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THEORETICAL ANALYSIS OF THE AlSi10Mg ALLOY SUSPENSION MANUFACTURING BY THE RSF PROCESS

ANALIZA TEORETYCZNA WYTWARZANIA ZAWIESINY STOPU AlSi10Mg W PROCESIE RSF

The mathematical model of the AlSi10Mg alloy suspension forming in Rapid Slurry Forming (RSF) method which allows for calculating the optimal process parameters for the presumed controlled properties of suspension is the purpose of the work. Physical system and heat exchange conditions of this process were presented and discussed in detail. Simplifications of the mathematical model and their analysis were presented. A model of the inner chill melting which generates the crystallisation nuclei was presented and solved. The suspension temperature and solid phase fraction in the forming metal slurry were calculated for a chosen model system. Experimental castings were made of metal slurry in cold chamber machine by using pressure die casting method.
Keywords: aluminium alloys, metal suspension, solidification, heat transfer

Celem pracy jest przedstawienie modelu matematycznego wytwarzania zawiesiny stopu AlSi10Mg w metodzie RSF (Rapid Slurry Forming), który pozwoli obliczyć optymalne parametry procesu dla zadanych kontrolowanych właściwości zawiesiny. Przedstawiono i szczegółowo omówiono układ fizyczny procesu i warunki wymiany ciepła. Opisano przyjęte uproszczenia i przedstawiono ich analizę. Przedstawiono model i rozwiązanie roztapiania ochładzalnika generującego zarodki krystalizacji. Wykonano obliczenia temperatury i odpowiadający jej udział fazy stałej tworzącej się zawiesiny metalowej dla wybranego układu modelowego. Wykonano odlewy doświadczalne z zawiesiny metodą ciśnieniowego odlewania na maszynie zimnokomorowej.

1. Introduction

Semi-solid metal casting brings many advantages related, on the one hand, to the casting quality improvement and, on the other hand, to the increase in the technology efficiency. Forming and crystallization of metal slurry during mixing gives rise to the non-dendritic structure characterised by the occurring of regular equiaxial crystals. Such crystals arise due to the breaking of dendrites and the subsequent rounding of crystals in the course of intensive mechanical, electromagnetic, or magnetohydrodynamic (MHD) mixing of the liquid metal [1, 2]. Such a structure significantly improves mechanical properties of castings, especially their plastic properties [3]. Mixing of metal makes the concentration of alloying elements (additions) uniform both in liquid and in solid phase, thus reducing macro- and microsegregation of chemical composition in castings. It also allows for eliminating microporosity of casting to the large extent and for reducing the solidification shrinkage, what improves the pressuretightness of castings and diminishes the risk of hot cracking as compared with conventional production methods. As a result of mixing, the apparent viscosity of metal is almost three times less than the viscosity value measured directly in the temperature of semi solid state. The reason of apparent porosity reduction is generating of a large number of growing primary crystals of the alloy and their nodulizing due to mixing [4, 5]. At sufficiently large mixing rate the viscosity of the alloy can be kept at a relatively low level even while the solid phase fraction reaches 50% [6, 7].

Despite of this, the increased viscosity of metal suspension reduces its castability in such a significant degree that castings can only be produced by the methods for which the cavity filling is forced by high pressure. The method of pressure casting is particularly useful in such a case. The low casting temperature increases the lifetime and the permanence of a pressure die and rises the efficiency by shortening the time for which an individual casting stays within a die. The methods of semi-solid casting demand for special equipment and for maintaining the strictly defined temperature range during the process

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to assure the uniform structure of castings composed of equiaxial crystals. Casting of metal suspension is limited by the size of castings, by the type of method applied for suspension achieving, and by the subsequent process of final product forming [2]. Many pressure castings made of aluminium alloys fulfill structural tasks, combining the intricate shape with high strength and low density. The presence of silicon in the most popular group of aluminium-silicon casting alloys significantly impairs the plastic properties, and for high cooling and solidification rates this results in relatively high strength properties and quite low plastic properties, including the low cracking resistance [3]. Therefore there exists a sensible reason for improving the plastic properties of these alloys.

