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CHARACTERISTICS OF SQUEEZE CAST AlZn5Mg ALLOY CASTINGS

CHARAKTERYSTYKA PRASOWANYCH ODLEWÓW ZE STOPU AlZn5Mg

The paper presents the results of investigations concerning the solidification kinetics, the mechanical properties, and the porosity of AlZn5Mg alloy castings produced by squeeze casting method and, for the purpose of comparison, by gravity casting. The examinations have been performed for 200×100×25 mm plate castings squeeze cast under the pressure values of 30, 60, or 90 MPa, at the constant die temperature of 250°C. The influence of the squeeze pressure value on the liquidus temperature of the considered alloy has been assessed on the basis of Clapeyron-Clausius equation. The characteristic phase transition points have been determined by means of derivative differential thermal analysis (DDTA) and then the maximum supercooling of the alloy in the initial stage of solidification has been calculated taking into account the influence of pressure on the equilibrium temperature value. Further the change of linear solidification rate of a casting has been determined depending on the squeeze pressure. It has been found that the supercooling of the alloy increases in proportion to the increase in squeeze pressure and reaches the highest value of 14°C for the 90 MPa pressure. For this pressure value the linear solidification rate is almost six times greater than for gravity castings. Metallographic examination has allowed for observing that the external pressure exerted on the solidifying casting results in the distinct refining of the alloy structure, the change in morphology of primary crystals, and the decrease of the gradient structure of the alloy. Squeeze casting advantageously influences the plastic properties of the alloy. The unit elongation of the squeeze cast alloy reaches the value of 16% and is twice the A_5 value determined for the gravity castings. The optimum squeeze pressure for achieving the highest mechanical properties is 30 MPa. The porosity of castings has been determined by the hydrostatic weighing method. The measurements have been performed for the specimens cut out of the middle parts of castings as well as of their edges. It has been found that the porosity of gravity castings reaches 4% and that the central part of the plate in particularly susceptible to the occurring of microporosity defects. The porosity distribution in squeeze castings is virtually uniform and its value is less than 1% for the entire examined range of squeeze pressure values.

Keywords: Al alloys, squeeze casting technology, solidification, porosity, mechanical properties, structure

Przedstawiono wyniki badań kinetyki krzepnięcia, właściwości mechanicznych oraz porowatości odlewów ze stopu AlZn5Mg wytwarzanych metodą prasowania w stanie ciekłym oraz dla porównania odlewów wykonywanych metodą grawitacyjną. Badania wykonano na odlewach płyty o wymiarach 200×100×25 mm prasowanych pod ciśnieniem 30, 60 i 90 MPa, przy stałej temperaturze formy 250°C. W ramach badań oceniono wpływ ciśnienia prasowania na temperaturę likwidus stopu w oparciu o równanie Clapeyrona-Clausiusa. Metodą ATD wyznaczono charakterystyczne temperatury przemian fazowych a następnie obliczono maksymalne przechłodzenie stopu w początkowej fazie krzepnięcia uwzględniając wpływ ciśnienia na położenie temperatury równowagowej. W dalszej kolejności wyznaczono zmianę linowej prędkość krzepnięcia odlewów w zależności od ciśnienia prasowania. Stwierdzono, że przechłodzenia stopu zwiększa się proporcjonalnie do ciśnienia prasowania i osiąga największą wartość 14°C dla ciśnienia 90 MPa. Przy tym ciśnieniu liniowa prędkości krzepnięcia odlewów prasowanych jest blisko 6-krotnie większa w stosunku do odlewów wytwarzanych metodą grawitacyjną. Na podstawie badań metalograficznych stwierdzono, że w wyniku oddziaływania ciśnienia zewnętrznego na krzepnący odlew następuje wyraźne rozdrobnienie struktury stopu, zmienia się morfologia pierwotnych kryształów oraz zmniejsza się gradientowa struktura stopu. Wykonywanie odlewów w technologii prasowania wpływa bardzo korzystnie na właściwości plastyczne stopu. Wydłużenie stopu prasowanego osiąga wartość 15% i jest dwukrotnie większe od A_5 wyznaczonego na odlewach grawitacyjnych. Optymalne ciśnienie prasowania, przy którym uzyskuje się najwyższe właściwości mechaniczne wynosi 30 MPa. Metodą ważenia hydrostatycznego oceniono porowatość odlewów. Pomiary wykonano na próbkach pobranych z części środkowej płyty oraz z jej brzegu. Stwierdzono, że porowatość w odlewach grawitacyjnych dochodzi do 4% i środek płyty jest szczególnie narażony na występowanie lokalnych rzadzizn. W odlewach prasowanych rozkład porowatości jest praktycznie jednorodny i kształtuje się na poziomie poniżej 1% w całym analizowanym zakresie ciśnień prasowania.

