designing of the casting, frequency of rejection rate occurrence and of overall reduction of production is higher[6][8][32].

The casting design process for die casting should fllow the steps given below:

- determination of the casting material;
- determination of wall thickness;
- determination of bevels of external and internal walls of castings;
- determination of taper degree of holes and their dimensions;
- resolution of the fins (in case the fins are needed to be used);
- casting of threads;
- dimensional tolerance of casting;
- specification of machining additives.

3.1.1. Determination of the Casting Material

Seleciton of casting material is given by the requirement for strength and physical properties of the final casting and only specific types of alloys suitabl for die casting can be used.

3.1.2. Determination of Wall Thickness

The castings are designed with even and balanced wall thickness. Excessive material accumulation must be avoided as it results in formation of contractions. If the casting must be strengthened, it can be achieved by appropriately situated ribs the thickness of which cannot exceed the one of the casting walls. It must be emphasized that lasrge smooth and flat areas are complicated to be die cast and their surface always shows signs of flowing material. These areas, if the casting functions makes it possible, are recommended to be treated with fine grooving or punching through which good appearance is achieved. Suitable roundness is desired to be carried out in case of all casting edges, if it is possible. It simplifies mould filling and prolongs the service life.

Recommended wall thickness values for castings made of the individual alloys are shown in Tab. 2.

Tab. 2
Recommended wall thickness values of the casting [9][32]

Alloy on the basis of:	Recommended wall thickness of the casting
Zn, Sn, Pb	1.0 – 2.5 mm
Al, Mg	2.0 – 3.0 mm
Cu	2.5 – 3.5 mm

Under certain circumstances, the recommended wall thickness can be diminished especially in cases with convenient flow and areas which are not extremely large. For example, in case of alloys of Zn, Sn, Pb the thickness can be diminished to the value of 0.5mm, in caseof alloys of Al, and Mg the thickness can be diminished ot the values o 1mm, and in case of alloys of Cu the thickness can be diminished to the value of 1mm. Thinner walls are not recommended as standard as the metal rapidly solidifies on the rather cold mould walls and the mould cannot be sufficiently filled.

The most complicated is the die casting of flat and thick-walled areas. In such cases the casting is recommended to be structurally modified by weakening the strong parts and consequently by their reinforcing with adequate ribbing arranged to assure even distribution of shrinkage and maximal filling of the mould.

In dependence on overall surface area of the casting it is convenient to select the wall thickness according to Tab. 3.

Tab. 3
Recommended thickness of casting walls in dependence on its surface area [15]

Surface area of the part [cm^2]	Type of alloy		
	Sn, Pb, Zn	Al, Mg	Cu
	Wall thickness [mm]		
Up to 3	0.6 – 1.0	1.0 – 1.5	1.5 – 2.0
3 – 100	1.0 – 1.5	1.5 – 2.3	2.0 – 2.5
100 – 500	1.5 – 2.0	2.3 – 3.0	2.5 – 3.0
over 500	2.0 – 2.5	3.0 – 3.5	3.0 – 4.0

*surface area refers to the area of any of the continuous plane taken into consideration

Castings subjected to risk of being deformed during ejection out of the mould must be equipped with suitable feeder heads intended for their reinforcement. Usually, the feeder heads serve as ejector supports.

Fundamental principle to be followed when designing the casting structure is to have the casting with all walls of identical thickness, to assure sufficient reinforcement of the casting, and, if it is necessary due to functional reasons stemming from the mould, to provide the casting with auxiliary feeder heads for ejectors.

Rather delicate are the areas of sharp transfer in contact of two casting walls. These shar transgers are always attempted to be replaced by suitable ratio of wall thickness or castings by means of which the casting gets solidified and mould filling is less complicated due to diminished local spinning of metal which often causes imperfect mould cavity filling.

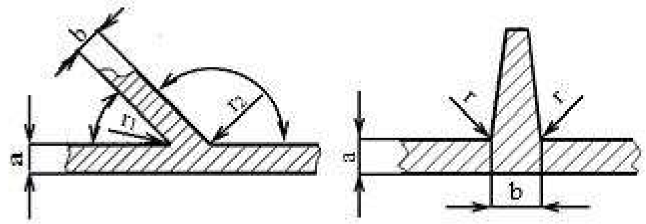


Fig. 12 Roundness of inner corners in contact of two walls [32]

According to Fig. 13 extent of roundness depends on the following:

a) thickness of contact walls;
b) angle formed by the walls.

Diameter of roundness is determined according to mean value “S” of the wall thickness or a rib in dependence on their thickness and connection of an angle by means of Tab. 4. Mean values of wall thickness is determined from the following relation:

$$S=(a + b)/2 \qquad (3.1)$$

with*a* and*b*standing for thickness of the wall or of the wall and of the rib.

Tab. 4
Radius of roundness in contact of two walls [15][32]

Angle		**radius*r***
over	**up to**	
45°	**90°**	0.25. *S*
90°	**120°**	0.50. *S*
120°	**160°**	1.00. *S*

*values of radius are rounded to the immediate values of standard series of radii

The walls with angle lower than 60 ° and larger than 120 ° are not recommended to be connected. If opposite is the case, the issue must be consulted with the mould proucer of with the foundry plant.

3.1.3. Determination of Bevels of External and Internal Casting Walls

The castings must always dispose of sufficient bevels on both external and internal walls in the direction perpendicular to dividing plane of the mouôd and in the cavities formed by diverse shaping cores. The larger the bevels of the casting are, the more reliable the function of the mould is in the operation and those castings, made of aluminium mainly, dispose of fewer surface defects occurring dur to adherence of metal onto the mould cavity wals, cores, inserts, etc. Selection of larger bevels of the casting results in basic principles for continuous operation during casting, in simpler removal of the casting out of the mould, in reduction of ejector stress, and it all contributes to assurance of expected production speed.

ČSN 42 1431 standard specifies these minimal bevels as follows:

- for castings made of alloys Zn, Sn, Pb … 1/2°;
- for castings made of alloys Al, Mg, Cu … 1°.

The casting drawing indicates the bevels either by dimensions *a*, *b*for the height*h* or by one of the dimensions of *a*, *b*, by an angle and by the height*h*.

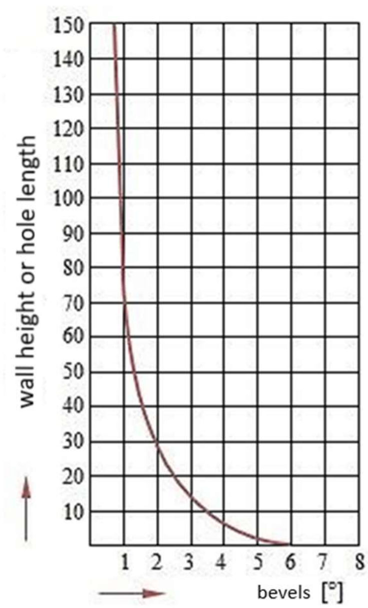


Fig. 13 Bevels of walls or holes in dependence on their height or lenght [32]

In the practice, mainly in case of castings made of aluminium alloys, larger bevels are recommended. Based on experience, in case of castings produced in die casting process it is advisable to opt for different bevels in dependence on wall depth or core length. The values of the bevels are shown in Fig. 14.

In individual cases, to observe limited tolerances of castings, smaller casting bevels are selected in particular parts contrary to recommended minimal bevels. In exceptional cases, bevels are completely omitted. In all of the cases mentioned above, it is inevitable to proceed with high precision and care and to consider all circumstances of operation economy during die casting process as well as potential difficulties influencing mould function and rejection rate. If economic reasons are not well grounded, it is more convenient to avoid such cases and to opt for additional mechanical machining. Sometimes the casting shape and structural design of the mould allow to produce casting walls without bevels. Those are the cases, in which the wall (at all times it is the external one) can be made with the moving core being withdrawn after the mould opening. Then the casting gets released and removed out of the mould. Otherwise, applicable is the following principle: in case of castings made of alloys Zn, Sn, and Pb it is possible to opt for bevels smaller than in case of alloys Al, Mg and Cu.

Technological bevels are specified by STN 04 2021 standard (see Fig. 15). Three types of bevels are noted: bevel A, B and C.

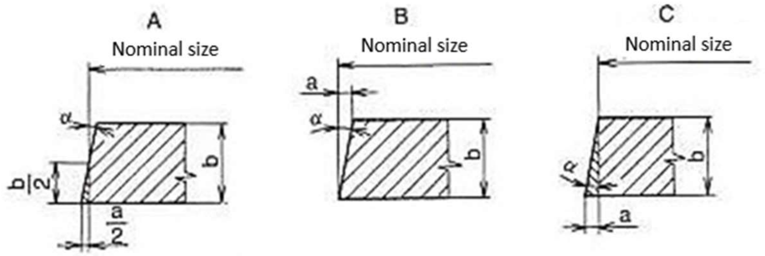


Fig. 14 Types of technological bevels [15]

Bevel A: made in case of areas of the castings which remain unmachined.

Bevel B: occurring in case of areas of the castings which remain unmachined yet the casting structure allows more extensive reduction of the given nominal dimension.

Bevel C: occurring in case of areas of the castings which will be machined or which will remaing unmachined yet the casting structure does not allow reduction of the given nominal dimension.

3.1.4. Determination of Taper Degree of Holes and their Dimensions

When determining taper degree of different holes in the casting which shall be produced by means of cores, either the fixed ones or the moving ones, the principles of bevel determination applicable in case of determination of external and internal walls are observed (Fig. 14). If it is possible, in case of cylindrical holes the taper degree is determined as high as possible. The same is applied in case of the bevels of the holes with diverse profiles. Especially, the holes with irregular profiles require design of sufficient bevels along the entire circumference. All the corners in the holes of square shape, of rectangle shape, etc. mut be rounded with suitable radius according to Tab. 4. Sharp corners cause formation of cracks, reduced casting strength, and complicated removal of casting out of the mould or difficult withdrawal of cores out of the casting.

In case of holes produced by means of the fixed cores and perpendicular to dividing plane it is important to take into consideration placement of rejectors which must be situated in the proximity of the hole (as close as possible) to assure reliable removal of the casting out of the core. The holes in the parallel line with the dividing plane which will be produced by means of the moving cores (hydraulical or mechanical control assured by a skew pin) must be provided with sufficiently wide front wall to assure reliable leaning of the casting during withdrawal of cores and to prevent casting deformation.

The lowest recommended diameters of the cast holes in dependence on alloy are present in Tab. 5:

Tab. 5
The lowest recommended diameters of casting holes[32]

Alloy on the basis of:	The lowest recommended hole diameter
Zn, Sn, Pb	1.0 mm
Al, Mg	2.5 mm
Cu	4.0 mm

When deciding whether all the needed holes of the casting must be die cast or they will be drilled or pierced after die casting it is important to observe an economic analysis. To assure smooth die casting operation, it is sometimes convenient to drill or to pierce small holes with diameter of up to 5 mm (with regards to the fact that in case of use of the cores with small diameters they frequently tend to break during operation). In such cases a consultation with the foundry plant professionals is a must.

In case of casting very small castings, especially those made of Zn alloys, the holes smaller than 1mm are cast. Such tiny castings are die cast with the hot-chamber machines in case of which specific pressure are considerably lower which eliminates the risk of breakage of weak cores.

Recommended depths of pre-cast holes in dependence on their diameter are shown in Tab. 6:

Tab. 6
Recommended depths of pre-cast holes [29][32]

Alloy on the basis of:	Cores	
	overhung	**placed bilaterally**
Zn, Sn, Pb	3. d	6. d
Al, Mg	2. d	4. d
Cu	1.5. d	3. d

The values shown in the table assure sufficient strength and stiffness of cores based on the operation experience. However, it does not mean that in some cases during designing of the casting the casting of holes longer than shown in Tab.6 could not be taken into consideration. Everyday practice of our foundry plants proves it in many cases. In such cases it is important point ou considerably higher risk of the core break during operation which always means delay during casting due to its replacement. In case of application of long or weak cores which are overhung the positioning of the ingate must not be ignored. The molten metal flowing to active mould cavity must be directed sidelong the core to prevet the flowing metal from breaking or bending the core. In case of the casting design there is a principle which states that the shorter the holes in relation to diameter are, the better casting conditions will be assured.

3.1.5. Designing of Inject Elements

One of the characteristic features of die casting is wide scale of utilization of diverse cast-in inserts, i.e. inject elements. Those are different screws, helices, pins, pivots, etc. These so-called inject elements are usually made of steel, grey alloy, brass, etc.

When designing the inject elements, their reliable insertion into mould and modification of their shaping must be taken into consideration to assure sufficienly firm connection with the casting. In some instances, the forces generated during casting shrinkage are sufficient for such connection yet in major cases the inject elements are modified to assure perfectly firm connection. Therefore, different grooves, corugations, holes, areas occur on the inject elemens. The inject elements are inserted into the holes in the particular half of the mould or they are mounted onto fixed or moving cores. Yet, it must be taken into account that they are protected against being shifted by the flowing metal by delimitation of the area of the inject element in the clamped mould or by shouldering on the cores or by means of the cores. The inject parts must be produced in the way which would assure their fast and simple insertion into mould. If it is the case of different sleeves or pins, their precise and correct dimensions and tolerances must be observed. Non-observance of dimensions assuring positioning of the inject part in the mould results in complicated insertion or allows penetration of metal into the gap between the inject and the mould or the core which causes difficulties in removal of the casting, even its damaging.

In connection with the inject pars in the castings produced in die casting process it is inevitable to mention diverse issues which represent accompanying phenomena during casting contrary to die casting of castings without inject arts which in many cases influences application of the method in the practice. The main difficulties and drawbacks include the following:

- lower production during die casting due to insertion of inject parts into mould;
- unconditional observance of functional dimensions of inject parts intended to be inserted into mould to assure safe and reliable operation;
- prolongation of working cycledue to insertion of inject parts which negatively influences maintenance of optimal mould temperature. It increases risk of occurrence of rejects, especially in case of die casting of thin-walled castings.

The presented examples of difficulties do not exclude use of inject parts which is proved by many castings produced by means of such method and applied in everyday practice in machinery production.

3.1.6. Die Casting of Threads

In case of several examples it is possible to produce castings along with external and internal threads. Those are mainly alloys of Zn, Al, Mg. Castings made of Cu alloy are not die cast with the threads due to high die casting temperature and short service life of thread inserts.
Die casting of threads includes more difficulties and therefore it is important to make calculations and to consult foundry plant professionals. Fine threads with pitch reaching less than 1 mm are strictly not recommended to be die cast. In case of lower precision requirements or if smaller fins, ovality or shift are acceptable between threads in the dividing plane (which can be rectified or flattened by means of additional slitting), the following principle is applicable in die casting of threads:

- external threads can be die cast from alloys of Zn, Al, and Mg with diameter over 12 mm and with pitch reaching at least 1 mm;
- internal threads can be die cast with the use of the alloys mentioned aboe with minimal diameter of 10 mm and with minimal pitch of 1.5 mm.

Die casting of thread follows a general principle that the process is preceded by economic analysis of costs and of circumstances whther it thicker design of thread with moderate ovality and bevel is acceptale.