Another way of achieving metal in semi-solid state is generating the nuclei in liquid metal due to the contact of metal which temperature slightly exceeds the liquidus temperature with a heat-extracting surface [6]. The NRC (New Rheocasting) method consists in pouring the liquid metal into a steel crucible. When the liquid metal touches the crucible surface, the primary phase begins to precipitate and then it is uniformly distributed within the volume of alloy by further pouring the metal into the crucible [3]. Next the growth of the primary phase crystals takes place. The development of a dendritic structure is prevented by multiple controlled cooling and heating of the suspension until the uniform globular structure is achieved [1, 4].

The SCP (Cooling Slope Plate) method relies on the pouring the liquid metal over an inclined cooling plate. When the liquid metal gets in contact with the plate surface, the rapid increase in number of primary phase nuclei occurs [8, 12]. The conditions stimulating the growth of primary phase into the dendritic shape cease to exist due to the free metal flow [9, 5].

Technological experience in metal suspension forming gave rise to the two ways of producing castings of semi-solid metal under industrial conditions. One group of methods, called 'rheocasting' by M.C. Flemings, includes these in which the final products is achieved directly from the solidifying metal after it has reached the semi-solid state, the second one called 'thixocasting' refers to the methods in which the final product is made of the pre-cast billet of equiaxial crystal structure re-heated directly before the shaping process to the temperature between the liquidus and the solidus [4].

One of the interesting methods of suspension forming by stirring is the RSF (Rapid Slurry Forming) method which relies on the introduction of a specified amount of solid alloy serving as an internal chill and simultaneously as a stirrer [2]. The crystallization nuclei arise at the surfaces of solid alloy (chill) during mixing process and are dispersed and uniformly distributed within the alloy volume by the centrifugal force, and the chill itself melts. The advantage of the method is that the relatively low solid phase fraction (20÷30%) provides for achieving a globular structure with simultaneous retaining the high fluidity of suspension, and the preparation of the suspension is much shorter and cheaper than for other methods [10, 11].

2. Mathematical description of the problem

The analysis has been done for the Rapid Slurry Forming method which is the most probable one for applying under industrial conditions thanks to the possibility of supervising and controlling the process by:

- determining the temperature of suspension arising during the process,
- calculating the volume (mass) of a chill depending on the solid phase fraction in the suspension,
- determining the suspension cooling rate and calculating of the size of arising equiaxial crystals,
- controlling the suspension properties (size and fraction of crystals, segregation of chemical composition, viscosity and castability) by changing the thermal properties of a system.

The simplifications of the mathematical description for this method of suspension forming can be assumed as follows. Mixing causes that the temperature is even within the volume of metal, so the temperature gradients do not exist in suspension and its temperature depends only on time. The heat exchange between the liquid metal and the chill fulfils the boundary conditions of the third type for which the heat transfer coefficient should be known. There is no heat transfer between the liquid metal and the crucible wall – this results from the assumption of minimised heat loss which enforces the ideal heat insulation of the system. It is assumed that metal crystallizes within a range of temperature, and the precipitation of solid phase is a linear function of temperature. The constant, temperature-independent thermophysical properties of the system are assumed.

The sought equation for the suspension temperature is obtained from the solution of heat balance of the system. A scheme of the system used for mathematical description of suspension forming and for calculations in presented in Fig. 1. The elementary amount of heat emitted by the liquid and the solidifying metal is described by the Equation 1, and the amount of heat absorbed by the chill is given by Equation 2.

$$dQ_z = -V_z\rho_z\left(c_z' + \bar{c}_z + \frac{L}{\Delta T_{kr}}\right)d\vartheta_z \tag{1}$$

where: V_z, ρ_z, $\bar{c}_z$ – volume, density, and the average specific heat of metal suspension, respectively; c_z' – specific heat of metal in liquid state; L – heat of crystallization; ΔT_{kr} – crystallization range; $\vartheta_z = T_z - T_{po}$, T_z – suspension temperature (variable); T_{po} – initial temperature of the chill.

$$dQ_o = \alpha_o F_o(t)\vartheta_z dt \tag{2}$$

where: α_o – the heat transfer coefficient at the boundary between metal suspension and the chill; $F_o(t)$ – chill surface area; t – time.