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1. Introduction

Squeeze casting technology applied for production of the high quality castings, mainly of aluminium alloys, is a method competitive to the pressure casting. Both methods are characterised by the large effectiveness and allow for producing castings of high shape and dimensional accuracy, low roughness, fine-grain structure, free of surface defects. They both enable casting of intricate shapes with thin walls and small machining allowances. The above detailed features make them the optimum methods for mass production of precision castings. But the main advantage of the squeeze casting technology over the pressure casting one is the rather insignificant porosity of castings, both shrinkage and gas one. Squeeze castings can be precipitation hardened by means of the thermal treatment, and their mechanical properties often exceed the values achieved by plastic worked products. They are particularly recommended for hydraulic elements working under high pressure values, from which the high pressuretightness is demanded. Squeeze castings significantly surpass the commonly used die castings or pressure castings in this respect [1-8].

The contemporary opinions [9-14] do not fully explain the problem of nucleation and crystal growth under high pressure. This results mainly from the experimental difficulties occurring while evaluating the kinetics of crystallization. The most frequent assumption is that a large quantity of nuclei, and by the same the considerable grain refinement, occurs due to the increase in the degree of supercooling caused by rapid heat exchange in the squeezed casting/die system. The shrinkage gap appears during the solidification of casting under external pressure remarkably later than in the case of common die casting solidification. Moreover, as far as very large pressures are concerned, castings can undergo plastic deformation and adhere to the die, allowing for intensive heat transfer during the whole solidification period. The degree of liquid metal supercooling is correlated with the squeeze temperature. Applying the pressure at the temperature close to the solidification point is the most effective [9, 13], since then the maximum supercooling and the maximum nucleating rate occur. On the other hand, too high squeeze temperature can almost completely nullify the effect of the risen pressure. The increased pressure results also in the increased coefficient of thermal conductivity and causes changes in the course of diffusion processes; activation energy grows with simultaneous decrease in the coefficient of diffusion [9,15].

The alloys of 7000 series (Al-Zn-Mg, Al-Zn-Mg-Cu) exhibit the highest strength properties among precipitation-hardened aluminium alloys. They have found a wide range of applications as structural materials in the aircraft, railway, and motor industry. They also serve as materials for viaduct and bridge girders, car armours, cryogenic pressure vessels, etc. [16,17]. The second factor significantly affecting the popularity of Al-Zn-Mg alloys is that their welding is easy. Differently from other precipitation-hardened aluminium alloys, the alloys of 7000 series are not sensitive to the cooling rate during their supersaturating [18]. They can be hardened both by cold and hot processes. During the ageing of the Al-Zn-Mg alloys the metastable dispersion phases precipitate in the following order [19]: supersaturated α solution $\rightarrow$ GP zones $\rightarrow$ η' phase $\rightarrow$ η ($MgZn_2$) $\rightarrow$ T ($(AlZn)_{48}Mg_{32}$).

The GP zones in conventional duralumin (Al-Cu) develop as flat coherent discs [20-22], while in Al-Zn and Al-Zn-Mg alloys they occur the most frequently in a spherical form [23-25]. The high strength properties at low temperature and at the temperature of 25°C are ensured either by dispersed η' phase particles or by GP zones. A significant loss of strength occurs, however, in elevated temperatures, what is the main disadvantage of zinc duralumin. The remarkable influence on the effectiveness of heat treatment of AlZnMg alloys is exerted by the primary structure of a casting, which in turn depends on refining and modifying treatment, conditions and rate of solidification, segregation of alloying elements, the quantity and types of impurities, shrinkage and gas porosity etc.

The purpose of the present work has been an assessment of the solidification kinetics, strength properties and porosity of plate castings made of AlZn5Mg alloy both by squeeze casting and by gravity casting method, the latter for the purpose of comparison.

