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R. PASTIRČÁK*[#], J. ŠČURY*

EFFECT OF PRESSURE ON THE CRYSTALLISATION OF AlSi7Mg ALLOY

This paper deals with influencing the crystallisation of Al alloys by a direct squeeze casting method. The effects of changed cooling rates of the casting is evaluated using a heat transfer coefficient at different casting conditions. The experimental results obtained by temperature measurement of the casting and the mould were used to predict the casting and mould surface temperatures using regression curves. The measured temperatures in the sub-surface layers were used to determine the amount of heat transferred from the casting to the mould. The amount of transferred heat increased 20-fold due to the effect of pressure. We also evaluated the effect of the acting pressure on the mechanical properties and microstructure of the alloy used. The process parameters were varied in the experiment.

Keywords: squeeze casting, heat transfer coefficient, heat flux, Al alloys, mechanical properties

1. Introduction

Squeeze casting is a technology currently used mainly in the automotive industry in order to improve the mechanical properties of the individual parts of products and to reduce their prices. The technology of crystallisation under pressure uses liquid molten metal that is squeezed under pressure within the metallic mould cavity in order to eliminate faults associated with shrinkage and porosity [7-9]. The pressure exerted on the melt results in a significant increase in the melt-mould heat transfer coefficient. This positive effect is associated with elimination of the air gap, which normally forms during the melt solidification at the mould-casting interface. Due to the exerted pressure, the melt and later the solidified casting are continuously in contact with the metallic mould. Rapid cooling results in a reduced solidification time of the casting, and thus in a finer structure of the alloy. The pressure also affects the structure of castings, where it causes a smaller grain size in the primary, structure, changes the morphology of eutectic and intermetallic particles that act less harmfully [6]. Affecting the structure results in changed mechanical properties. It is favourable that strength, elongation as well as fracture toughness increase, similarly as after grain refinement through melt inoculation, which is commonly used in foundry practice of Al, Mg or Zn-based alloys, e.g. [1-3]. Materials crystallised under pressure have properties surpassing the same materials that are gravity cast and solidified in permanent casting moulds [5]. This technology is not suitable for large castings and alloys with high melting temperature, as indicated by Chatterjee and Das [4]. Moulds used in squeeze casting have the advantage that they enable to produce high quality surfaces and narrow dimensional tolerances. The method of squeeze casting also makes it possible to limit, or in some cases completely prevent, the formation of casting defects. The main disadvantages of this method include especially high investment costs, reduced technical life of the moulds due to high pressure load, and little experience with the practical usage of the method [10].

2. Experiment methodology

Direct squeeze casting method was used for casting with crystallisation under pressure. A precisely measured amount of liquid metal was poured into the mould cavity. The mould was made of low carbon steel. The surface of the mould cavity and of the piston was treated with a protective coating of Terracotta type. Subsequently, the mould was closed using the piston that exercised pressure on the melt. The piston had a square section with an area of 1,000 mm^2. The onset of exercising pressure was approximately 5 seconds after the mould was filled. The samples were affected until the melt cooled down to 200°C. During the experiment we cast 10 samples at different casting temperatures and applied pressure. Table 1 shows individual parameters of casting. The first sample was gravity cast at a casting temperature of 670°C. Other samples were made using squeeze casting technology of casting under pressure. In both cases, the metallic mould was preheated to 200°C. To measure the mould and melt temperatures we used 8 Cr-Ni K-type thermocouples with a wire diameter of 0.25 mm in order to achieve rapid response. Figure 1 shows the position of the thermocouples.

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* KTI, SJF, ŽILINA, UNIVERZITNÁ 1, 010 26 ŽILINA

[#] Corresponding author: richard.pastircak@fstroj.uniza.sk

TABLE 1

Casting parameters for individual samples

Sample	Pressure (MPa)	Casting temperature (°C)
1	0,1	670
2	50	670
3	100	670
4	150	670
5	50	690
6	100	690
7	150	690
8	50	710
9	100	710
10	150	710

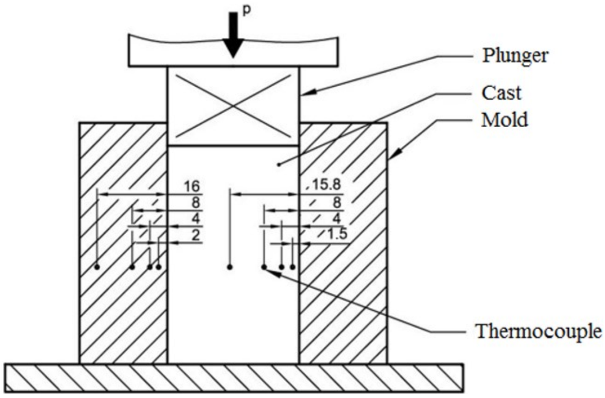

Fig. 1. Schematic diagram of the thermocouples position

The governing heat transfer equation in one-dimensional cylindrical coordinates is given by Eq. (1):

$$c_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(K_{al}(T) r \frac{\partial T}{\partial r} \right) \tag{1}$$

where $K_{al}(T)$ is the thermal conductivity of aluminium metal which varies with casting temperature and r is radius of working area of the piston[5].