3.1.7. Dimensional Tolerances of Casting

Pursuant to STN 42 1431 standard permissible deviations in case of dimensional tolerances are J13.These values are also for diverse distances of holes, feeder heads, etc. In case of requirements for more limited tolerances stemming from requirements for elimination of mechanical machining it is advisable to proceedcarefully to prevent risk high rejection rate during castin due to extremely limited tolerances. Based on the practice, there are castings being die cast within the range of such tolerances that their assembly is possible without any further machining. It refers usually to a single casting dimension of the part with circular cross section. This part of the casting must be placed in the mould to prevent its separation by the dividing plane, i.e., its shape must be formed in one part of the mould. In these rare cases with smaller castings it is possible to cast different diameters of both external and internal dimensions with precision of up to H11/h11. In each case the lengths are rather short under the condition that the casting material is easily meltingalloy such as Zn, Sn or Pb. In case of alloys Al,

Mg, and Cu a more careful procedure is desired as these alloys require during casting sharper bevels than low melting alloys and tend to adhere to the mould face.
Therefore, in case of limited tolerances with castings made of alloys Al, Mg, and Cu it is more convenient and more economic to opt for mechanical machining which assures unconditional observance of prescribed dimensions when gaining desired surface quality according to requirements stemming from the function of the parts. Furthermore, such technological procedure allows to select in the spots of presupposed mechanical machining of the casting sufficient bevel owing to respective machining additive which positiviely influences the mould operation during die casting. Therefore, when determining the casting tolerances, it is convenient to opt for the widest possible ones.

3.1.8. Determination of Machining Additives

The areas which must be machined are necessary to be marked clearly in the casting drawing. The machining of casting being die cast is opted for only in the case if limited tolerances with respective smoothness of functional area are observed.
Machining additives must be minimal at all times. On average, according to the casting size selected are the addives within the range from 0.2 up to 1 mm per area. Minimal prescribed additives must not be exceeded due to material saving and for possibility of revealing the internal microporosity of tha casting when removing a thicker layer during machining which at times occurs in some parts yet does not represent severe defect.

3.2. Designing of Gating Systems

The gating system structure and adjustment of technological parameters of die casting process correlate. Correct connection of the gating system structure and of the technological parameters becomes visible in final quality of castings.
Design of the mould gating system includes the following steps:

- analysis of liquid metal flow;
- selection of the most suitable position for location of the ingate and of the gate and venting system;
- calculation of time of mould cavity filling;
- calculation of metal flow in the gate;
- determination of spew volume;

- determination of ingate cross section;
- determination of sprue cross section;
- determination of geometric characteristics and of structural design of part of the gating system.
-

3.2.1. Analysis of Liquid Metal Flow

Ideal shape of the casting allows flowing of liquid metal in the mould cavity along clear and straight trajectories. Rarely, the ideal shape can be designed, especially in case of sprues and ingate. Under the real conditions, a compromise must be often made. A designer shoul consider both the technological and the foundry aspects. When designing the gating system, consultations and discussions with the professionals from the field of die casting are inevitable as these experts perceive the issue from practical point of view. Consequently, the designer is forced to search for a suitable compromise between desired shape, ideal shape and suggestions of professionals and to find the most convenient trajectory for the molten metal flow. Right the trajectory will determine the borderlines for location of the ingate.

3.2.2. Selection of Position for Location of the Ingate and of the Venting System

All of the known alloys used in the foundry industry tend to shrink during solidification and cooling. If the property is not taken into consideration when the mould is designed, the final castings will dispose of different defects caused by shrinkage during solidification. These defects will become evident in the form of cavities in the casting volume (higher porosity) and sink marks of different sizes.
In case of die casting with sand moulds, gravitation die casting, low-pressure die casting and die casting to meltable model the mould shrinkage is compensated with the mould volume increase by the value pertaining to shrinkage. Consequently, the final casting disposes of the required dimensional properties after shrinkage. The volume increase is realized by formation of feeder heads. The feeder heads are conical offsets situated above the areas, which arecomplicated to be reachedand in the casting volume of the section solidifying as the last one.
Die casting represents an exception among casting technologies due to the fact that feeder heads are not situated in the mould shaping cavity. Shrinkage is eliminated by means of holding pressure and therefore the gating system must be designedto

assure transfer of pressure by the molten metal for the maximum period and the lowest losses. The designer must take into consideration pressure gradient and actions being in progress in the mould cavity including the ingate and venting channels. It is convenient and many times realized in the practice to design the gating system so that the ingate is located in the dividing plane with the venting system situated on the opposite side. The suitable solution of the ingate and of the venting system location should assure molten metal flow in the mould cavity along the shortest trajectories.

When designing the sprues, it is advisable to avoid concurrence of two different flows of molten metal prior to ingate. The situation is rather undesirable yet not possible to always be eliminated. In such situation, the ingate should be located from the inner side of the casting. The weakness of the central gating system rests mainly in the fact that multiple cavities are absent and excessively long structure of the gating system causes premature decelaration of molten metal speed before entering the mould shaping cavity.

3.2.3. Calculation of Mould Cavity Filling Time

The diecast part should be designed to assure sufficient area for placement of the ingate and of the venting channels. The width of the ingate shall be achieved when the ingate area is divided by its height. The ingate area depends on selection of period of the mould cavity loading and on the melt flowing speed in the ingate. The mould cavity loading period is selected on the basis of the following:

- Thinnest walls of the diecast part – thick walls allow longer period of loading contrary to thin walls as those tend to get solidified prematurely. For that reason die casting of the thin-walled diecast parts requires shorter period of the mould cavity loading. At the same time the flowing length must be taken into consideration. In case the diecast part contains thin walls with large areas or the thin walls are placed in considerable distance from the ingate, the period of the mould cavity loading must be shorter.
- Thermal properties of alloys and materials – temperature of liquid, range of solidification and thermal conductivity of mould material. These materials influence the period of solidification.
- Combination of diecast part volume and fins – thin-walled diecast parts, diecast parts with long trajectory of the melt flowing through the mould cavity and diecast parts with special requirements regarding quality need larger fins. The requirement is justified by the fact that higher metal volume can preserve required temperature for longer time.

- Permitted percentage ratio of metal solidification during loading – in case of higher surface quality requirement it is inevitable to preserve the melt with lower ratio of solidification and shorter period of the mould cavity loading.

The ČSN 22 8601standard states recommended values of mould loading time derived from prevailing thickness of the cast wall according to Tab. 7.

Tab. 7
Recommended values of mould loading time [4][30]

Prevailing thickness of cast wall [mm]	Mould loading time with melt [s]
up to 1.5	0.01 to 0.03
up to1.8	0.02 to 0.04
up to 2.0	0.02 to 0.06
up to2.3	0.03 to 0.07
up to2.5	0.04 to 0.09
up to3.0	0.05 to 0.10
up to 3.8	0.05 to 0.12
up to 5.0	0.06 to 0.20
up to 6.3	0.08 to 0.30

Since the values presented in Tab.7 are of informative character only and bring into a gating system design certain impreciseness dependent on designers' experience, it is advisable during determination of mould loading time to follow the relation (3.2) presented in Gating Manual published under umbrella of North American Die Casting Association:

$$t = K.\left\{\frac{T_Z - T_{LIK} + S.Z}{T_{LIK} - T_f}\right\}.h_{ch} \tag{3.2}$$

with:

t – loading period of mould shaping cavity [s],

T_Z – melt temperature in the ingate[°C],

T_{LIK} – liquid temperature [°C],

T_f – mould temperature [°C],

S – permitted solidification percentage at the end of loading [%],

Z – conversion factor of stable units connected with the range of solidification [°C/%],

K – empirically derived constant related to mould conductivity [s/m],

h_{ch} – characteristic wall thickness of diecast part [m].

Part of the equation in the brackets expresses thermal relations and actions occurring in the in the mould.

The K constant gains the following values:

- 0.0312 s/mm between steel AISI P-20 (pre-hardened nitrated steel for plastic injection moulds) and zinc alloys,
- 0.0252 s/mm between steel AISI H-13 (alloys of steel and chromium) and AISI H- 21 (alloys of steel, chromium, and wolfram) and alloys of magnesium,
- 0.0346 s/mm between steel AISI H-13 and AISI H-21, alloys of aluminium and brass,
- 0.0124 s/mm between alloys of wolfram and magnesium, zinc, aluminium, and brass.

The following table 8 presents permitted values of material solidification in dependence on the wall thickness:

Tab. 8
Permitted values of material solidification in dependence on the wall thickness [24]

Wall thickness [mm]	**Permitted values of material solidificationS [%]**		
	aluminium	**magnesium**	**zinc**
< 0.8	5	10	5 - 15
0.8 – 1.25	5 – 25	5 – 15	10 - 20
1.25 - 2	15 – 35	10 – 25	15 - 30
2 - 3	20 -50	20 – 35	20 - 35

The Z constant gains the following values:

- 4.8 °C/% for alloys of aluminium ASTM 360, 380 and 384, all sub-eutectic alloys AlSi (Cu/Mg) containing less than 12% of silicium,
- 5.9 °C/% for alloys of aluminium ASTM 390, supra-eutectic alloys AlSi (Cu/Mg),
- 3.7 °C/% for magnesium alloys,
- 3.2 °C/% for zinc alloys 12 and 27,
- 2.5 °C/% for zinc alloys 3, 5 and 7,
- 4.7 °C/% for brass.

3.2.4. Calculation of Metal Flowing Speed in the Ingate

Flowing speed of the molten metal in the ingate influences mechanical properties of the diecast part and the quality of its surface. Higher flowing speed results in better mechanical properties and in lower porosity. New hig-pressure die casting machines can generate speed of up to $100 m.s^{-1}$, yet degradation of the mould commences approximately at $40 m.s^{-1}$. Thus ranking the speed within the range from 40 up to $100 m.s^{-1}$ is rather impractical. Porosity caused by bonding of gas in the diecast part volume can be decreased without extreme increase of speed by designing the gating system and ingate so that avoidance of shocks and consequent reversible flowing and mixing of the melt is assured. Flowing of the melt through the gating system must be continuous. The reversible flowing effort can be made when the trajectory of melt flowing contains lugs, sharp direction changes or incorrectly reduced diameters.

The STN 22 8601 standard states recommended values of the melt speed in the ingate for the individual types die cast alloy according to Tab. 9.

Tab. 9
Recommended values of melt speed in the ingate[4]

Type of alloy	Doporučené hodnoty rýchlosti v záreze [$m.s^{-1}$]	
	Standard casting	**Vacuum casting**
aluminium	20 – 60	15 – 30
zinc	20 – 30	
magnesium	40 – 90	
copper	20 – 50	

Since the values presented in Tab.9 are of informative character only and bring into a gating system design certain impreciseness dependent on designers' experience, it is advisable during determination of melt flowing speed to follow the relation:

$$v_z = \frac{m_O}{\rho . t . d_p .0{,}785} \qquad (3.3)$$

with:

v_z – melt flowing speed in the ingate [$m.s^{-1}$],

m_O – diecast part weight [kg],

ρ – alloy density [kg.m^{-3}],

d_p – machine loading chamber [m],

0.785 – constant.

3.2.5. Determination of the Fin Volume

The fin or vent hole serves as a heat accumulator and oxidized metal tank of insufficient quality. The fins are inevitable in case if the casting wall thickness is low or if the casting must be solidified at higher temperature. The example is die casting of cores situated in remarkable distance from the ingate. The melt flows aroung the core through the thin walls bilaterally and it is necessary to assure such temeperature to provide firmly connected and unified bond. Selection of fin volume is thus related to and derived from wall thickness and volume of diecast part.Tab**. 10** presents recommended fin volumes for conventional die casting machines in dependence on the lowest thickness of the wall.

Tab. 10
Recommended volumes of fins[24]

Characteristic wall thickness of diecast part [mm]	**Fin volume, percentage ratio out of segment volume**	
	High surface quality	**Lower surface quality**
0.90	150%	75%
1.30	100%	50%
1.80	50%	25%
2.50	25%	25%
3.20	---	---

3.2.6. Determination of the Ingate Cross Section

Pursuant to ČSN 22 8601 standard the cross section of the ingate $S_Z$is derived from the following relation:

$$S_Z = \frac{G}{\rho . t . v_z} \qquad (3.4)$$

with:

G – total of weigh of casting and of fins.

To calculate the ingate cross section S_Z the following relation can be used:

$$S_Z = \frac{G}{\rho(k_1 k_2 . v_t)(k_3 k_4 t)} \qquad (3.5)$$

with:

v_t – according to ČSN 22 8601 standard defined per 15 m.s^{-1}

k_1, k_2, k_3, k_4 – see Tab. 11 – Tab. 14

Tab. 11
Values of the $k_1$coefficient – stemming from the casting wall thickness [4]

Wall thickness [mm]	1 up to 4 including	4 up to 8 including	over 8
Coefficient k_1	1.25	1.00	0.75

Tab. 12
Values of the k_2 coefficient – stemming from the acting pressure [4]

Pressure acting upon the melt [MPa]	up to 20	20 up to 40	40 up to 60	60 up to 80	80 up to 100	Over 100
Coefficientk_2	3	2	1	0.8	0.6	0.4

Tab. 13
Values of the k_3 coefficient – stemming from the type of casting alloy [4]

Type of alloy	Pb, Sn	Zn	Al	Mg, Cu
Coefficientk_3	1.1 up to 1.2	1	0.9	0.75 up to 0.8

Tab. 14
Values of the $k_4$coefficient – stemming from the ration of the wall thickness [4]

Ratio of the wall thickness	constant	nonconstant
Coefficient k_4	1.0	1.5

For the castings made of alloy Al with weight ranging from 30g up to 200g it is possible to use simplified equation for calculation of the cross secton area S_Z:

$$S_Z = 0{,}1\sqrt{V.e} \tag{3.6}$$

with:

V – total of the volume of casting and fins [m^3]

e – prevailing thickness of the casting walls [m]

0.1 – constant defined pursuant to ČSN 22 8601 standard

Fast calculation of the ingate cross section can be carried out according to the following relation:

$$S_Z = 0{,}016(V)^{0,745} \tag{3.7}$$

with:

V – total of volume of casting and fins [m^3]

3.2.7. Determination of the Cross Section of Sprues

Cross section ratio of the secondary sprue S_{KV} (prior to passage to the ingate) to the area of the ingate follows the casting principle as follows:

- cold-chamber machine SZ:SKV ……………1 : 1.3 až 1 : 1.8
- hot-chamber machine SZ :SKV………………...1 : 1.5 up to 1 : 2

Ratio of starting cross section of the main sprue $S_K$to ingates of all castings in the mould should not be lower than 1.

Calculation of the cross section of the sprue depends on mould multiplicity. The sprue cross section areas are influenced mainly by branching of the sprues and if the sprue hole branches (i.e., if the sprue hole is divided), its entire cross section should increase by 5 -30% after each branching in the direction from the ingate towards the tablet. The calculation follows the principle of designing of the sprue cross section in the direction from the ingate.