2. Material and the methods of examination

The examination has been performed for the standard EN AB-71000 (EN AB-AlZn5Mg) alloy of the following chemical composition: 92.50%Al, 0.3%Cu, 0.32%Mn, 0.57%Mg, 0.48%Cr, 0.30%Ni, 5.25%Zn, 0.18%Ti, total content of impurities (Pb, Sn) – 0.10%.

Castings have been squeeze cast by means of PHM-250C hydraulic press equipped with a metal die of cavity dimensions 200 mm×100 mm×50 mm. The forging die consists of the punch-type upper die and the shaped lower die. Side walls of the cavity have no draft and the removal of a casting is realised by means of the ejection plate mounted in the lower part of the lower die. The upper die is attached to the press plunger. The pressure is applied by the hydraulic system after setting of its value. The die has been heated up to the temperature of 150°C and its surface has been covered with a protective insulating and lubricating substance (water solution of colloidal graphite). The charge of individual examined alloys has been melted in the PIT 50S/400 medium-frequency crucible induction furnace. The liquid metal has been overheated up to the 700°C and taken from the crucible with a pouring cap in portions of about 1500 g. Each portion has been poured into the lower die, than the pressing die has been lowered, the die closed and the squeeze pressure applied. The pressure has affected the solidifying and cooling casting for 30 s. After that time the die has been opened and the casting has been ejected by a set of four ejectors placed in corners of the plate. The castings have been produced under pressure values of 30, 60, or 90 MPa, as well as without applying pressure, i.e. by gravity method at the die temperature of about 250°C. Due to applying the direct squeeze method the thickness of obtained castings has been about 25 mm, being slightly varied because of the lack of the precise dosing of liquid metal. Figure 1 presents a photo of the lower die along with the fixed thermocouples.

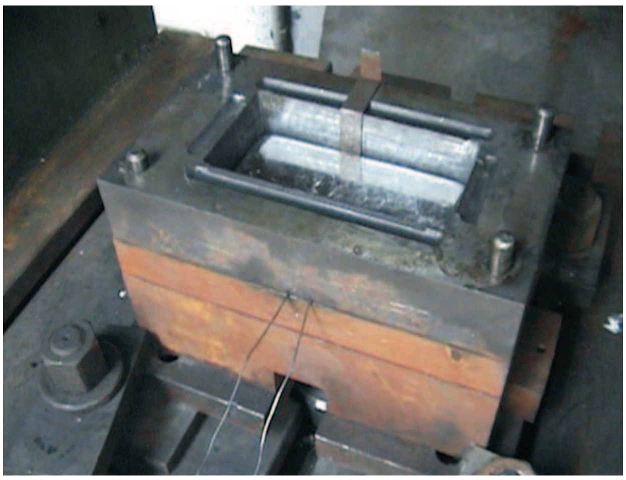

Fig. 1. Lower die used for examinations

3. Examination of the solidification process

Examination of the solidification process has been carried out by the DDTA method using the Crystaldigraph PC device. Two sheated NiAl-NiCr thermocouples of 1.5 mm diameter has been used, one of them placed 10 mm from the cavity wall (measuring the die temperature), the other in the thermal centre of the plate casting (DDTA measuring). Sampling time has been equal to 0.2 s. Before carrying out the examinations, the relationship between squeeze pressure and the liquidus temperature has been derived basing on the Clapeyron-Clausius equation in the following form:

$$\frac{dT}{dp} = \frac{V_L - V_S}{L_t} \cdot T_r \qquad (1)$$

where: dp – pressure increment, dT – temperature increment, V_L – specific volume of liquid phase, V_S – specific volume of solid phase, T_r – equilibrium transition point, L_t – heat of solidification.

A graphic representations of the above relationship are shown in Fig. 2. Calculations prove that for maximum pressure of 90 MPa applied during the examinations, the value of equilibrium transition point rises by about 10°C.

Starting from the DDTA measurement results, there have been determined the actual phase transition points, and then the supercooling of the alloy depending on the squeeze pressure. The results of these examinations are gathered in Table 1 and graphically presented in Fig. 2.

