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INTRODUCTION

In the crystallization interval the viscosity and the initial stress get out mainly. According to Figure 1 the Newton law is valid for liquids (Ragan et al., 2007)

$$\tau = \eta \frac{dv}{dx} \qquad (1)$$

with:

τ – tangential stress of the streaming liquid layer in dependence on the distance x from the border [Pa]

η – dynamic viscosity of the streaming liquid [Nm^{-2}s]

v – speed of the streaming liquid layer in the distance x from the border [m.s^{-1}]

x – distance from the border perpendicularly on the streaming liquid direction [m]
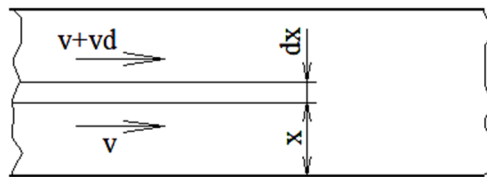

Fig. 1 A scheme of the single liquid layer streaming

The liquids that are governed by Newton's law are called Newtonian, and those that are not governed by Newton's law are called non-Newtonian. Among them are particularly important Bingham fluids governed by Bingham law (Ragan, E., 2007)

$$\tau = \eta_p \frac{dv}{dx} + \tau_0 \qquad (2)$$

with:

η_p – plastic viscosity [Nm^{-2}s]

τ_0 – initial stress that it is necessary to overcome for the movement on the liquid [Pa]

Further the seeming viscosity gets out here

$$\eta_s = \tau_0 \frac{dv}{dx} + \eta_p \qquad (3)$$

with:

η_s – seeming viscosity [Nm^{-2}s]

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At streaming Bingham liquids by Figure 2 the grain of the stream with the diameter d_0 behaves as a stiff bar and streams by the normal maximum speed v_0 proportional τ_0 (Ragan et al., 2007)

$$d_0 = k.\tau_0 \tag{4}$$

with:
d_0 – diameter of the stream grain streaming by the equal maximum speed v_0 [m]
τ_0 – initial stress [Pa]
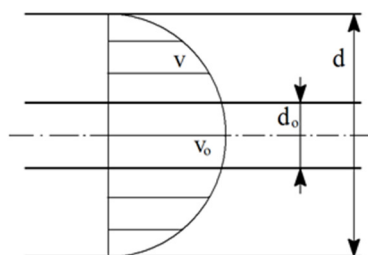k – constant [$m^3.N^{-1}$]

Fig. 2 The streaming liquid with representing of "the stiff" grain with the diameter d_0 and profile of the speed

Bingham fluids are alloys in the crystallization interval and suspensions for example liquid lubricants for the treatment of die casting molds, where solid particles float in the liquid solvent of the concentrate. Alloys up to the deposition of crystallization nuclei just above the liquid and solid phase crystals between liquid and solid at the crystallization interval are governed by Newton's Law, with a mixture of solid particles floating in the liquid phase by the Bingham Law.
When the tangential forces F of Figure 3 the imaginary layer A begins to move along the imaginary layer B in the direction of application of the tangential force F. For solids apply Hooke's law skid

$$T = G\frac{d_y}{d_x} \tag{5}$$

with:
T – tangential stress originated from the force F [Pa]
G – modulus of elasticity of the material in skid [Pa]
y – distance in the direction of the force F working [m]
x – distance perpendicularly on the direction of the force F working [m]
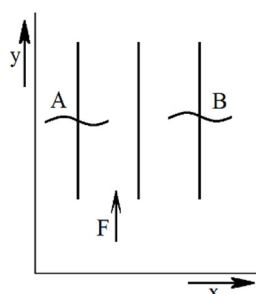

Fig. 3 The displacement of layer A over layer B under the force F

At liquids the Newton´s law is valid. If the liquid contains stiff particles in large concentration then at working the force F the behaving the liquid is expressed by the

Maxwell´s pressure equation (Ragan, E., Ružbarský,J., 2007)

$$\frac{d^2y}{dxdt} = \frac{\tau}{\eta} + \frac{1}{G}\frac{d\tau}{dt} \qquad (6)$$

with:

t – time [s]

This relation passes for

$$G \rightarrow \infty \qquad (7)$$

Then for liquids on the Newton´s law and for

$$\eta \rightarrow \infty \qquad (8)$$

Then for stiff phases on the Hook´s law for the skid.