In case of the cold-chamber machines, the sprue croess section prior to its ending in the ingate is determined according to the following relation:

$$S_K = n.(1{,}3 - 1{,}8).S_Z \tag{3.8}$$

with:

n – number of castings into which the melt flows out of the sprue.

Area of the branching sprue is determined according to the following relation:

$$S_{KZ} = (S_{K1} + S_{K2} + ... + S_{KN}).k \qquad (3.9)$$

with:

S_{KZ} – area of the sprue after fusion,

S_{KN} – area of the n-th fusing spure,

k – coefficient of the extension of sprue cross section extension (5 – 30%).

3.2.8. Determination of Geometric Characteristics and Structural Design of the Gating System Part

Design of the gating system geometry and structure must include functionality of the die casting mould, simplicity of the casting ejection out of the mould, shaping of the casting in the mould as well as laws of hydromechanics and thermomechanics.

Casting Attachment to the Gating System – Ingate

The ingate intended for attachement of the gating system to the casting is designed individually. Fig. 16 presents a few typical examples of structural design of casting attachment to the ingate.

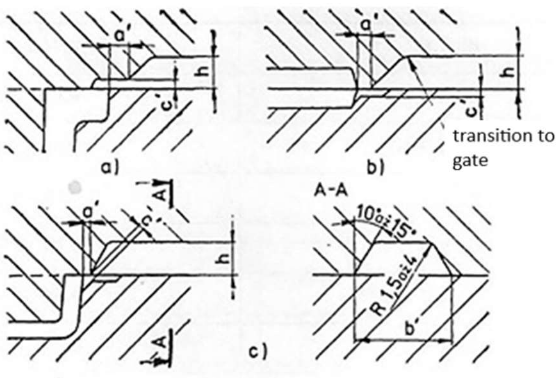


Fig. 15 Alternatives of the gating system attachment [4]

Tab. 15 presents recommended geometrical characteristics for attachment of the ingate to the casting for the individual alloy types.

Tab. 15
Recommended values of attachment dimensions [4]

Alloy	Dimensions of the ingate attachment [mm]	
	a'	**b'**
Zn	0.0 up to1.5	0.35 up to 1.2
Al	0.0up to 3.0	0.7 up to 2.5
Mg	2.0 up to 3.0	0.6 up to 2.0
Cu	2.5 up to 3.0	0.8 up to 3.0

Attachment of the Ingate to the Casting with Cylindrical Area

The ingate shape must exactly copy the cylindrical area shape and thus radius of its curvature must be identical with the area curvature intended for attachment. If the casting is of a rotating character, its radius indicates the radius of the ingate curvature. The following instructions can be observed when designing the ingate shape in the dividing plane [13]:

1. sprue axis will be constructed with the beginning of the coordinate system compatible with the casting roration axis;
2. in the initial point of the coordinate system a circle will be created which will intersect the sprue axis with the radius equal to the casting radius
3. from the initial point of the coordinate system two diagonals intersecting the circle will be directed towards the sprue. Both diagonals form an angle of $\alpha = 30°$ with the main axis. The formed circular segment is identical withe the shape and length of the ingate;
4. in the distance of R/3 from the initial point of the coordinate system an auxiliary point A will be drawn. Two straight lines will be drawn to connect the A point with the ends of the circular segment. Thus a bevelled edge of the gate is formed. Its length is selected according to the regulation of the melt flow by the ingate.

The back bevelled edge is formed at an agle of $\beta = 30°$ from the straight line passing through the end of the front bevelled edge. At the same time, it is parallel with the sprue axis

The following Fig. 17 shows a scheme of the methodology of determination of the sprue geometry.

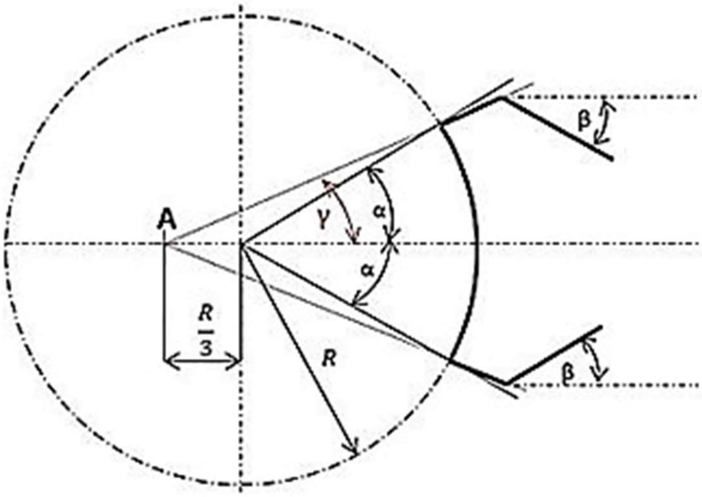


Fig. 16 Scheme of the ingate attachment to cylindrical area [13]

Based on the instructions described above the ingate length can be determined by the following raletion:

$$a = \frac{2.\pi.R.\alpha}{360} = \frac{2.\pi.R.60}{360} = \frac{\pi.R}{3} \qquad (3.10)$$

with:

R – radius of cylindrical area/casting [mm]

The ingate height will be determined as follows:

$$b = \frac{S_Z}{a} \qquad (3.11)$$

Sprue

As standard, the sprue cross section is circular or trapezoidal. In practice, the most common is the application of the trapezoidal shape (Fig.18).

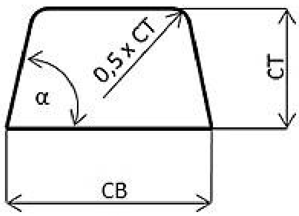


Fig. 17 Sprue cross section [8]

$$S_K = CB.CT - CT^2 \,.\, tg(90^\circ - \alpha) = 2.CT^2 - CT^2 \,.tg(90^\circ - \alpha) \Rightarrow CT = \sqrt{\frac{S_K}{2 - tg(90^\circ - \alpha)}} \quad (3.11)$$

with:

CB – sprue width [mm],

CT – sprue height [mm],

α – angle of inclination of the sprue walls [°].

Consequently, the sprue width is determined by the relation as follows:

$$CB = 2.CT \quad (3.12)$$

Venting System and Fins

Venting channels oriented towards face-line of the casting in the dividing plane or between fixed and moving parts of the mould serve for drawing the air and the gas off the melt and for removal of the separation agents out of the cavities. The recommended sprue depth values are shown in Tab. 16. It is advisable to have the ingate cross section identical with the cross sections of the casting venting channels.

Tab. 16
Recommended depth values of the venting channels [4]

Casting material	Depth [mm]
Zn, Pb	0.05 up to 0.10
Al, Mg	0.10 up to 0.20
Cu	0.15 up to 0.30

Inappropriate mould venting and insufficient filling of the castings up result in-formation of fins as it is shown in Fig. 19. Their basic dimensions are presented in

Tab. 20. The fins are arranged with respect to mould shaping cavity filling. At the same time, their gradual outsortin must be assured. Inevitaable fin volume is shown in Tab. 10.
As standard, the fins containing the ejectors inside are located in the moving part. The overflow shape must allow penetration of the primarily oxidized metal and-must not prevent air and gas release out of the mould [29].

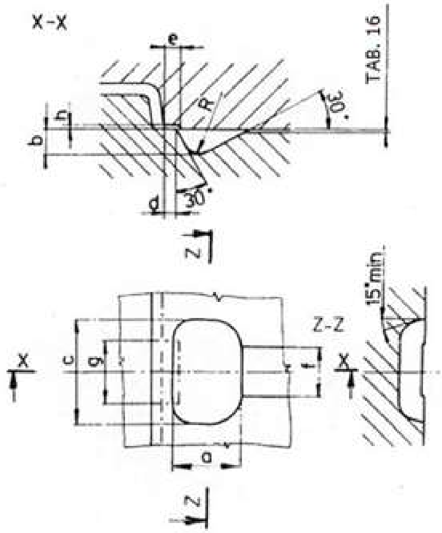


Fig. 18 Structural design of the fin [4]

Tab. 17
Basic recommended dimensions of fins [4]

	Dimensions according to marking [mm]							
	8	10	12	14	17	22	28	34
a	8	10	12	14	17	22	28	34
b	3	3.7	4.3	5	6.5	8.5	11	13.5
c	Specified by a design engineer *)							
f	Specified by a design engineer *)							
R	1	1.8	2.4	3	3	3	3	3
d	2	2	2	2,5	2,5	3	3	3.5
e	*d* + 1up to 2							
g	5	6	6	8	10	10	12	15
h	for Al ranging from 0.6 up to 1.5 – for Zn ranging from 0.3 up to 0.8							

4. Analysis of Influences of Strutural Modifications of the Selectd Parts of the Gating System upon Qualitative Properties of Castings with Regards to Gas Entrapment Elimination in the Melt Volume with Direct Impact on Qualitative Properties of Castings.

Die casting of metals allows production of thin-walled castings with high geometrical precision, good mechanical properties, and low prices. However, defects such as porosity, which is primarily caused by air entrapment by the melt during the illing stage, influence casting quality [33]. Reduced quality caused by air entrapment in the casting volume becomes visible when the mechanical properties and machinability decrease. Apart from the eventual difficulties, the air entrapment leads to oxygen reaction with chemical components in the melt durin mould fillind in case of which oxidic inclusions are formed and those can be distributed to the casting volume. In case of aluminium castings, the metal is subjected to free surface turbulences and primarily oxidized crust gets into contact with the melt and other oxides and can form double oxidic films – biofilms which manifest themselves as kerfs and decrease resistance of castings to mechanical stress [20][11]. In general, castings contain high amount of pores due to air or gas entrapment in the molten metal during mould filling due to high speed and high pressure when the mould is filled.

In its experimental part, the monograph deals with elimination of gas entrapment from the mould cavity during die casting process. It focuses on design and geometry of the selected structural nodes and on its influence on gas entrapment in the casting volume.

4.1. Ingate Geometry Influence on Mechanical and Structural Properties of Castings

According to the aforementioned, the casting quality depends on mechanical properties which are conditioned by the casting structure. The casting structure depends on alloy preparation and on content of the retained air, i.e., on porosity. With regards to the aforementioned facts, it can be assumed, that porosity depends on the gating system structure and on setting of technological parameters. Morphology of structural phases of the casting depends on metallurgical preparation of alloy, especially on modification. The chapter deals with the issue of possibility to influence mechanical properties and structural composition of castings by structural modifications of gating system or of its parts. At the same time, mutual correlation of gating system structure, of technological parameters of die casting, and of mechanical and structural properties of castings is examined. The variable height of gate was selected to be the assessed parameter. Five sets of castings were die cast in case of which the influence of the gate height on change of the selected mechanical properties, porosity of castings, and change of eutectic structure of the casting was subjected to examination. It has been proved that the gate height influences both quality and quantity properties of castings and its change can influence the structure of castings. On the basis of the performed experiments, it has also been proved that the structure of casting correlates with mechanical properties and ratio of eutectic phases in the casting influences its surface hardness. Since technological parameters of die casting cycle as well as metallurgical preparation of the melt were maintained on the constant level and the only variable parameter was the gate height, it can be assumed thatby means of correct design of gating system and especially of the gate it is possible to modify mechanical and structural properties of mutually correlating castings. Through examination of causes of change of eutectic structure of casting by utilization of simulation program MAGMASOFT 5.3 it was proved that the change of gate height influences also technological parameters of die casting process.

The chapter stems from the conclusions of the publication “Possibility of Utilization of Gate Geometry to Modify the Mechanical and Structural Properties of Castings on the Al-Si Basis”[19].

4.1.1. Experimental Materials and Methodology of Work

Experimental examination was carried out with the series of castings of electric motor flange (Fig. 20) made of alloy EN AC 47 100. The measurements were performed in the proximity of structural hole of the casting. The location was considered to be the critical one with regards to further machining and mechanical stress after the casting was fixed into the electric motor setup.

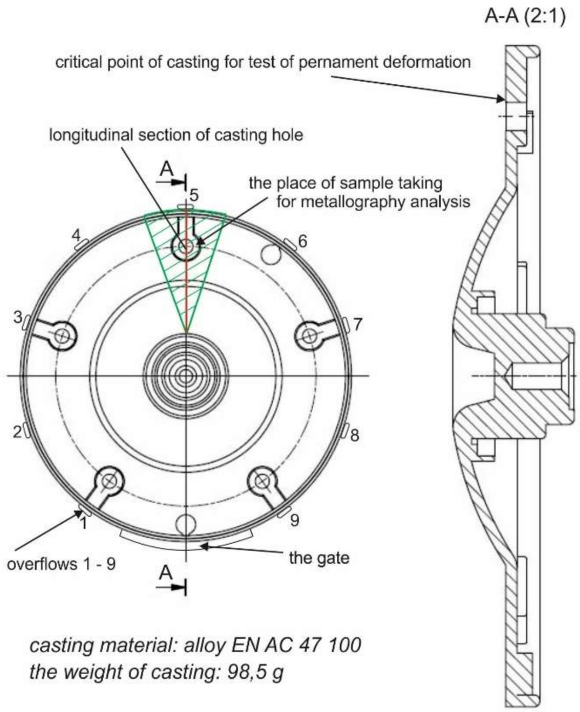


Fig. 19 Measuring points of mechanical properties

Castings were die cast in a quadruple mold. The gating system, the structural design of connection of casting to the gating system by means of a gate and its shape are shown in Fig. 21a) b).

Structure of the gate stems from methodology described in publication [21]. The gate length for the respective type of casting is constant following the aforementioned publication and its methodology of structure of gate connection to casting with cylindrical area. From the point of view of structure, the only parameter to influence the filling mode of mold shaping cavity is gate area $\mathbf{S_z}$. Since the gate area is in this case the function of width and height of the gate and the width is constant according to [8], the gate height b_n was selected to be the examined parameter (Fig. 21c)).

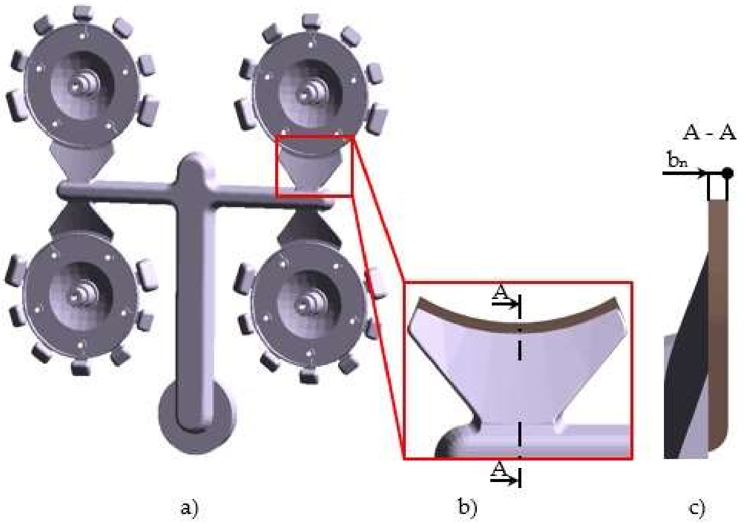


Fig. 21 Structural design of the gating system a) and of the gate b) c)

Chemical composition of the alloy was verified in the laboratory by means of spectrometer Q4 TASMAN. The ambient temperature during the test reached the value of 22°C and relative air moisture content reached the level of 50%. The measuring was performed with the test samples and was evaluated through the average of three sparks. The measured values of chemical composition are shown in Table 18.