TABLE 1

Phase transition points depending on the squeeze pressure

Type of alloy	Pressure MPa	Temperature, °C	
		Beginning of α-phase solidification, T_α	Solidus T_{sol}
AlZn5Mg	atm.	641	618
	30	642	608
	60	643	605
	90	645	607

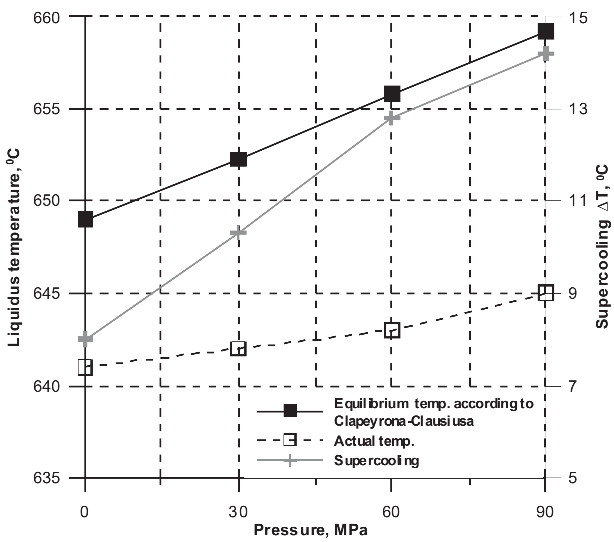

Fig. 2. Influence of pressure on the liquidus temperature and the supercooling of AlZn5Mg alloy

Crystallization of the alloy under external pressure is started with dynamic nucleation. The mechanism of this process is explained by creating and closing of cavities. The pressure in liquid metal increases during the cavity closing, therefore enabling generation of nuclei at higher temperature, however the pressure value do not affect the degree of supercooling ΔT. The supercooling both under the atmospheric pressure and under the increased pressure is the same [14]. The plot (Fig. 2) points out that as pressure increases, supercooling also rises and reaches maximum value 14°C for 90 MPa pressure. The increase in supercooling results from the fact that, on the one hand, the pressure causes an increase of the equilibrium liquidus temperature

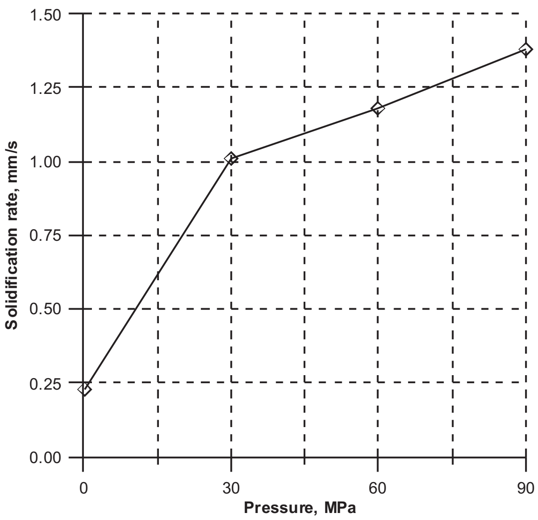

Fig. 3. The influence of squeeze pressure on the solidification rate of plate castings of AlZn5Mg alloy

(Clapeyron-Clausius relationship), while on the other hand, it rises the rate of heat transfer from metal to the die due to partial or total elimination of the gap between the casting and the die. The influence of squeeze pressure on the increase of cooling rate is reflected in the solidification kinetics. Figure 3 depicts a change in linear solidification rate versus squeeze pressure. The solidification rate for a gravity casting is at the level of 0.25 mm/s, while a casting squeezed under 90 MPa pressure solidifies at a rate of about 1.40 mm/s.

The characteristic feature of castings solidifying under external pressure is refining of their structure and the resulting strengthening of the alloy. Structural changes caused by squeeze casting of AlZn5Mg alloy are shown in Fig. 4. The size of α-phase crystals in squeeze castings is significantly smaller than in gravity castings. The morphology of the primary α-phase crystals is changed due to the applying of the external force. The gravity castings reveal grain structure, whereas the squeeze castings exhibit dendritic structure. Structural differences between these castings can be found also over the cast plate cross-section. A distinct gradient structure can be seen in a gravity casting (Fig. 4a, 4b). The grain density in the plate corner is remarkably greater than in the middle of the plate. The assessment of the degree of structure refining in squeeze castings brings us to the conclusion that the size of α-phase crystals is much the same over the whole plate casting. Squeezing leads to the increase in supercooling of the alloy and temperature gradients over the plate cross-section vary to the less degree than for the gravity casting method.