RESULTS AND DISCUSION

Initial stress

According to (2) we can get the relation for the initial stress in the crystallization interval

$$\tau_0 = C.\Delta T^a K^{b\Delta T} \qquad (9)$$

with:

τ_0 – initial stress of the alloy in the crystallization interval [Pa]

ΔT – lowering temperature against the beginning creation temperature of crystallization germs [°C]

C – constant

K – constant

a, b – exponents

At the experimental measurement it was measured for Wood´s metal

$$\tau_0 = 0,01.\Delta T^{1,5}1,15^{10\Delta T} \qquad (10)$$

For the tin solder SnPb40

$$\tau_0 = 10.\Delta T^{1,5}1,02^{14\Delta T} \qquad (11)$$

For silumin with 88% Al, 7% Si, 0.5% Mn, 1.5% Fe and 0.5% Mg

$$\tau_0 = 0,6.\Delta T^{1,5}1,02^{15\Delta T} \qquad (12)$$
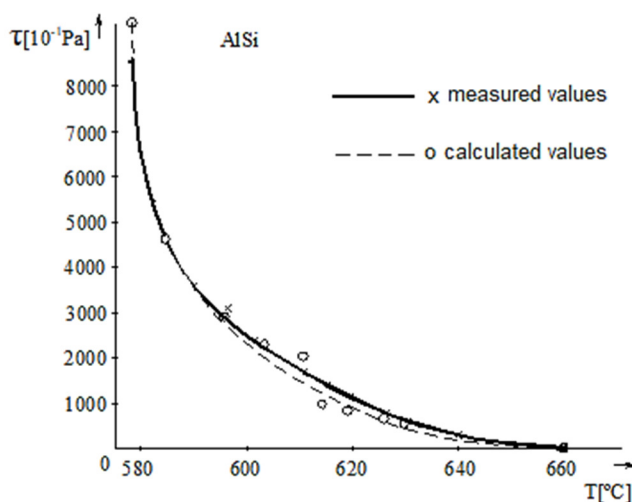
This dependence is represented on Figure 4.

Fig. 4 The measured and computed dependence of the silumin initial stress on the temperature lowering

Viscosity

According to Bingham's equation (2), movement occurs in the alloy after exceeding the initial stress τ_0.

According (Ružbarský at. al., 2014) a relationship can be obtained from the viscosity of the alloys in the crystallization interval

$$\eta_p = \eta \left[1 + c_1 \left(\frac{V}{V_0} \right) + c_2 \left(\frac{V}{V_0} \right)^2 \right] \tag{13}$$

with:

η_p – plastic viscosity [Nm^{-2}s]

η – dynamic viscosity of the liquid alloy [Nm^{-2}s]

c_1, c_2 – constants

V – volume of stiff particles [m^3]

V_0 – total volume [m^3]

And with regards on alloys in the crystallization interval

$$\eta_p = \eta(1 + k1\Delta T\alpha + k2\Delta T2\alpha) \tag{14}$$

with:

k_1 – constant [℃$^{-\alpha}$]

k_2 – constant [℃$^{-2\alpha}$]

ΔT – temperature lowering of the alloy against the beginning crystallization creation temperature [℃]

At the experimental measurement the relations are ushered for Wood´s metal

$$\eta_p = 0,125(1 + 0,0657\Delta T + 0,002\Delta T2) \tag{15}$$

for the tin solder SnPb40

$$\eta_p = 0,22(1 + 4,55.10 - 4\ \Delta T + 4,5.10 - 5\ \Delta T2) \tag{16}$$

and for silumin

$$\eta_p = 0,5(1 + 3,33.10 - 3\ \Delta T + 4.10 - 5\ \Delta T2) \tag{17}$$

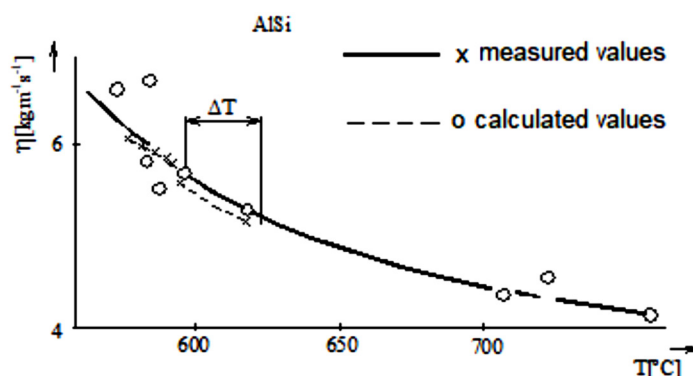This dependence is represented on Figure 5.