Tab. 18
Chemical composition of alloy

Chemical composition of the experimental melt of the used alloy [%]											
Al	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Ni**	**Zn**	**Pb**	**Sn**	**Ti**
85.27	12.02	0.71	1.19	0.21	0.13	0.02	0.02	0.35	0.02	0.03	0.03

Five sets of castings were die cast with variable gate height. Table 19 presents the assessed variables and constant structural parameters of gates.

Tab. 19
Basic gate dimensions

Gate height b [mm]	**b_1**	**b_2**	**b_3**	**b_4**	**b_5**	**Gate width[mm]**
	1.25	1.03	0.92	0.82	0.75	60.968
Gate area [mm]	**S_{Z1}**	**S_{Z2}**	**S_{Z3}**	**S_{Z4}**	**S_{Z5}**	
	76.210	62.797	56.090	49.994	45.726	

To assure the relevant results pointing out the independent influence of the gate on the examined properties, the individual series of castings were produced with the constant setting of technological parameters of die casting cycle. Table 20 shows the values of setting of technological parameters.

Tab. 20
Technological parameters of casting cycle

Technological parametres of the casting cycle	
Parameter	**Value**
Melt temperature [°C]	708
Mould temperature [°C]	220
Moudling piston velocity [$m.s^{-1}$]	2.9
Holding pressure [MPa]	25
Filling time of the die cavity [s]	0.019

Surface hardness, permanent deformation and porosity of castings were selected to be representative qualitative properties of casting. Metallographic examination of structures of castings was focused on evaluation of eutectic structure with regards to percentage share of α and β phases in eutectic.

Static pressure test was carried out with the equipment TIRAtest 28200. Measuring was performed in accordance with GME 06 007 and GME 60 156 standards. The initial loading force was set to the value of F_a = 16kN, force after release reached the value of F_m = 8kN and loading speed reached the value of 10 $mm.s^{-1}$.

Measurement of hardness of samples was carried out with the Brinell method using the hardness tester HPO 250. The measurement conditions were specified in accordance with the STN EN ISO 6506-1 standard. The input values were as follows: intendor diameter D = 2.5 mm, loading force F = 613N, loading time t = 10s.

Assessment of porosity f was realized with the samples approximating with their values of permanent deformation s to arithmetic average of deformation intended for the respective set of samples. Inner homogeneity of the analysed castings was carried out by means of non-destructive method in the RTG laboratory through evaluation of the images obtained by the device of VX 1000D.
Assessment of structures of eutectic structures was carried out in the locations in case of which measuring of the selected mechanical properties was performed. It was the case of critical locations of castings, i.e., structural holes in the body of casting. During die casting the cores are situated in these locations and on the basis of assessment of hydrodynamics principles and on the basis of liquid metal flowing around the cores those were assessed as the locations with high probability of occurrence of foundry defects in the casting. Fig. 22 shows the locations of sampling and samples were used for assessment of metallographic structure. The quality of castings is influenced by the method of filling of shaping mould cavity and proceeding of the melt flow in the shaping mould cavity. Due to the aforementioned the F samples were taken in the location occurring opposite to gate in case of which the melt flow hits the mould flange and splits itself to two flows moving along the mould wall towards the gate. The R samples were taken in the locations in case of which the melt flow reflected from the head of the shaping cavity gets blended with the melt flowing through the gate.

The locations of scratch patters were selected also with regards to diverse thermal procedures in the casting volume. The scratch patterns were made on the front part below the surface as well as in cross section of the casting according to zones in the direction of the thermal gradient during cooling.

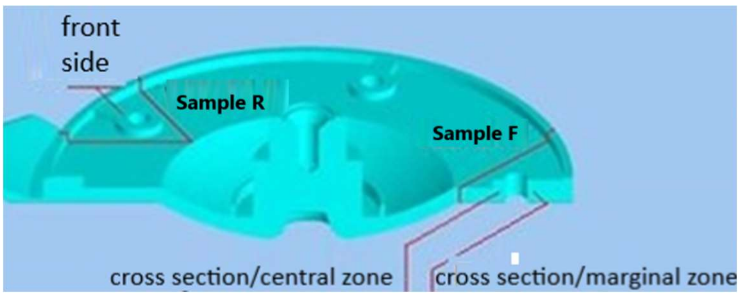


Fig. 20 Evaluated locations of eutectic structures

The scratch patterns of samples taken in the selected locations of casting were realized in accordance with the STN 42 0491 standard. To highlight the structure the scratch patterns were etched with 0.5% hydrous solution of fluorhydric acid at temperature of 22°C. The images were evaluated by the microscope OLYMPUS GX51 with a hundredfold magnifying effect. The scratch patterns were realized with the samples taken from the sets of castings labelled Sample 1, Sample 4 and Sample 5. Linear change of values of examined properties could be observed in case of samples ranging from Sample 1 to Sample 4. The samples with minimal and maximal values of examined properties were selected. Sample 5 was selected because of local extremes occurring within the linearity of the examined parameters.

4.1.2. Achieved Results

The results obtained through performed experiments can be divided into three parts as follows: evaluation of mechanical properties, evaluation of porosity, and evaluation of metallographic structure.

Analysis of Mechanical Properties

<u>Analysis of Permanent Deformation</u>

Measuring of permanent deformation was performed in case of 15 test samples and evaluated by the software of TIRAtest 28200. The achieved results are shown in Table 21.

Tab. 21
Values of permanent deformation

Sample No.	Gate height b[mm]	Permanent deformation s[mm]	average	variance of values
1.A		0.077		
1.B	1.25	0.065	0.068	0.015
1.C		0.062		
2.A		0.048		
2.B	1.03	0.057	0.053	0.009
2.C		0.055		
3.A		0.041		
3.B	0.92	0.045	0.044	0.006
3.C		0.047		
4.A		0.037		
4.B	0.82	0.032	0.033	0.006
4.C		0.031		

5.A		0.057		
5.B	0.75	0.054	0.058	0.008
5.C		0.062		

Analysis of Surface Hardness

The hardness values HB were measured in case of five locations of the selected and assessed samples in relation to gate height change. The results are shown in Table 22.

Tab. 22
Values of surface hardness of castings HB

Sample No.	Gate height b[mm]	Measuring					Aver-age
		No. 1	No. 2	No. 3	No. 4	No. 5	
1	1.25	108 HB	107 HB	108 HB	107 HB	107 HB	**107 HB**
2	1.03	109 HB	107 HB	106 HB	107 HB	106 HB	**107 HB**
3	0.92	106 HB	108 HB	107 HB	108 HB	107 HB	**107 HB**
4	0.82	106 HB	104 HB	107 HB	107 HB	107 HB	**106 HB**
5	0.75	105 HB	107 HB	105 HB	106 HB	107 HB	**106 HB**

A remarkable difference in values of surface hardness of the casting in case of gate height change was not proved and thus it can be assumed that the influence of gate height change on values of hardness can be neglected.

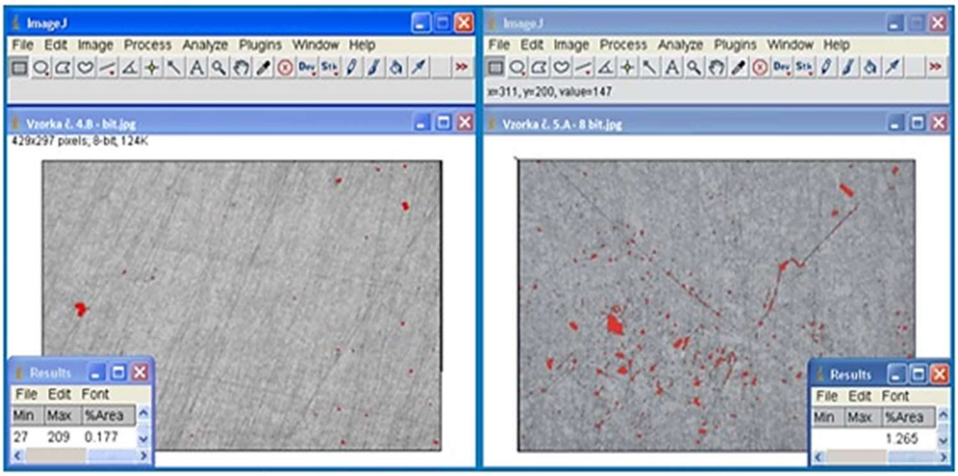
Analysis of Porosity of Castings

Inner homogeneity of castings was assessed in case of samples which served as test samples during analysis of permanent deformation. The measuring location in case of assessment of homogeneity was also the location of measuring of permanent deformation. It was a suitable alternative in order to detect mutual correlation between inner homogeneity of castings and of permanent deformation. Analysis of porosity f of scratch patterns was carried out with microscope OLYMPUS GX51 with a hundredfold magnifying effect. The results were processed by the programme ImageJ which evaluated percentage share of porosity in the examined location. Evaluation of porosity f was performed with the samples the permanent deformation values of which in a high degree approximated arithmetic average of deformation intended for the given set of samples according to Table 21. The porosity values measured in relation to gate height are given in Table 23.

Tab. 23
Values of porosity f

Sample No.	Gate height b[mm]	Porosity f[%]
1.B	1.25	0.89
2.C	1.03	0.87
3.B	0.92	0.85
4.B	0.82	0.18
5.A	0.75	1.27

Table 23 presents porosity values in case of scratch patterns in cross section made through the structural hole of the casting (Fig. 20). Fig. 23 shows evaluation of percentage content of pores around the scratch pattern using the ImageJ program. Fig. 23a) shows content of pores in case of the 4B sample the porosity values of which were the lowest ones. Fig. 23 b) shows pores in case of the 5A sample which reached the highest porosity content around the scratch pattern.



a) b)

Fig. 23 Evaluation of porosity by the program ImageJ

Analysis of Metallographic Structure

The detection of the eutectic component percentage was realized using the program ImageJ. Table 24 represents the measured values of the α-phase fraction in the grinding of individual samples.

In Fig. 24 the structure on the metallographic grindings plane on the samples taken from the location against gate is presented.

Fig. 25 presents a comparison of metallographic grindings and structure of the samples taken from the location around the outlet of the gate into the cavity mould.

Tab. 24
Percentage share of α-phase in the grinding

	Percantage share of α-phase[%]		
area F	**sample 1**	**sample 4**	**sample 5**
front side	19.440	32.281	40.955
cross section/centre zone	24.931	41.390	46.186
cross section/peripheral zone	24.853	37.368	47.267
area R	**sample 1**	**sample 4**	**sample 5**
front side	19.540	39.093	42.376
cross section/centre zone	30.421	46.452	51.637
cross section/peripheral zone	26.614	37.621	43.799

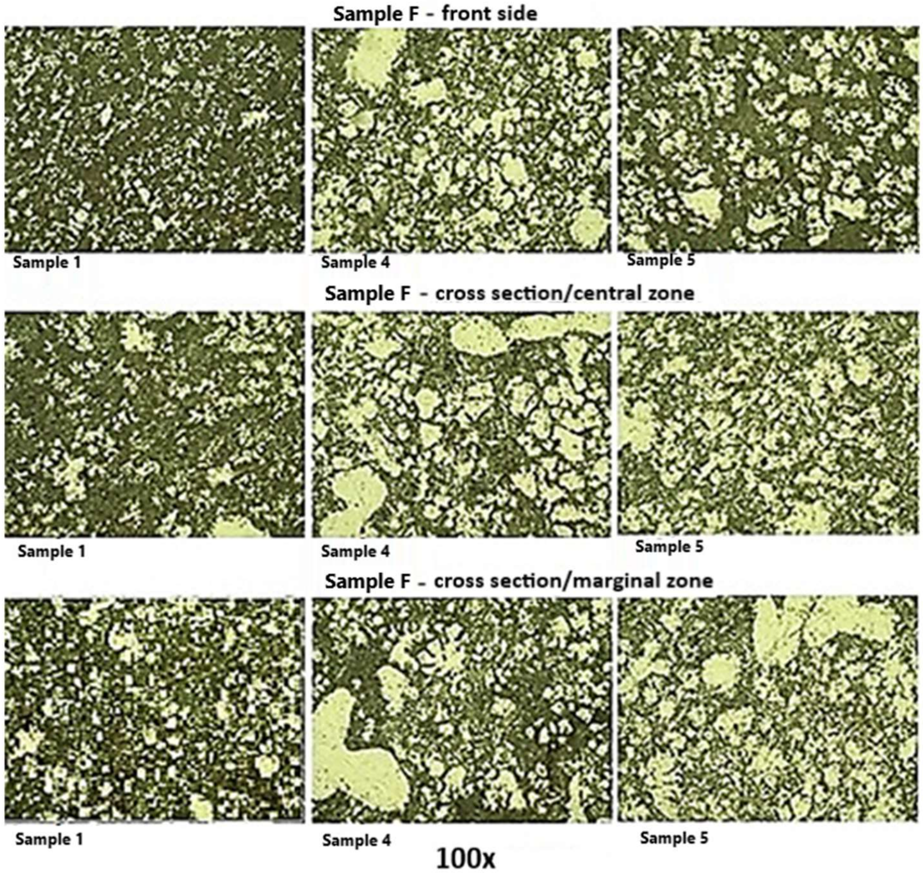


Fig. 21 Structure in the location of scratch pattern of samples taken from the F area

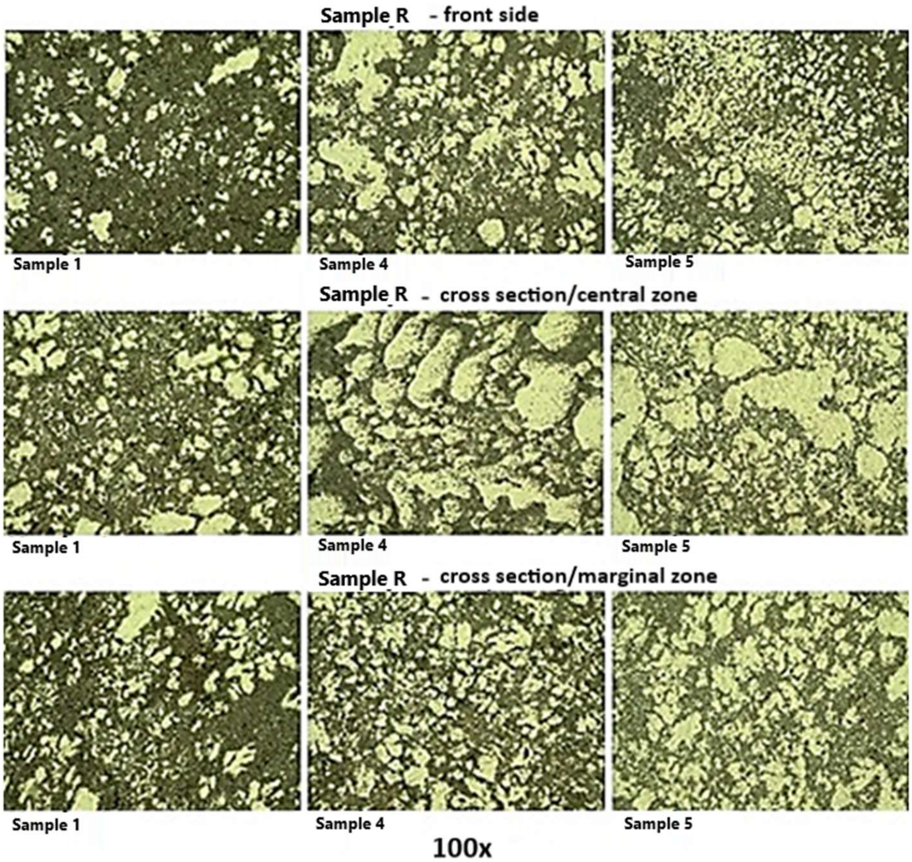


Fig. 25 Structure in the scratch pattern location of samples taken from the R area

Based on the comparison of the sample structures taken from the castings made with different gate height, it can be stated that in case of all the observed locations a noticeable increase of the α-phase in the grinding plane with decreasing height of the gate is apparent. It is possible to claim that the change in the height of the gate has a direct effect on the structural composition of the eutectic.