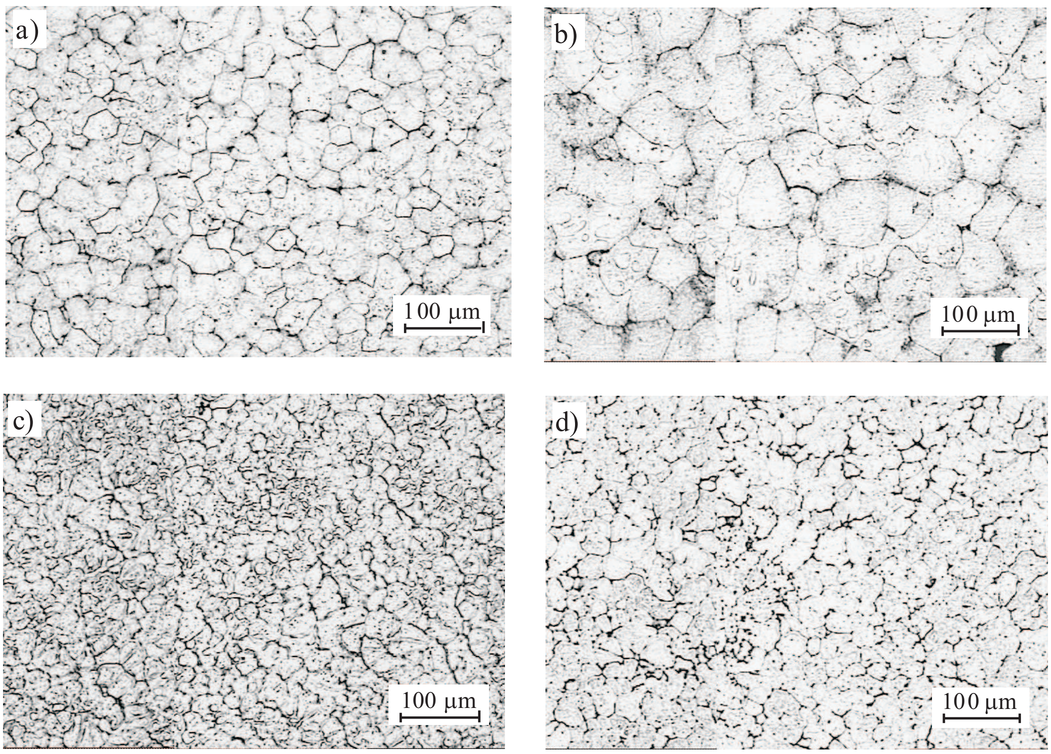

Fig. 4. The AlZn5Mg alloy structure: a) gravity die casting slab corner; b) gravity die casting, slab centre; c) squeeze casting, slab corner; d) squeeze casting, slab centre; etched with 4% HF

4. The assessment of mechanical properties

Examination of mechanical properties has been performed for the standardized tensile bars with length-to-diameter ratio of 5:1 by means of the ZWICK-1488 servo-hydraulic testing machine. The average values of tensile strength and elongation (from five measurements) are presented in Fig. 5.

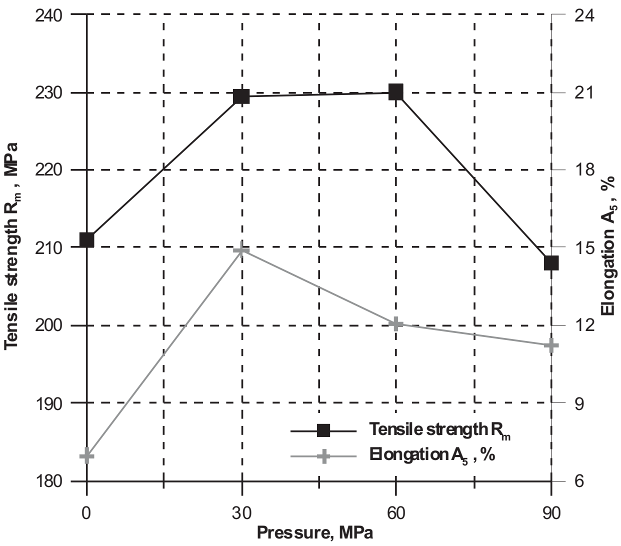

Fig. 5. Tensile strength and elongation of the AlZn5Mg alloy

The performed examinations clearly indicate a significant advantage of squeeze casting over gravity casting method. The AlZn5Mg alloy castings made by squeeze casting technology are characterised most of all by the very high plasticity: their unit elongation reaches about 15% and is twice the A_5 value for the gravity castings. Tensile strength of squeeze castings achieves the level of 230 MPa and is by 20 MPa higher than for gravity castings. A slight decrease in tensile strength and plasticity of the alloy has been noticed at 90 MPa squeeze pressure. The optimum squeeze pressure (from a set of considered values) bringing forth the high properties of AlZn5Mg alloy castings is equal to 30 MPa. The significant increase in plastic properties of the alloy results both from the refining of the primary structure and from the reduction of micro- and macro-porosity due to the influence of external pressure. The observed drop in mechanical properties of castings squeeze cast under 90 MPa pressure is probably caused by strong restraining of the material free shrinkage and thus originating remarkable shrinkage and thermal stresses.