Fig. 5 The measured and computed dependence of the silumin viscosity on the temperature lowering ΔT

At filling the die cavity the laminar stream for aluminum alloys is by (4)

$$\frac{p}{sg} = \frac{32wv}{gd^2} + lg\frac{dw}{dt} + \frac{4\sigma}{dcos\vartheta} + \frac{p_{ox}}{sg} + \frac{p_g}{sg} \tag{18}$$

with:

p – pressure of the liquid metal in the die cavity [Pa]

p_{ox} – pressure necessary on disrupting the surface oxide membrane of the liquid metal [Pa]

p_g – pressure of the air and gasses working against the stream of the liquid metal in the die cavity [Pa]

w – liquid metal stream speed in the die cavity [ms^{-1}]

v – kinematic viscosity of the liquid metal [m^{2}s^{-1}]

σ – surface stress of the liquid metal [Nm^{-1}]

ϑ – adhesion angle of the liquid metal to the die material [°]

l – length of the liquid metal stream [m]

d – hydraulic diameter of the liquid metal stream [m]

s – specific mass of the liquid metal [kgm^{-3}]

g – gravity acceleration = 9,81 ms^{-2}

t – time [s]

According to the transferred measurement the value of viscosity for aluminum alloys increases up to eight times then almost one row more. By this ratio then the value of the first member of the right side equation (18). The laminar stream introduces the territory up to the critical Re=2300. Also when at higher alloy viscosity the speed can at fulfilling preceding condition raise its value get this raising is not expressive. Then value of the acceleration and by it also the second member on the right side expressing influence of acceleration is not remarkable. The change of the alloy viscosity is not a reason for the substantial change of the alloy surface stress and pressure necessary on disrupting the surface oxide membrane of the liquid metal. It means that the third and fourth member of the equation (18) on the right side would not also change substantially. Also it is not the reason to change the last member expressing resistance of the air and gases against the liquid metal stream in the die cavity on the right side of the equation (18).

From the brought analysis wastes that for overcoming the resistance of the alloy viscosity it is necessary the raising pressing force of the die casting machine. It is possible to reach by raising pressure of the machine working medium or lowering of the pressing piston diameter in the filling chamber. In both cases it is a danger of overcoming the die casting machine closing force (Ružbarský and Majerník, 2017). From it wastes that the value of the alloy viscosity it is not allowed to overcome the belonging frontier. It is possible to reach thus that undercooling the cast alloy in the crystallization interval against the liquids does not overcome the stated limit.

From the experimental results (Majerník and Ružbarský, 2016) follows that the admissible limit at aluminum alloys is

$$\Delta T_{ad} = 0{,}8\Delta T \tag{19}$$

$$\Delta T = T_L - T_S \tag{20}$$

with:

ΔT_{ad} – admissible undercooling aluminum alloy against the liquids [°C]

ΔT – temperature crystallization interval of the alloy [°C]

T_L – temperature of the aluminum alloy liquids [°C]

T_S – temperature of the aluminum alloy solidus [°C]

CONCLUSION

When this limit is exceeded, the viscosity value of the aluminum alloy increases significantly. Then, in the first case, the aluminum alloy does not enter the die cavity through the indentation, solidifies in the inlet channel without filling the die cavity and forming a die casting. There is a risk of mold damage.

In the latter case, after a necessary increase in the pressing force, there is a risk of exceeding the closing force of the machine for die-casting and splashing of liquid metal in the mold dividing surface, which has often led to very severe and fatal injuries. Such extreme conditions can be excluded only by controlling the mold temperature when casting under pressure to an optimum value. In principle, cooling and heating ducts are provided in the mold with the respective working medium, which is water and oil, or in other ways, for example, air-cooling or electrical resistance heating. By means of a suitable combination it is possible to achieve directed solidification of the casting with the elimination of pores, cold joints and defects, whereby a significant improvement of the quality of the die casting can be achieved. This is provided by a mold temperature control device.

When the liquid metal enters the mold cavity, the surface layer in the mold cavity heats up very quickly. During cooling and ejection of the casting from the mold, cooling of the surface layer of the mold cavity takes place again. This process is repeated for each casting cycle, resulting in thermal fatigue of the mold material. The plastic deformation capacity of the mold material is exhausted and surface cracks and end of life of the mold occur. By controlling the temperature of the mold, the thermal stress significantly decreases and the mold life is extended by at least one third.

ACKNOWLEDGEMENTS

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Abstract. In the contribution the high growth of viscosity and initial stress of alloys in the crystallization interval with undercooling against of the liquidus follows from theoretical analysis. At these alloys used in pressure die casting the permissible undercooling that does not endanger pressure die casting operation. The application of the device for die temperature regulation ensures the safe operation.