4.1.3. Discussion

Evaluation of Permanent Deformation

The shape of the selected casting did not allow production of testing bars designed for statistic pull test. Therefore, the pressure test was performed (permanent deformation s) and its measuring was carried out in the critical location of the casting (flowing around the cores), installation hole according to Fig. 20. The lowest values of permanent deformation were detected in case of samples which were made of the castings having been die cast at the gate height of 0.82 mm. Based on such observation, it can be assumed that the values of permanent deformation depend on gate height due to modulation of flow and speed of the melt passing through the gate. Then it determines mould cavity filling mode. The presumption is that at the gate height of 0.82 mm the melt flow reaches such speed which determines the mould cavity filling mode in combination with turbulent and disperse flow.

Evaluation of the Surface Hardness

Considerable difference between measured surface hardness values dependent on gate height change within the framework of the performed analysis has not been proved which is also clear from the obtained values. The analysis confirms the fact the hardness of castings depends especially on casting structure and size of grains. Size of crystal grains is derived from the level of undercooling of the melt when getting into contact with the mould and speed of cooling of the melt. The determining factor of the grain size is thermal gradient between the melt and the mould.

Analysis of Porosity of Castings

Porosity f was evaluated in case of test samples taken from the critical location of the casting by cutting perpendicularly in relation to axis of the installation hole (Fig. 20). The influence of the gate height affects the porosity values especially by shaping and directing the flow of melt being forced into the shaping mould cavity and by change of the melt speed flowing through different areas of gate, i.e., by change of mould cavity filling mode.

Reasons for Structural Changes

Searching for the reasons of the structural change it is possible to rely on the experimental research carried out by Borisov and Batyšev. It is possible to hypothesize that the pressure has a similar effect in the process of crystallization and solidification of Al-Si alloys castings as their modification. According to the Batyšev's research, the effect of high pressure evinces a never increasing eutectic temperature and the point of eutectic crystallization is shifted to a higher silicon volume. The eutectic temperature is increased by about 6.3 °C every 100 MPa and the maximum solubility limit of silicon in aluminium is shifted by about 0.25 weight percent of silicon at the eutectic conversion. With the increasing pressure, the diameter of the primary α-phase is descending, meaning that the structure is finer, and the influence of the holding pressure increases with the increasing of the casting wall thickness. In terms of the reduction of structural parameters, only qualitative changes occur due to the pressure in the structure. Reducing the volume of the eutectic in the Al-Si alloy against the equilibrium state while increasing the silicon concentration in eutectic and refining the structure is the more visible the higher is the pressure value. Due to the shift of the eutectic point in the equilibrium diagram of the Al-Si system, the proportion of primary α-phase with increasing the pressure decreases.

It is not possible to accept the claim mentioned afore in full, since the technological parameters of the casting process were maintained by casting of each series of castings at a constant level. As mentioned above, the limiting factor is pressure. Therefore, it is possible to hypothesize that the height of the gate affects the transfer of the hydrostatic pressure and the length of the holding pressure phase, which subsequently manifests on the internal structure of the casting. To verify this assumption, a series of simulations were performed in MAGMA5 version 5.3.1.3 where the input parameters were identical to the real process ones. To assure detailed examination it was inevitable to set up fine distribution of the net. Number of cells is 52635960 and number of cavity cells is 1640521. The dimensions of cell 0.5x0.25x0.5mm were set up for the gate. Such fine set up of the network allows detailed examination of the assessed parameters.

The gate solidification time was selected as an evaluation parameter. The location where the temperature change was evaluated is shown in Fig. 26.

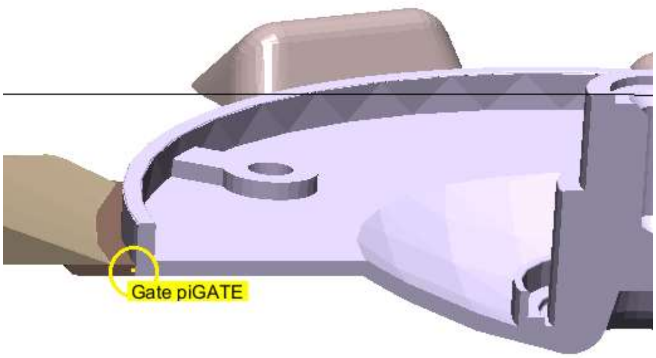


Fig. 22 The location of the melt temperature evaluation in the gate

The length of the holding pressure phase is the time from the complete filling of the cavity mold to the time at which the temperature in the gate drops to the solid temperature of the alloy. For EN AC 47 100 alloy, the solid temperature is set to T_S = 560 °C. Table 25 shows the solidification times of gates for each series of castings.

Tab. 25
Solidification time around the gate

Sample No.	Gate height [mm]	Time of solidification [s]
1	1.25	0.354
2	1.03	0.278
3	0.92	0.264
4	0.82	0.207
5	0.75	0.205

Based on the simulations performed, the evaluation of solidification around the gate shows, that with decreasing the height of the gate is decreasing the time of solidification. Gate with lower height solidifies in a shorter interval of the time, thus the influence time of the holding pressure is also shortening. The difference between the solidification times in the extreme values of the gates heights is Δt = 0.149 s. As discussed above, the proportion of primary α-phase decreases with increasing pressure. Based on observations of metallographic samples grindings taken from the volume of casting and based on evaluation of simulations, it is relevant to claim, that the proportion of α-phase in eutectics decreases depending on the time of the holding pressure influence.

Eutectic is a mixture of a solid solution of α-phase and β-phase crystals resulting from eutectic conversion. The silumin eutectic is characterized by a concentration of 11.7 to 12.5 % of silicon. The α-phase is a solid aluminium solution with different volumes of other elements excreted as white formations. The β-phase is a solid aluminium solution of almost pure silicon (containing over 98 % of Si) excreted as grey formations. Silicon increases the strength of a solid solution and its corrosion resistance. With higher volume, it is present as a pure silicon, which increases the hardness but reduces the deformation characteristics and toughness. This can be associated directly with the permanent deformation values [25][27][28].
Comparing the structures of metallographic grindings taken from the castings with different heights of gates, the increase of a β-phase proportion in the grindings plane with increasing of gate height has been demonstrated. Since the grindings

were performed on samples taken in different locations of castings, we can state, that the increase of β-phase is in the whole volume.

Comparing the average values of mechanical properties of individual series of castings listed in Tables 21,22,23 with the results in Table 24, the following conclusions can be drawn:

a) The ratio of both the α-phase and the β-phase in eutectic is directly dependent on the time of the holding pressure
With increasing of the gate height, the effect of the holding pressure over a longer period is more effective, resulting in a better eutectic conversion and the increase of β-phase in entire casting volume.

b) The increase of a β-phase adversely affects the values of a permanent deformation
Since β-phase consists of the proportion of silicon above 98 %, its higher proportion causes a reduction in toughness and hence resistance to deformation due to permanent load. Table 21 presents decrease of the linear deformation within the range from Sample 1 to Sample 4. Certain local extreme is Sample 5. This fact can be explained by the proportion of porosity in individual specimens where specimens within Sample 5 evinced high porosity values. The cause of the extreme porosity formation is the cavity mould filling mode. The height of gate, which is the lowest in these castings, gives acceleration to the melt flow giving a dispersive character to the cavity mould filling mode. Dispersion filling allows the closing of the gas in the melt volume and thus genesis of increased porosity.

c) An increasing proportion of β-phase affects the castings surface hardness values

As demonstrated, the casting surface hardness values are not dependent on the height of gate but on the degree of subcooling of the melt upon contact with the face of the mould. Minimum hardness difference ΔHB = 1 is detectable between Sample 1 and Sample 2 casting series. When compared to the metallographic grindings of the samples, it is clear that Sample 4 and Sample 5 have lower proportion of β-phase contrary to Sample 1. Silicon increases the hardness of the alloy, so its higher volume in the casting can influence the castings surface hardness.

Evaluation of Mutual Correlation of the Observed and Evaluated Faactors

On the basis of the aforementioned and pursuant to the described experiments and expressed mutual relations between observed and evaluated factors influencing die casting process and experiments described in technical literature the mutual correlation between the gate structure, mechanical properties of cast, its structural composition, and technological parameters can be expressed by Fig. 27.

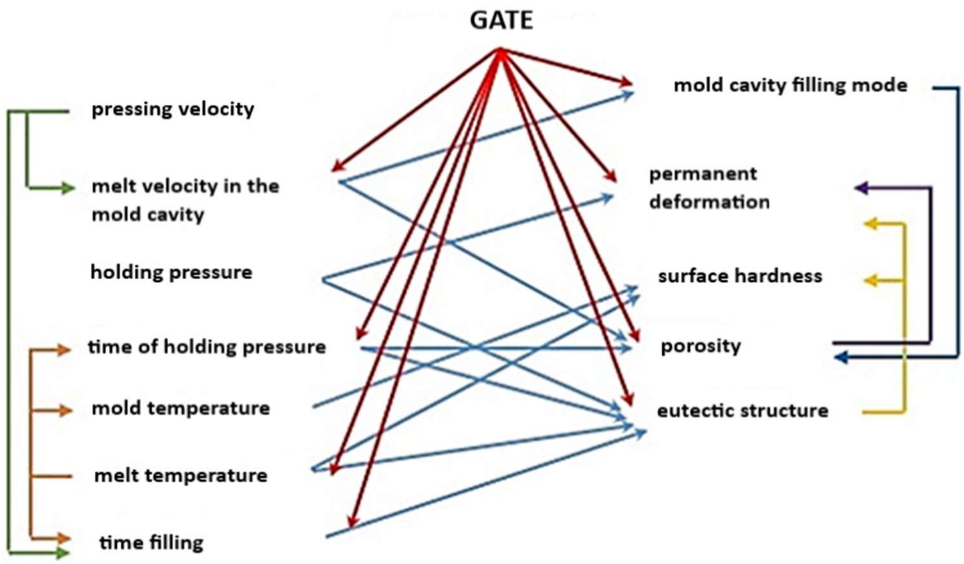


Fig.23 Mutual correlation of factors

4.1.4. Conclusions

The chapter presented the results of study concerning the influence of gate geometry on possibilities of affecting the mechanical properties and the eutectic structure of silumin based castings. The achieved results have proved that the gate height represents one of the basis structural factors which influences qualitative properties of die cast castings and determines speed and mold cavity filling mode. It has been proved that the value of permanent deformation corresponds with porosity which reduces the cross section of casting. A significant factor, apart from the size of cavities, is also the location in the casting volume. It can be assumed that evenly distributed cavities of smaller dimensions reduce mechanical properties to a lower degree contrary to cavities with relatively large dimensions or clusters of cavities with the same volume share in the casting volume. When comparing the values of casting porosity f and permanent deformation s in relation to change of the gate height it can be stated that with the increase of gate height the permanent deformation s increases as well. The exception to the facts mentioned above, is represented only by the value of 0.75 mm. With regards to the increasing gate height the casting porosity f tends to increase as well with deviation in case of value of 0.75 mm. The results point out to the fact that filling mode of the shaping mold cavity is a combination of turbulent and disperse flow.

Comparison of surface hardness values HB points out the fact that the change of gate height has not any relevant influence on hardness since its values depend on alloy structure.

The causes of changes in eutectic structure morphology were presented and clarified and the influence of components of eutectic on mechanical properties of castings was evaluated as well. It has been proved that the gate height can influence the share of the α phase in relation to the β phase in eutectic in the entire volume of casting. Monitored properties were subjected to confrontation with the change of share of the β phase. With the change of the share of the β phase in the volume of casting, the mechanical properties of the casting changed as well. Therefore, there exists a justified reason to state that the share of the β phase influences the change of mechanical properties, particularly it influences the permanent deformation values and in a certain degree even the values of surface hardness of castings are also affected.

The paper presented the influence of gate height on formation of the eutectic alloy structure and its influence of properties of castings. It has been proved that the formation of eutectic structure is influenced not only by the height of hydrostatic pressure but by the holding phase duration as well. Period of gate solidification is thus one of the determining parameters in case of the melt crystallization with the possibility of partial influence of mechanical and qualitative properties of castings. The achieved results unambiguously have proved that the gate height represents a significant structural dimension of the mold gating system because right in the gate the change of the melt flow speed and modulation of the melt flow leading to the shaping mold cavity occurs. As the consequence, the flow determines the filling mode which influences the cast homogeneity.

4.2. Influence of Runner Branching Geometry on the Air and Gas Entrapment in Die Cast Volume

From the technological aspect it is possible to reduce the air and gas entrapment in the melt by suitable adjusting of the input parameters of the casting cycle, which affect the size and distribution of the pores in the cast volume and the filling mode of the die cavity. The filling mode is dependent on the melt flow rate when transiting through the gate. It is directly proportional to the pressing piston velocity in the filling chamber. In various scientific works, the correlation of the pressing velocity and the porosity of the castings, respectively air entrapment in the filling phase has been demonstrated. Higher pressing velocity changes the character of the melt flow in runner from laminar-planar to the turbulent-non-planar causing a mismatch in the melt flow. Through the reduction of the pressing velocity, it is possible to achieve calming of the melt flow. In this way, a continuous and regular melt flow face is achieved over the entire cross-section of the runner which does not entrap the air and gas in its volume. On the other hand, it is assumed that the elongation of the casting cycle at a low pressing velocity leads to a decrease in the melt temperature due to the long casting cycle time, which leads to other casting errors such as cave-ins and cold joints[1][20][25].

Regardless of the technological parameters, the key factor which is affecting the air entrapment in the melt volume is the proper gating and ventilation system design. Ventilation channels should be placed on the cast respecting the die cavity filling mode, so that the air contained in the die cavity had a sufficient time to leak and would not remain entrapped in the cast volume. Liquid metal is required to flow through the straight paths without sudden changes in the flow direction as far as possible. It has been observed that the angle between the main and secondary runner affects the specific pressure, filling time, residual stresses and resulting porosity. The casting process can be adjusted, and the occurrence of defects reduced by changing of the gating and ventilation system design according to observed die melt flow[1][31].