5. Porosity measurements

Porosity has been examined by the method of hydrostatic weighing for the cuboidal block specimens of dimensions 25×25×100 mm. The specimens have been cut out both of the central and of the external parts of the plates, the latter from its shorter side, to evaluate the distribution of porosity within the volume of castings. The specimen have been weighted in air and in the water, then their densities have been calculated from a formula:

$$\rho_P = \frac{m_1}{m_1 - m_2} \cdot \rho_W \tag{2}$$

where:

ρ_P – specimen density, m_1 – weight of the specimen in air; m_2 – weight of the specimen in water; ρ_W – density of water.

Then in turn the porosity of the examined specimens has been calculated from the relationship:

$$P = (1 - LG) \cdot 100\% \tag{3}$$

where:

LG – the so-called 'gas number' determined by the expression LG= ρ_P/ρ_T; ρ_T – theoretical (standard) density, equal to 2762 kg/m^3 for AlZn5Mg alloy.

The employed test method allows for calculating the total porosity of a casting which is a sum of gas and shrinkage porosity. The results of density and porosity measurements held for castings made at various squeeze cast parameters are gathered in Table 2 and illustrated in Fig. 6. Figure 7 presents the results of shrinkage simulation for gravity cast plate. The simulation has been held by means of NovaFlow & Solid program for conditions corresponding to those realised during the experiment. This figure indicates that maximum porosity occurs in the middle of the plate and exceeds the value of 20%. The carried out experiments have revealed significant differences in size and distribution of porosity depending on the casting technology. Porosity of gravity castings determined for specimens taken from their central parts amounts to almost 4%, while for squeeze castings it stays at the level of 1% or is even lower. The effect of micro- and macro-porosity elimination is distinct even for the lowest squeeze pressure applied during the tests. Further growth of the pressure value up to 90 MPa does not significantly change the porosity value. The beneficial influence of pressure on the solidifying and cooled plate casting can also be seen while studying porosity distribution. The densities of specimens cut out both of central part and of the edge of a plate are of comparable level for all considered squeeze pressure values. It can be concluded that the porosity distribution in squeeze castings is virtually uniform. Results of porosity examination for gravity casting technology are different. The difference in porosity between the individual parts of the plate reaches about 2%, and the middle part of the plate is particularly susceptible to the occurring of local microporosity defects.

TABLE 2

Record of measurement results concerning density and porosity of specimens cut out of central parts and external parts (edges) of examined plate castings

Pressure, MPa	Specimens from the centres of plates		Specimens from the edges of plates		Average porosity of castings, %
	Density, kg/m^3	Porosity, %	Density, kg/m^3	Porosity, %	
atm.	2656.5	3.82	2656.5	1.86	2.84
30	2733.3	1.04	2733.3	0.87	0.96
60	2737.4	0.89	2737.4	0.61	0.75
90	2736.0	0.94	2736.0	0.75	0.85