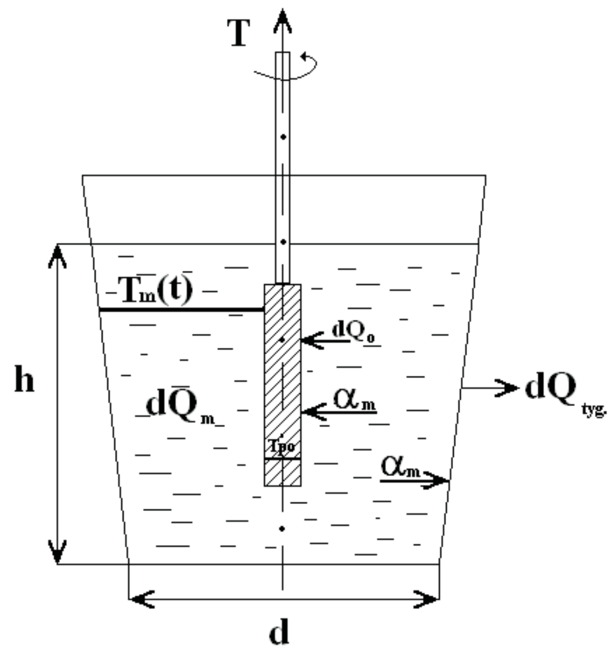

Fig. 1. Scheme of heat exchange during suspension forming in the RSF method

By comparing Equations (1) and (2) we arrive to the equation describing the metal suspension temperature in the form:

$$\frac{d\vartheta_z}{\vartheta_z} = -\frac{\alpha_o F_o(t)}{\left(c_z' + \bar{c}_z + \frac{L}{\Delta T_{kr}}\right)}dt \tag{3}$$

The unknown function $F_o(t)$ have to be determined from the solution of the problem of melting the chill in liquid metal and then integrated.

The optimum shape of a chill from the effectiveness of mixing point of view would be a propeller. Producing such chills would increase costs of the method so significantly that it would become uneconomic. The best solution is applying the chill in the form of infinite plate which performs well as a mixer. Therefore the chill in the form of infinite plate has been assumed for solving the considered problem, what allows for assuming the constant value for the area of heat exchange F_o (heating of the chill) during the process. Then the solution of Equation (3) for the initial condition $\vartheta_z(0) = \vartheta_{zal}$ (degree of overheating), the initial temperature of the chill and its area of heat exchange for a given size (mass) takes the following form:

$$\frac{T_z - T_{po}}{T_{zal} - T_{po}} = \exp(-At) \tag{4}$$

where:

$$A = \frac{\alpha_o F_o}{\left(c_z' + \bar{c}_z + \frac{L}{\Delta T_{kr}}\right)V_z\rho_z}.$$

3. Methodology and the results of investigation

In order to verify the presented mathematic model, the temperature of forming suspension has been calculated from Equation 4 for various V_0/V_m values, namely 0.1, 0.2, and 0.3. The lack of heat exchange between liquid metal and the crucible wall has been assumed for simplification, what corresponds to the ideal thermal insulation of the crucible. The following geometrical parameters of the system have been assumed: crucible diameter d=0.20 m, the height of metal in the crucible h=0.20 m; this gives the volume of liquid metal equal to V_m=0.00628 m^3. The chill has a shape of a plate of constant dimensions a = b = 0.15 m and variable thickness resulting from the volume changes. The calculations have been performed for AlSi10Mg alloy of the following chemical composition (% by weight): 89.33%-Al, 10.15%-Si, 0.31%-Mg, 0.41%-Mn, 0.59%-Fe, 0.09%-Zn, 0.11%-Cu, 0.01%-Ti. The following thermophysical properties have been assumed for calculations: initial temperature of liquid metal 923 K, liquidus temperature 868 K, average eutectic temperature 850 K, solidification temperature range 16 K, specific heat in liquid state 1250 J/kg·K, specific heat in solid state 1060 J/kg·K, heat of crystallization 390·10^3 J/kg, initial temperature of the chill 293 K, heat transfer coefficient $\alpha = 6.5\cdot10^3$ W/m^2·K.

Results of calculations are presented in Fig. 2. The obtained solution allows for designing the technology of suspension forming and the suspension properties. The suspension temperature, easy to control during the process, can be changed depending on the volume (size) of the internal chill and on the initial temperatures of liquid metal and the chill.