Although the reduction in pressing velocity eliminates the air entrapment when filling the die, there is a risk of surface defect such as cold joints and cave-ins. The presented contribution is focused on the design of the runners. It has been hypothesized that the gating system needs to be designed such way to obtain the least possible vortex formation which leads to the gas entrapment within the cast. Turbulent melt flow in runners and gas entrapment is avoided by roundness the transitions in the constrictions and subdivisions of the runner. Thus, the equation of the direct proportionality should be applied: the smoother the transition of the main runner into secondary one, the lower the proportion of the air entrapment in the melt and cast volume. Therefore, the influence of the runner branching geometry on the air entrapment in the cast volume is investigated. The percentage of the air entrapment is evaluated at the time just before the start of the holding pressure phase, when the die cavity is filled to 100%. This time period of the casting cycle was chosen with regard to the fact that the holding pressure significantly reduces the air entrapment and porosity. Measurement and observations of the melt flow in runners were made using the Magmasoft simulation program. The chapter is grounded in conclusions included in the publication "The Influence of Runner Geometry on the Gas Entrapment in Die Cast Volume"[16].

4.2.1. Experimental Material and Methodology of Work

The numerical simulation of the air entrapment is the cast volume is carried out on the cast of the electric motor flange (Fig. 20). Air entrapment measurement is performed at locations where further mechanical machining of the castings occurs (Fig. 28). At these locations, the circumfluence of the cores forming the structural apertures in cast arise during the die cavity filling. While circumfluencing of the cores, two melt streams join into one and the assumption of air entrapment in the cast volume arises. The monitoring points are 3mm behind the core and 2mm from the cast surface to its volume (C1a – C4e).

The air entrapment has been investigated on castings attached to four different gating system designs. Fig. 28 shows a design based on the real gating system, where the secondary runner is connected to the main runner at an angle of 90° (hereinafter referred to as GS – a90°). Modified designs are provided with a continuous transition of the main runner into the secondary one, with a change in the radius of runner branching r_1 = 15 mm, r_2 = 25 mm a r_3 = 35 mm, as shown on the Fig. 2. Cross-section of runners are for all gating system design solutions constant.

The melt velocity in the secondary runner is assessed in the middle of the runner, on the middle pipe diameter (Fig. 28). Monitoring points MPR1a/b are placed opposite to the gates. The location of the MPR2a//b monitoring points is at the same distance from the end of the gate in all variants of the gating systems. The distance of 83mm is chosen with regard on the ensuring of the relevance of the melt flow velocity assessment. It is therefore desirable to measure the velocity in the locations where the melt flows in linear paths. The distance of the monitoring points MPR2 is determined according to the runner branching design MGS – r35. In the design of MGS – r35 the circular melt path while transition through the branching is being changed into linear 2mm before the monitoring point MPR2a/b.

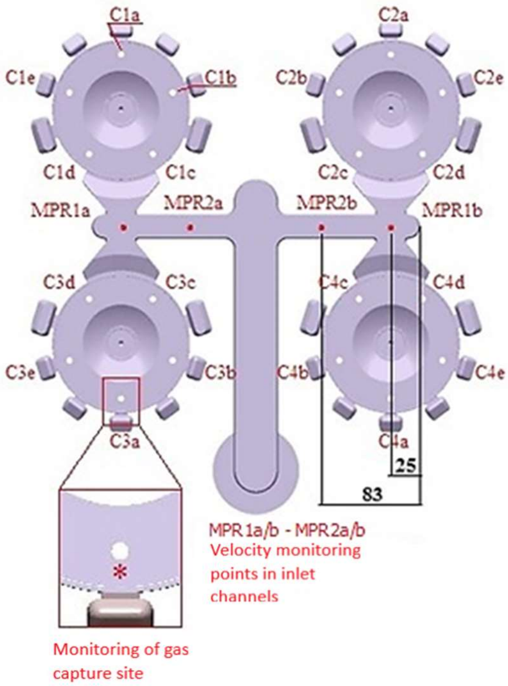


Fig. 28 Location of monitoring points

Fig. 29 Modified solutions of the main runner branching

Measurements were carried out using the Magmasoft MAGMA 5 simulation program – HPDC module. The cast is made of EN AC 47100 alloy. The machine selection and the setting of input technological parameters in the simulation is identical with the conditions in real production. It is presented in the Table 26.

Tab. 26
Setting of technological parameters

Technological parameters of the casting cycle	
Parameter	**Value**
Melt temperature in the filling chamber [°C]	617
Mould temperature [°C]	200
Piston velocity [$m.s^{-1}$]	2.9
Holding pressure [MPa]	25
Mould shaping cavity filling time [s]	0.016

4.2.2. Achieved Results

Using the MAGMA5 – HPDC module the values of air entrapment in monitoring points were found in the section Result/Air Entrapment. Measurement is performed at the time when the entire gating system including the overflows is filled at 100% of the volume, just before the start of a holding pressure phase. The filling time of the die cavity is 546.9 ms. Table 27 presents the average values of air entrapment in castings for the assessed gating systems designs.

Tab. 27
Values of Air Entrapment in Castings

Gating system	**Air entrapment [%]**
GS – a90°	6,006
MGS – r15	3,516
MGS – r25	4,549
MGS – r35	5,343

As it is shown in Table 27, the lowest percentage of the air entrapment in the cast volume is achieved in the gating system designated as MGS – r15, where the radius of the secondary runner curvature is r_1 = 15mm. Thus, the hypothesis: The smoother the transition of the main runner into secondary one, the lower the proportion of the air entrapment in the melt and cast volume, has been disproved. It was assumed that in the initial gating system GS – a90°, the vortices that assist the air entrapment in the melt will be arising at the branching point, and thus the air entrapment values in the cast will reach the highest values. Conversely, the gating system MGS – r35 provides the direct melt flow where the flow direction change is continuous and most direct from all of the selected variations of the gating system modification. The question to be solved refers to the cause of this condition.

The first step to solve the problem was to assess the melt flow at the main runner branching point and in the transition through the secondary runner. In MAGMA5 – HPDC module, the Result/Flow Tracer section was used to visualize the flow. Fig. 30 presents the melt flow in individual gating system design variants shortly before the end of the filling phase at 546 ms.

As anticipated, in the GS – a90° gating system, vortices occur at the branching point, which are observable throughout the filling phase. The flow in modified gating systems MGS is fluent and has the same character in all designs. Local swirling occurs at the end of the secondary runner, which serves as a buffer and its role is to calm the melt flow before entering the gate. Although the melt flow monitoring by trace parts confirms the presumption of vortex formation in the GS – a90°gating system, it does not clarify the increase in air entrapment in the melt depending on the increasing radius of runner curvature.

Since the melt flow assessment in the gating system did not provide the desired explanation, the issue solution was directed towards the secondary runner melt flow velocity monitoring. The distribution of monitoring points was constant for all the gating system design variants (Fig. 28). Table 28 presents the average velocity values at the monitoring points. The velocity values measured when the melt fully filled the cross-section of a runner were considered relevant.

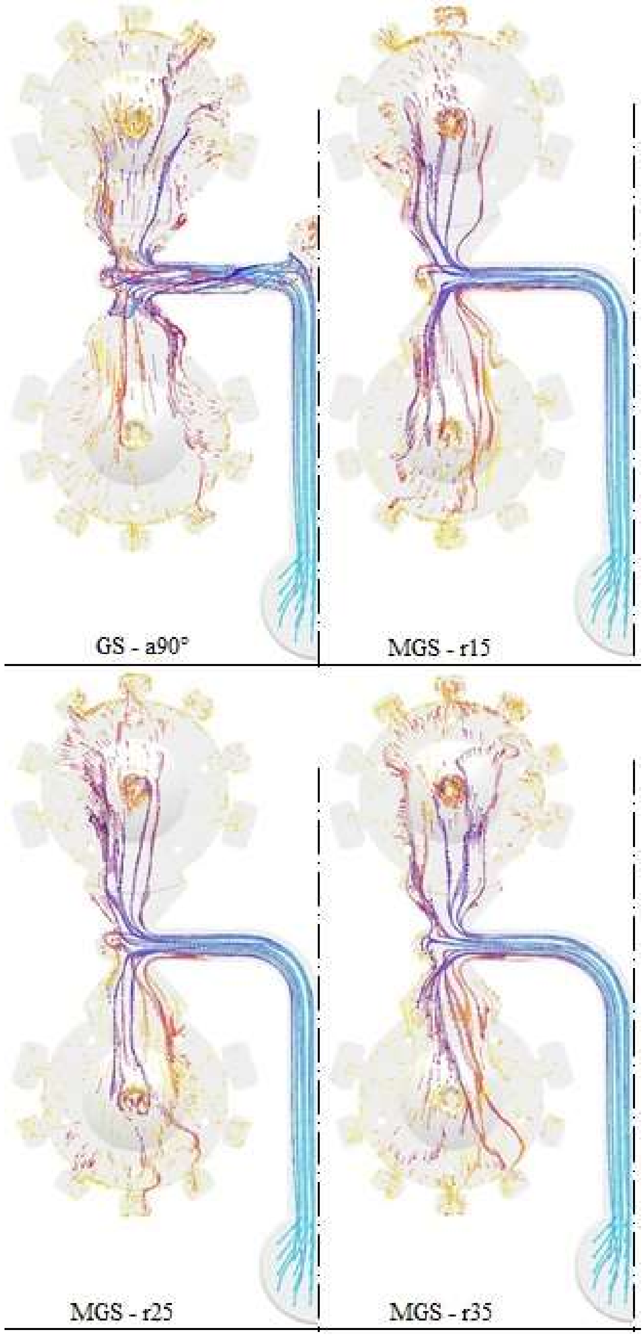


Fig. 30 Melt flow in runners

Tab. 28
Melt flow velocity in runner

Gating system	Velocity in measuring point [m.s^{-1}]		
		MPR1	MPR2
GS – a90°	average	9.95	19.54
	max.	11.10	21.56
MGS – r15	average	8.90	23.13
	max.	10.99	24.54
MGS – r25	average	10.90	23.18
	max.	12.31	24.50
MGS – r35	average	11.64	23.22
	max.	12.70	25.16

Table 28 implies that the MGS – r15 gating system achieves the lowest melt flow velocity at the monitoring points. Referring to the publications cited in the introduction [2][5][6][7], the cause of the refutation of the initial hypothesis is explained. Obviously, the air entrapment and melt flow velocity values in modified gating systems correlate with each other.

Adjusting of the pressure piston velocity is constant for all gating system variations. According to the hydrodynamic fundamentals, referring to the Bernoulli equation, the melt velocity in the secondary runners should remain constant. However, the measured values show that with increasing curvature radius of the secondary runner, the melt flow velocity increases. This phenomenon is explained with the reference to the dissipation of the melt flow mechanical energy. To put it simply, the kinetic energy of the melt flow is converted into other forms of energy. With smaller curvature radius, the melt fiber filaments are locally densified on the inner arc, increasing their internal friction which is converted into thermal energy and decreases the melt flow velocity behind the curvature. Runner velocity is also influenced by the gate velocity. The gate velocity determines the die cavity filling mode. For this reason, the gate melt velocity was also observed. The monitoring point was located in the middle of the gate, according to Fig. 26. Only the values of the melt velocity subtracted when the gate was completely filled were considered relevant. Table 29 presents the gate melt velocity values.

Tab. 29
Melt flow velocity in the gate

Gating system	Velocity in the gate [m.s^{-1}]	
	max.	priemer
GS – a90°	40.68	37.58
MGS – r15	39.92	35,48
MGS – r25	40.11	37.83
MGS – r35	40.75	38.40

The maximum gate velocity value is relatively constant for all gating system modifications. Variations can be observed at average velocity values. Upon observing the melt flow through the die cavity, the formation of discontinuity of melt flow behind the cores was noticeable at higher melt flow velocities. At higher velocities, the melt breaks out, allowing gases to enter the melt volume. It can be stated that the gate velocity and formation of the melt flow when transiting through the die cavity have a significant influence on the gas entrapment proportion in castings.

4.2.3. Conclusions

The chapter examined the influence of the main runner branching geometry on the air entrapment within the pressure die cast volume. Measurements were carried out using the Magmasoft simulation program. Based on the measurements, the direct effect of main runner branching geometry on the values of air entrapment has been demonstrated.

It was assumed that the smoother the transition of the main runner into secondary one, the lower is the proportion of the air entrapment in the melt and cast volume. Although the fluent transition is desired, the above statement does not apply.

The reasons for refuting this fact can be outlined into following points:

a) The theoretical melt flow velocity of runners can be determined based on the Bernoulli equation. However, the mechanical energy dissipation of the flow which affects the flow velocity is not counted with. Higher values of curvature radii eliminate the dissipation, thereby increasing the runner melt flow velocity. Higher value of the melt velocity during the transition through runner changes the character of the melt flow from laminar to turbulent, allowing easier air entrapment by the melt and its distribution to the cast volume.

b) As demonstrated, the higher runner curvature radius imparts the melt higher velocity during the transition through the secondary runner. This also influences the gate melt velocity under influence of which the melt flow during the transition through the die cavity and die filling mode are formed. When colliding the obstructions in the flow direction, such as cores or various protrusions on the cast, melt breaks behind these obstructions, thereby supporting the further air entrapment by the melt.

Based on the simulations and measurements, general recommendations for the gating system designs with the aim of air entrapment reduction can be outlined:

1. It is desirable to select fluent transitions between the main and secondary runners and to avoid the sharp angles when changing the melt flow direction,
2. When designing the runners, to find a suitable proportion between runner curvature radius and the melt velocity behind this curvature,
3. If possible, to guide the melt flow so that it does not collide with obstructions such as cores, ribs and protrusions during the transition through the die cavity,
4. It is advantageous to use CAE support, which enables to analyse the gating system design and discover hidden issues and their solutions.

4.3. Influence of Runner Branching Geometry on Air Entrapment in Die Castings Volume

The issue of air and gas entrapment by the melt flow when passing through the runners and their distribution along with elimination alternatives are explained in chapter 4.2. Air entrapment in the melt volume is conditioned by mould geometry. Complicated geometry leads to heavy three-dimensional melt flow with significant fragmentation of free surface and spatters.Alleviation of free surface fragmentation can be achieved either by suitable adjustment of input parameters of casting process or by adequate structure of the gating system [2][16].