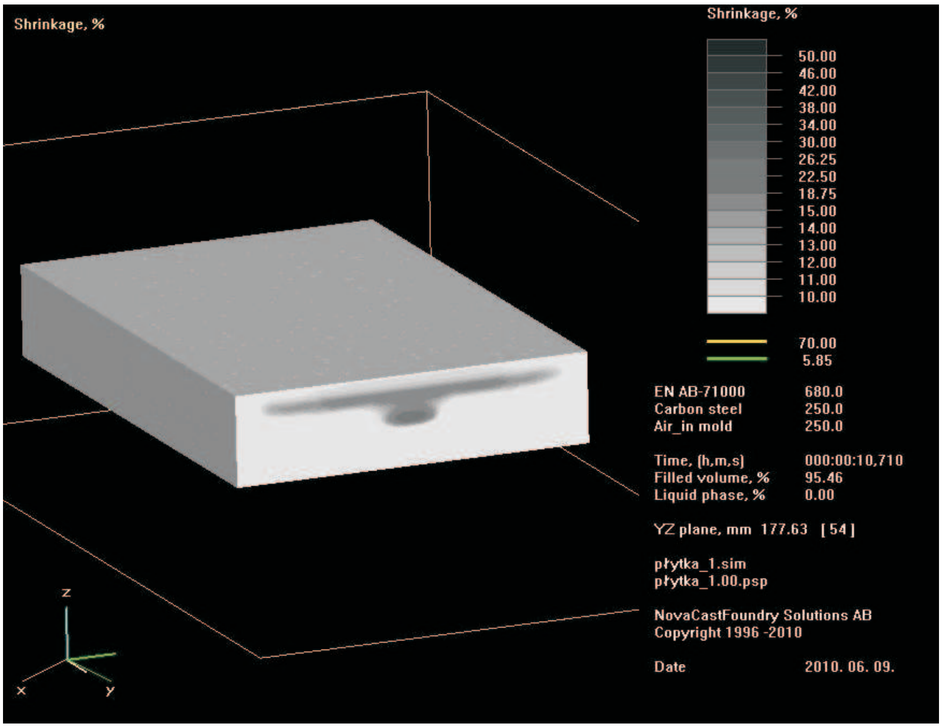

Fig. 6. Results of porosity simulation for a plate casting made by gravity casting method

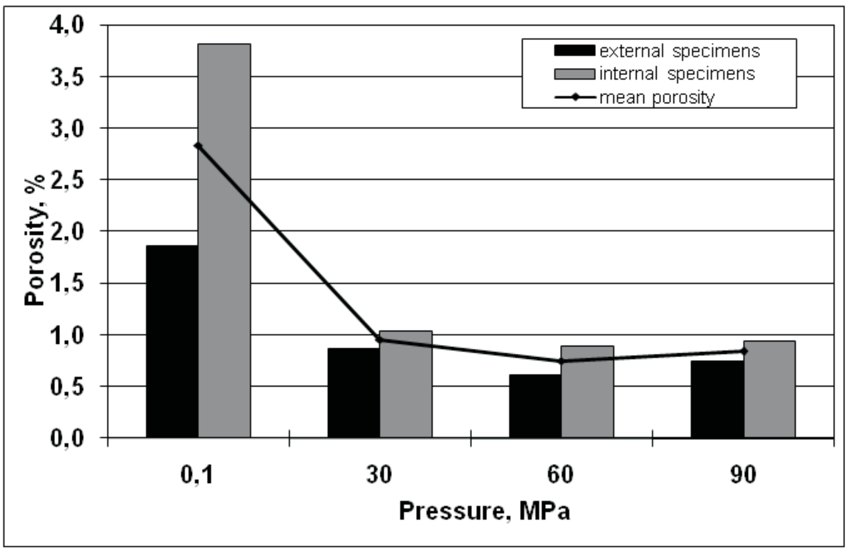

Fig. 7. Porosity of castings in their central part and at the edges depending on the squeeze pressure

6. Final conclusions

1. Squeeze casting significantly changes the solidification kinetics of AlZn5Mg alloy. Elimination of the shrinkage gap between the solidifying metal and the die results in almost sixfold increase in linear solidification rate of squeeze castings as compared with gravity castings.
2. The external pressure exerted on the solidifying casting increases the supercooling in proportion to the squeeze pressure value. For the examined castings the maximum supercooling has occurred for 90 MPa pressure and has been equal to 14°C.
3. Squeeze casting distinctly refines the structure of AlZn5Mg alloy and changes the morphology of primary crystals. The transformation of grain structure to the dendritic structure is observed.
4. The intensive heat exchange in the die/squeezed casting system results in the decreased temperature gradients over the cross-section of a casting. Therefore the castings of great structural homogeneity are achieved.
5. Squeeze casting technology ensures the high quality of AlZn5Mg alloy castings. Squeeze castings are characterised mainly by the high plasticity. The elongation of squeeze cast alloy reaches 15% and is twice the A_5 value determined for the gravity castings.
6. The optimum squeeze pressure for achieving the highest mechanical properties is 30 MPa.
7. Squeeze casting eliminates the macro- and microporosity of AlZn5Mg alloy castings i.e. decreases it under the 1% level and prevents the occuring of local micro-porosity.

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