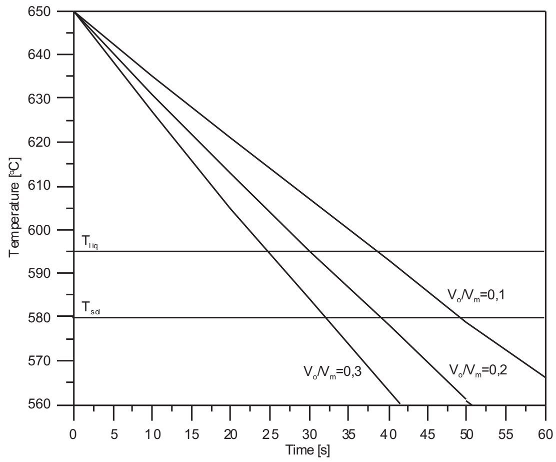

Fig. 2. Temperature of suspension for the RSF method

The time of suspension forming in the crucible can be determined from the obtained solution. This is very important from the technological point of view, because it suggests when the process should be stopped. As the chill volume grows, this time shortens, what makes the process more difficult to control. For a given suspension temperature the solid phase fraction can be calculated, being expressed for the present model by the following equation:

$$S(T_m) = \frac{T_L - T_z}{T_L - T_S} \tag{5}$$

where: T_L i T_S – actual liquidus and solidus temperature, respectively.

Figure 3 shows microstructure of AlSi10Mg alloy in a pressure casting made of alloy suspension according to the above presented method using the chill of a volume equal to the 0.1 of liquid metal volume. The characteristic non-dendritic structure was obtained, where the equiaxial crystals of primary phase (α) of the Si solution in aluminium (light areas) are surrounded by the eutectic phase (dark areas), being a mixture of α phase and Si crystals formed in the later stage of the suspension crystallization.

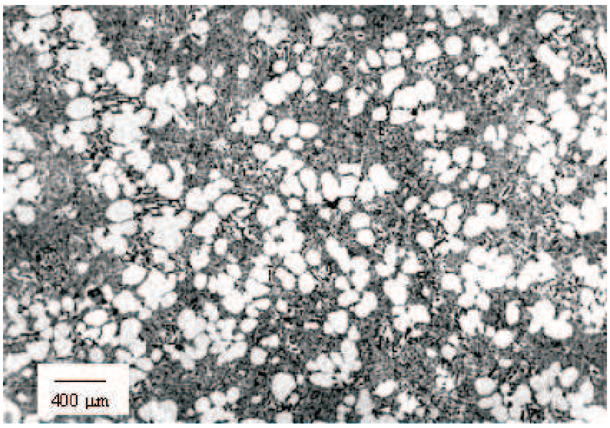

Fig. 3. Microstructure of AlSi10Mg alloy pressure cast of metal suspension

4. Conclusion

Production of suspension containing a given solid phase fraction $S(T_z)$ relies on stopping the mixing process after a time which corresponds to the T_z temperature (measured during the process). A separate problem is an analysis of heating and melting of the chill in the course of suspension formation. The optimum solution is that the chill completely dissolves during the specified period of time, after which the suspension achieves the presumed solid phase content (corresponding to the momentary suspension temperature value). Such a solution minimises the quantity of energy demanded for the suspension production. Optimizing of the process consists therefore in comparing the melting time of a chill of an assumed volume (mass) and a given shape with the time of forming the suspension of a presumed temperature (solid phase fraction). Finding a solution can demand for a series of approximations changing the suspension volume V_z.

It is possible to find, in a separate analysis, the equations for dissolving a chill of any shape, and by the same determining the function $F_o(t)$, which can be substituted to the balance equation (Eq. 3). Then the equation can be numerically integrated for a general case, and accurate solutions are possible for simple shapes of the chill. The problem can also be further developed by taking into account other functions of solid phase fraction within the metal solidification range. The mechanism of complete mixing of liquid occurs in most cases of metal crystallization, as well as the segregation model described by Scheil model, therefore the suitable temperature-dependent function of solid phase fraction exists. Mixing of solidifying metal applied in the analysed method comply with such a crystallization mechanism, however – differently from Scheil model for which segregation is the largest – mixing and growth of equiaxial crystals can lead to the levelled concentrations in crystals.

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