The amount of air entrapment in the cast volume can be influenced by selection of technological parameters and by suitable structures of runners.The publication

“Optimization of the Runner Numerical Design Dimensions Using the Simulation Program”[17]proved correlation of technological parameters (such as melt temperature prior to entering the mould shaping cavity), velocity of meld flow in the ingate and filling period of mould shaping cavity with the cross section of the main and lateral runner. The chapter is devoted to assessment of cross section of the runner on air entrapment in the cast volume. The publication [17] proved that the increasing cross section of runner leads to decrease of melt flow velocity prior to entering the ingate. It presupposes more compact melt flow after passing through the ingate and smoother filling mode of mould shaping cavity [18]. A hypothesis was made: if spattering of liquid metal and fragmentation of melt flow after passing through the ingate must be avoided, it will be inevitable to select cross section of the runner so that compact and smooth melt flow is assured prior to entering the ingate. At the same time lower velocity should be assured as well. If the input technological parameters remain constant, especially plunger velocity, the following dependence must be applicable with the Bernoulli Equation being in force: the larger the ingate cross section is, the lower the melt flow velocity is. This fact thus determines smoother transfer of melt through the ingate and lower values of air entrapment in the melt volume. Therefore, the study revolves around influence of the ingate cross section on air entrapment in the cast volume. Percentage of air entrapped in castings is evaluated during the period right before holding pressure phase is triggered in case of which the mould cavity is 100% filled. This period of casting cycle was selected with regards to the fact that holding pressure considerably reduces entrapment of air and porosity. [7] Measurement and monitoring of the melt flow in runners were realized by simulation programme Magmasoft. The presupposed hypothesis was proved only partially, i.e., the melt flow reaches lower velocity right before the ingate yet values of air entrapment in the melt remained without noticeable changes. It is clear that excessive increase of cross sections of runners is undesirable in practice therefore the final part of the paper is devoted to designs of precautions regarding the factors which must be taken into consideration in case of selection of suitable ingate structure.

4.3.1. Experimental Material and Methodology of Work

Numerical simulation of air entrapment in the cast volume is realized with the cast of thrust face of a gear pump. Since pressure loss is unacceptable in case of the gear pump, the porosity value of castings must range within the values below 1%.

Measurement of air entrapment was realized in the areas behind structural holes of the cast which are designed for placement of friction bearings. In case of selected areas, the confluence of melt flows around the cores can be observed and thus there exists the highest probability of air entrapment in the cast volume (Fig. 31). In bearings a cyclic dynamic stress occurs and thus possible gas cavities in their proximity can act like a notch therefore they must be eliminated to the lowest possible value. Monitoring areas were in the middle of cast height h = 10.15 mm and 1mm behind the core.

Fig. 24 Location of monitoring points

Air entrapment was examined in case of castings attached to seven alternatives of gating system. Fig. 32 shows basic shape of primarily designed gating system. Table 30 presents basic geometric characteristics of the examined modified alternatives of the runners.

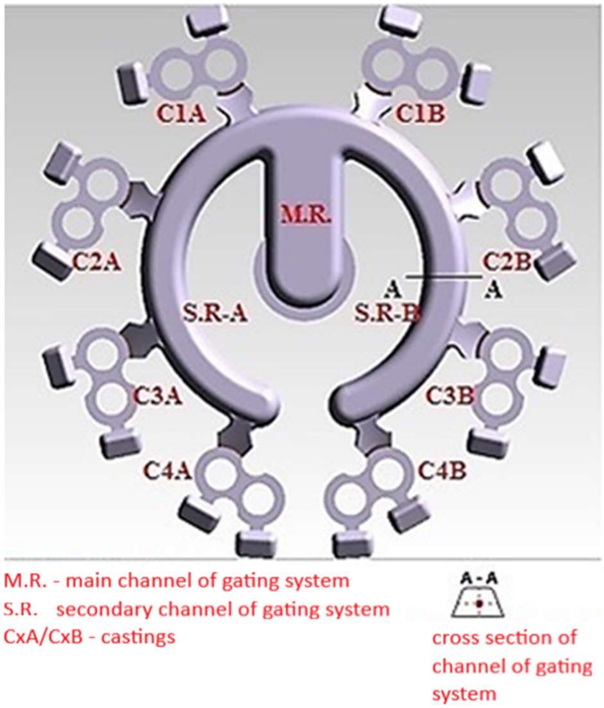


Fig. 25 Scheme of gating system

Tab. 30
Reviewed parameters of gating systems

Dimensions of runners		Cross-section area of the runner [mm^2]	Runner width [mm]	Runner height [mm]
S.R. 440 computing	S.R.	440.098	31.88	15.94
	M.R.	831.9	56.46	15.94
S.R. 420	S.R.	420	30.62	15.94
	M.R.	792.45	53.98	15.94
S.R. 400	S.R.	400	29.36	15.94
	M.R.	754.72	51.62	15.94
S.R. 380	S.R.	380	28.10	15.94
	M.R.	716.98	49,24	15.94
S.R. 360	S.R.	360	26.84	15.94
	M.R.	679.25	46.88	15.94
S.R. 340	S.R.	340	25.58	15.94
	M.R.	641.51	44.52	15.94
S.R. 320	S.R.	320	24.35	15.94

M.R.	603.77	42.15	15.94

Measurements were carried out with the use of the programme Magmasoft MAGMA 5 – HPDC module. The cast is made of alloy EN AC 47100. Setting-up of input technological parameters which is constant for all variations of structural design of ingate system is given in Table 31.

Tab. 31
Technological parameters of the casting cycle

Parameter	**Hodnota**
Melt temperature in the filling chamber °C	610
Mould temperature °C	200
Tempering medium temperature °C	190
Final piston velocity/1st stage, $m.s^{-1}$	0.9
Final piston velocity/2nd stage, $m.s^{-1}$	3.6
Piston velocity after decelerating, $m.s^{-1}$	1.5
Holding pressure, MPa	25
Mould cavity filling time, s	0.0226

The velocity of piston during the first phase of filling is required not to be high which prevents melt from being splashed in the filling chamber and air from being entrapped in the melt volume. It is useful to select velocity switching between the first and the second phase when the melt flow approaches the gate [26]. Fig. 33 shows development of velocity of plunger in relation to its position in the filling chamber.

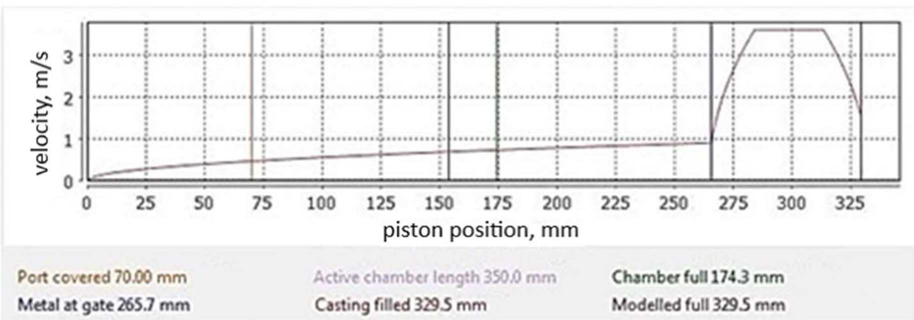


Fig. 26 Development of pressing piston velocity

4.3.2. Achieved Results

The values of air entrapment in the measurement points were detected with the use of the programme MAGMA 5 – HPDC Využitím programu MAGMA 5 – HPDC module, in section Result/Air Entrapment. The measurement was carried out during time when gating system along with spews were 100% filled right before the holding pressure phase was triggered. Tables 32 and 33 present average values of air entrapment in the castings behind the cores in the reviewed areas. Table 5 presents final average values o fair entrapment in the castings based on measured values in the individual measuring points. entrapment in the castings behind the cores in the reviewed areas. Table 34 presents final average values o fair entrapment in the castings based on measured values in the individual measuring points.

Tab. 32
Values of air entrapment behind the first core

Average values of air entrapment in the points X.A, [%]							
Cast /	**Cross-section of runner**						
m. point	S.R. 440	S.R. 420	S.R. 400	S.R. 380	S.R. 360	S.R. 340	S.R. 320
C1/1A	0.180	0.232	0.259	0.221	0.315	0.398	0.403
C2/2A	0.231	0.259	0.243	0.366	0.521	0.552	0.533
C3/3A	0.448	0.452	0.513	0.643	0.660	0.692	0.723
C4/4A	0.759	0.702	0.776	0.788	0.811	0.894	0.917
Average	0.405	0.411	0.448	0.505	0.577	0.634	0.611

Tab. 33
Values of air entrapment behind the second core

Average values of air entrapment in the points X.B, [%]							
Cast /	**Cross-section of runner**						
m. point	S.R. 440	S.R. 420	S.R. 400	S.R. 380	S.R. 360	S.R. 340	S.R. 320
C1/1B	0.335	0.321	0.381	0.396	0.395	0.405	0.543
C2/2B	0.325	0.318	0.362	0.447	0.575	0.635	0.637
C3/3B	0.513	0.729	0.766	0.769	0.769	0.735	0.795
C4/4B	0.807	0.819	0.828	0.890	0.871	0.925	0.965
Average	0.495	0.547	0.584	0.633	0.653	0.675	0.735

Tab. 34
Final average values of air entrapment in the volume

Average values of air entrapment in the castings [%]						
Cross-section of runner						
S.R. 440	S.R. 420	S.R. 400	S.R. 380	S.R. 360	S.R. 340	S.R. 320
0.450	0.497	0.516	0.596	0.615	0.655	0.690

Primary assumption that increasing cross-section area of the runner leads to lower value of air entrapment in the cast volume proved to be true. However, considerable differences among individual structural solutions of gating systems were not detected and values of air entrapment in case of all alternatives ranged within the scope of required values which was below 1%. The facts mentioned above lead to the conclusion that the area of the runner does not considerably influence the values of air entrapment in the melt volume.

It is inevitable to be cautious about increasing values of air entrapment in the cast volume between measuring points X.A and X.B, i.e., behind the first and behind the second core. In case of all castings the increase of air entrapment in the area behind the second core could be observed. The cause of such phenomenon could be searched for in the filling mode of the mould shaping cavity and melt flowing around the cores (Fig. 34).

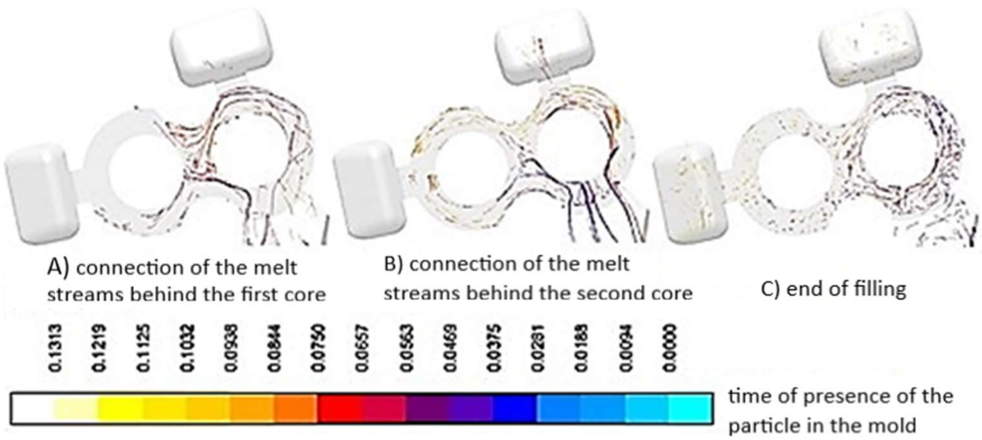


Fig. 27 Melt flowing along the cores

Filling of the mould shaping cavity was carried out by MAGMA 5 – HPDC module in the section Result/Tracer. The module allows monitoring the flowlines of liquid metal which present the filling mode and graphically determined the length of activity of particles in the gating system. Fig. 34 A shows confluence of melt flows behind the first core. In case of confluence of flows, the melt gets blended which is accompanied by whirling. Consequently, the melt is poured into the point behind the second core (Fig. 34B) in case of which further confluence of divided flow and blending of melt occurs. At the end of filling (Fig. 34C) the melt flow behind the cores is massive and major part of the melt which passed through double whirling is transferred to deaerating basins. Right the double confluence of the melt flow is the cause of increasing entrapment of air behind the second core.

Step increase of air entrapment in the melt can be observed in all alternatives of gating systems in case of castings C4. The reason of increase of air entrapment is position of deaerating basin which is situated behind the cast. The structure of gating system did not allow positioning of deaerating basin in the direction of flow, i.e., in the cast axis. Offset of deaerating basin results in change of direct melt flow through the cast leading to backward melt flowing around the core which does not allow full transfer of the melt to the basin. It supports air entrapment in the cast volume.

4.3.3. Results of the Experiments

The submitted paper is devoted to review of influence of cross-section area of the runner on the values of air entrapment in the cast volume. As it has been proved the cross-section area of the runner does not considerably influence the values air entrapment in the cast volume. The increase of air entrapment in the cast volume was detected in case of castings between the first and the second core. The influence on air entrapment in cast was proved also in case of change of position of deaerating basin.

Based on results presented in the paper the following conclusions can be drawn:

a) The change of area of the runner does not remarkably influence the values of air entrapment in the cast volume. Therefore, excessive enlargement of the area of cross section to reduce the melt velocity in the runner and to sedate the flow has no relevant significance in practice.

b) The values of air entrapment in the cast volume are influenced by the position of deaerating basins. The basins must be positioned so that direct melt flow through the cast is allowed. Thus, backward flow of melt in the mould shaping cavity is avoided. The melt containing air after flow blending behind the cores is directly drained to deaerating basins.

c) In case of production of quality castings with high requirements for tightness it is adequate to select the volume of deaerating basins so that their volume corresponds to the volume of melt flowing through the cast. The same is applicable especially in case when the filling of the mould shaping cavity is accompanied by bypassing of several cores placed in successive order. Thus, multiple whirling and blending of the melt can be observed during flow confluence in the area behind the cores. Therefore, it is desired to have the melt volume, which contains the air entrapped during pressing, drained to the deaerating basin and to have the cast made from continuous melt flow freshly delivered.

d) Evaluation of the porosity of castings cannot be considered as the average of the detected values. As it is shown in Table 32, Table 33, Table 34 the average value of air entrapment in cast is lower than the values detected in the individual points behind the second core. Therefore, in case of evaluation of the air entrapment it is inevitable to relate the entrapment values or porosity value to a particular point in the cast.

Based on the performed measurements it is possible to define basic factors influencing the air entrapment in the cast volume:

1) The cross section of the runner designed by calculation can be structurally modified by use of simulations. Cross-section area does not considerably influence the porosity values. When assessing the optimal solution, it is useful to focus on the temperature and flow velocity of the melt before entering the runner.
2) If the main and lateral runners must be branched, the branching must be performed with smooth transfer without sharp changes of the flow direction.
3) The melt flow must be directed to avoid hitting the cores and lugs when passing through the mould shaping cavity. If hitting the cores cannot be avoided, the deaerating basins must be positioned in the axis of the melt flow and their volume must be enlarged adequately.
4) It is useful to use the CAE support during technological preparation of production which allows analysing the structural design of the gating system and revealing the hidden problems along with their solutions.

4.4. Analysis of Interaction between Position of the Ingate and Selected Properties of Castings

In general, it is true that the cast homogeneity is significantly influenced by type of the alloy flowing in the runners and mode of filling of the die cavity. Laminar flow of the melt through the runners is preferred, which whirling of the melt supporting the enclosure of air and gasses in the melt volume is eliminated. The state can be achieved by correct dimensioning of runners, by continuous transition in case of change of runner sections and without sharp change of direction of the melt flow. It is also necessary to correctly adjust the speed of the filling piston during the filling phase of die casting cycle, i.e. in the course of time before the melt reaches the gate. The change in type of flowing occurs when the melt passes through the gate. Abrupt reduction of section of the sprue and increase of speed of the filling piston during moulding stage the melt flow reaches its final speed and shape which determines the filling mode of mould shaping cavity. The assumption that different area of connection of the cast to gate causes different mode of mould cavity filling led to a hypothesis that mechanical properties and homogeneity of the castings shall be different as well. The chapter deals with examination of influence of the gate position on values of porosity f and ultimate strength R_m in the selected cast. Using the numerical tests using the simulation program NovaFlow & Solid, the mode of filling the mold cavity was investigated, and the prediction of the development and occurrence of porosity in individual castings was performed. The experimental tests carried out with physical castings under operation conditions verified the values of porosity achieved by numerical method. At the same time the static test of tensile strength was carried out. On the basis of the results achieved through experiments the interaction dependences between position of gate, mode of filling of die cavity, values of porosity f and ultimate strength R_m were deduced. In conclusion these dependences have been transformed to recommendations for practice, especially for structural and design stage of the development of dies. From the scientific point of view of they serve to clarify all dependences between the individual parameters (not possible to be merged at the first sight) and aspects of die casting.

4.4.1. Experimental Material and Methodology of Work

Numerical and experimental tests were carried out with the cast of the test bar according to ČSN 420315 standard shown in Fig. 35.

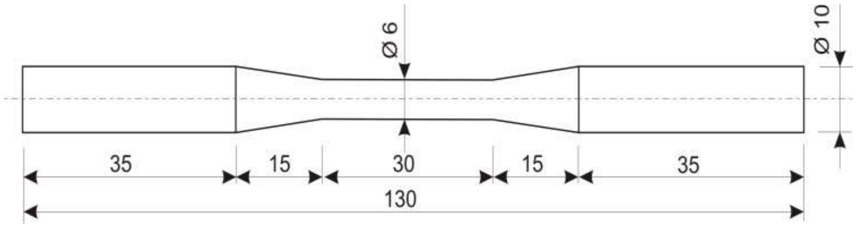


Fig. 28 Test bar 6x30

For the casting of test bars, a die casting mould was used designed for casting of testbars in accordance with ČSN 420315 standard. Fig. 36 shows the schematic placement of bars in the die with the gate being mouthed. The different way of the cut mouthing, its different structure and dimensions also assured different mode of filling of both the left and the right test bar. The influence of the cast shaping upon the level of inhomogeneity and upon the change of ultimate strength R_m was monitored. The test samples were made of alloy EN AC 47100.

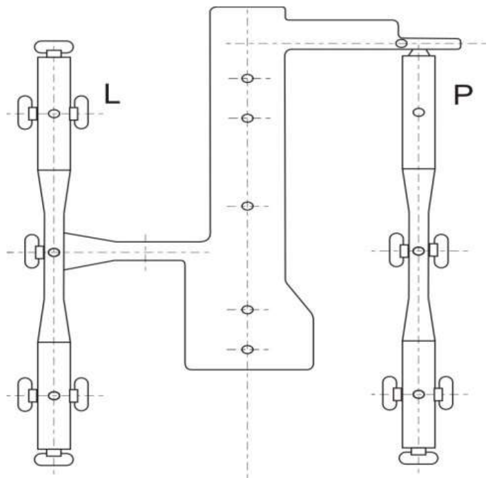


Fig. 29 Placement of castings in the die

Realization of production of test samples was carried out using the die casting machine Müller Weingarten 600. Setting of technological parameters of casting cycle was kept on the constant level according to Table 35. These parameters were followed even in case of realization of numerical tests of the set.

Tab. 35
Setting of technological parameters of casting cycle

Parameter	Value
Melt temperature in the die cavity °C	660 ± 10
Die cavity temperature °C	200 ± 10
Pressing piston velocity $m.s^{-1}$	0.75
Holding pressure MPa	20
Time of die cavity filling s	0.010

Static test of tensile strength was carried out using the device of ZDM 30/10, speed of jaw shift was set up to $10 mm.min^{-1}$. Assessment of homogeneity of castings was realized with scratch patterns of the samples taken off the volume of test bars. Assessment of macroscopic structure was carried out with the microscope Oplympus GX 51. The program of ImageJ determined porosity ratio expressed in percentage per area of scratch patterns.
For the realization of numerical tests, the 3D model of the ingate system was created by means of the program Autodesk Inventor. Simulations of the melt flowing through the gating system, cast solidification and assessment of porosity were carried out with the program of NovaFlow&Solid.

4.4.2. Achieved Results

The test samples were subjected to a simulation test by means of the software of NovaFlow&Solid in order to predict occurrence of defects of castings, especially of porosity assessment. Technological factors of the casting process were set up on the constant level in accordance with Table 35. During simulation it is possible to see clearly the flow of melt and method of the die filling for both test samples. Fig. 37 shows filling of the die cavity for the individual test bars.

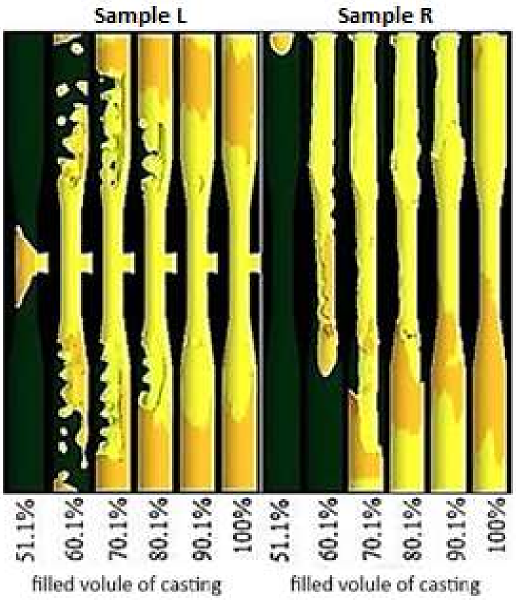


Fig. 30 Melt flowing in the die cavity

On the basis of the performed simulations, it was possible to assess porosity of the individual test bars. The summary of the assessed parameters is shown in Table 36.

Tab. 36
Parameters assessed by means of simulation

Location	Parameter	Value
	Time of die cavity filling [s]	0.0105
L	Time of cast solidification in the die [s]	5.018
	Porezita[%]	0.9
	Time of die cavity filling [s]	0.011
R	Time of cast solidification in the die [s]	5.018
	Porosity [%]	5.5

Experimental Analysis of Ultimate Strength *Rm*

Static test of tensile strength was carried out in case of seven sets of castings. The results of stating test of tensile strength are given in Table 37.

Tab. 37
Values measured in case of ultimate strength R_m

Sample		**Ultimate strength R_m [MPa]**	**Sample**		**Ultimate strength R_m [MPa]**
L bar	1	231	R bar	1	202
	2	239		2	204
	3	232		3	207
	4	235		4	209
	5	240		5	213
	6	242		6	211
	7	244		7	209
Average		237.57	Average		207.85

Fig. 38 shows a graph plotting the comparison of the individual values of ultimate strength R_m among the individual samples.

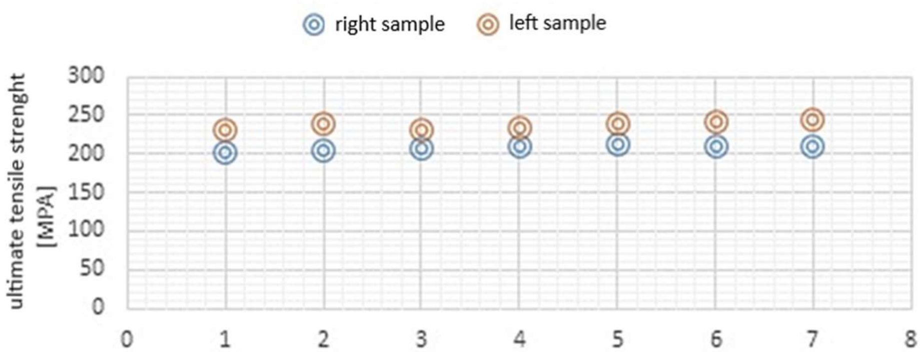


Fig. 38 Comparison of ultimate strength R_m of the individual samples

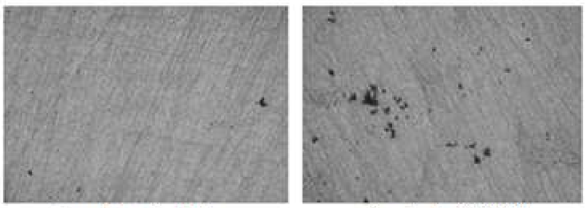
<u>Experimental Analysis of Porosity *f*</u>

To a relevant extent the CA programs can predict occurrence of defects of castings. To verify the results obtained by the simulation program applied in case of the examined samples the macroscopic analysis of porosity was realized. Scratch patterns were taken off several spots in the section of the test bar. As the scratch patterns were realized in several randomly selected spots of the test bar it can be assumed that the average value of percentage ratio of pores in the individual scratch patterns equals to overall value of porosity in the volume of the entire test bar. The detected results by means of scratch patterns are shown in Table 38.

Tab. 38
Average percentage ratio of porosity *f*

Sample		**Porosity *f* [%]**	**Sample**		**Porosity *f* [%]**
L bar	1	0.79	R bar	1	5.32
	2	0.96		2	4.79
	3	1.23		3	5.04
	4	0.82		4	4.97
	5	1.04		5	4.86
	6	1.15		6	5.28
	7	0.91		7	5.37
Average		0.99	Average		5.09

Fig. 39 shows the selected examples of the scratch pattern produced from the sample of L Bar – 4 and of R Bar – 1.



Sample L - 4/x100/ Sample R - 1/x100/

Fig. 39 Representative examples of scratch patterns of the selected samples

4.4.3. Conclusions of the Performed Experiments

On the basis of performed experiments it can be stated that the position of the cast in the die and its point of connection to the gating system is influenced by the values of ultimate R_m and porosity *f*. According to numerical tests carried out by means of simulation program and on the basis of their consequent verification by experimental test with the test samples it was detected that the values of monitored parameters were more favourable in case of samples of test bars with the left position.

The explanation of the phenomenon can be sought for in the mode of the melt flowing through the die shaping cavity. Theoretical aspects of projection of the gating systems do recommend the melt flow to avoid hitting the lugs and cores or the wall of the working die cavity after passing through the gate. At the same time, it is desired to have the melt flow parallel with longer dimension of the cast by means of which it is possible to eliminate absorption of air and gasses in the die by the melt. The cast placed in the die on the right meets the aforementioned conditions yet despite this fact it shows higher values of porosity. Right the simulation can offer the explanation of negation of theoretical bases. During the filling of the right bar (Fig. 37) the melt flow appears to be compact when passing through the die shaping cavity. Passing through the cavity is followed by the flow hitting the opposite side at the place of which a backward wave is formed proceeding towards the gate and pushing in front of its head the air in the die cavity to the areas with inactive bleeding (placement of bleeding holes is shown in Fig. 36). By means of the aforementioned behaviour of the holding pressure is not absolute and the air remains enclosed in the cast volume which results in increased values of porosity. Vice versa, in case of bars placed on the left the melt flow hits the opposite side of the die cavity, it splits up and an abrupt spattering of the melt in the area of the working cavity occurs (Fig. 37). This fact supports enclosure of the air in the melt, yet the melt flow is modulated so that the air pushed in front of its head is gradually released through the bleeding system out of the area of the working cavity. Placement of the bleeding holes (Fig. 36) consequently allows additional displacement of the air out of the melt volume during the stage of holding pressure activity. On the basis of these facts, it can be stated that the final porosity of the cast is influenced not only by the cast moulding in the die but also by distribution of the bleeding channels and holes so that their gradual ejection by the melt flow as well as preservation of their functionality is guaranteed as long as possible.

Experimental analysis of porosity confirmed assumptions obtained by means of simulation tests. It was detected that the average value of porosity f reached the value of 0.99% in the sample with the left position – L Sample and in the sample with the right position – P Sample it reached the value of 5.09% (Table 38). The reason has been explained above.

Ultimate strength R_m with the samples L Sample reached the values ranging from 230 up to 245 MP. Samples R Sample reached the values ranging from 20 up to 215 MPa (Table 37, Fig. 38). When comparing the values of ultimate strength R_m and those of porosity f, provable shall be their close correlation. Based on this fact, it can be stated that ultimate strength R_m depends on porosity f of castings.

Ultimate strength R_m depends on porosity f and porosity f depends on the mode of filling of the die cavity, on the moulding of cast in the die, on the placement of gate and on the distribution of bleeding channels and thus ultimate strength R_m is in close interaction with described structural adjustments of the gating system.

Since the interaction of ultimate strength R_m and position of the gate were proved, it is possible to express an experimentally supported statement that the ultimate strength R_m does not represent a purely material constant stemming from the properties of casting alloy, yet it depends on moulding mode of the cast and thus on the position of its connection to the gating system.

The experiments carried out on numerical and laboratory level proved that the position of the gate influences both selected properties of the castings. By moulding of the cast as well as by the structure and placement of the gate it is possible to influence the mode of filling of the die cavity, which determines tendency of absorption of air and gasses in the volume of the melt during filling. Imperfect air discharge from the working die cavity causes increase of porosity of castings, which can be, consequently, observed in reduction of mechanical properties, i.e. in this case, the values of ultimate strength are reduced. Ultimate strength is therefore indirectly proportional to porosity, which depends on air discharge out of the die cavity. Position of the runner of the cast and distribution of bleeding channels represent thus determining factors of the quality of castings.

CONCLUSION

The monograph presents clear overview if the issue of projection and design of gating systems of moulds and castings for die casting of metals.

The experiments show that even a slight variation of the gating system structure will cause a change of casting quality as mainly to porosity. It has been proved that change of the ingate geometry can influence mechanical properties and inner homogeneity of the casting. The ingate geometry influences the eutectic structure and share of its phases which influences back the mechanical properties. Since final increase of speed and modulation of the melt flow occur in the ingate and a direct impact on both the qualitative and structural properties was proved, it is inevitable to pay increase attention right to the design of this area of the gating system.

Influence of the sprue geometry is not negligible as well. The cross section of sprue and mode of its branching considerably influence the mode of the melt flow and thus the possibility of gas entrapment and vapour in the melt volume along with their distribution to the casting volume where they consequently decrease quality characteristics of the castings.

The experiments presented in the monograph are supported by the utilization of the simulation software. At present, the simulation software are of irreplaceable character and representation in the foundry plants and in the gating system structure. The application of simulation saves even 40% of time inevitable for design of the gating system, 30% of time inevitable for verification of the result in the laboratory and thus the entire process yield of 25% will be achieved.

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DESIGN OF CASTING AND GATING SYSTEMS – PRIMARY PREDICTION OF QUALITY OF DIE CASTING COMPONENTS

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