The heat flux at the casting-mould interface can be calculated from the temperature gradient on the surface and in the subsurface layer using the following Eq. (2):

$$q = -\lambda \frac{\partial T}{\partial x} = -\lambda \frac{T_1 - T_2}{\Delta x} \tag{2}$$

where λ is the coefficient of thermal conductivity from the casting to the mould, $T_{1,2}$ are the measured points temperatures, and Δx is the distance between these points. At the interface, the average heat transfer coefficient (*HTC*) can be expressed mathematically as Eq. (3):

$$HTC = \frac{q}{(T_O - T_F)} \tag{3}$$

where T_O is the casting temperature, and T_F is the mould temperature at the casting-mould interface.

Experimental works were carried out in the alloying and casting laboratory of University of Žilina. As indicated by Aweda [5], the most significant effect of pressure on the mechanical properties of aluminium alloys occurs in Al-Si alloys. This is mainly due to changed morphology of eutectic silicon. Therefore we chose AlSi7Mg alloy as experimental material. Its chemical composition is given in Table 2.

TABLE 2

The chemical composition of AlSi7Mg alloy

The chemical composition [wt. %]			
Si	**Mg**	**P**	**Ca**
7,18	0,29	0,0005	0,0005
Ti	Fe	Sr	Pb
0,096	0,12	0,04	0,0005
Mn	Na	Sn	Zn
0,002	0,005	0,001	0,01

3. Results

The measured values were processed in Microsoft Excel spreadsheet. We used the measured data of temperature in the casting and in the mould to estimate the temperature of the casting surface and the mould surface. Fig. 4 and 5 show the courses of temperature for individual sample. At individual time sections, we used the regression curve to determine the temperature at zero distance from the surface. Fig. 2 and 3 show the principle of evaluation.

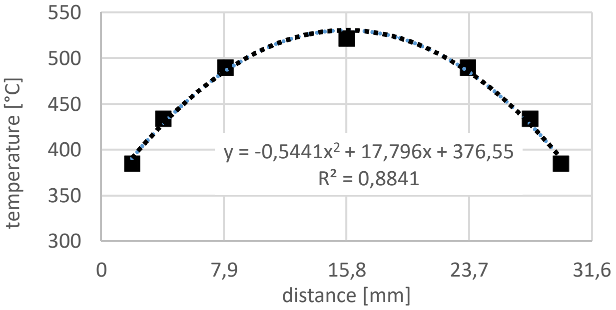

Fig. 2. The regression curve of temperatures in the casting

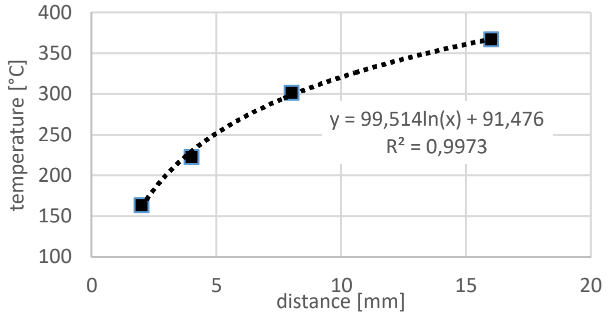

Fig. 3. The regression curve of temperatures in the mould

Figure 4 shows the course of temperature when casting without the application of pressure.

Figure 5 shows the course of temperature when using the technology of squeeze casting.

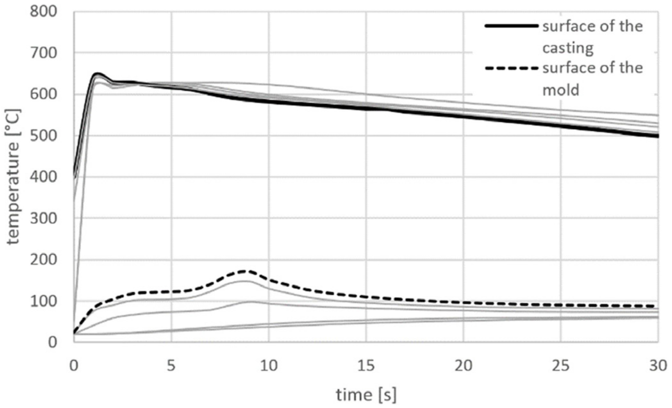

Fig. 4. The temperatures in the casting and in the mould at gravity casting

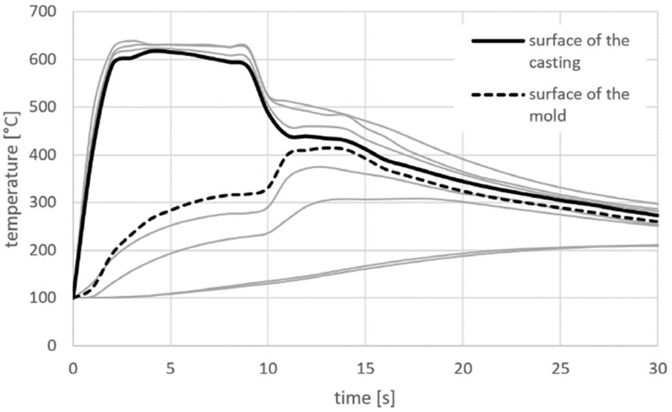

Fig. 5. The temperatures in the casting and in the mould at the operating pressure 150 MPa

3.1. Heat flux and heat transfer coefficient

The heat flux at the casting-mould interface was determined from the temperature at the mould surface and temperatures 2 mm below the mould surface using equation (1). The results of heat transfer coefficients were calculated by equation (2). The course of heat flux and heat transfer coefficient for each sample is shown in Figures 6-15.

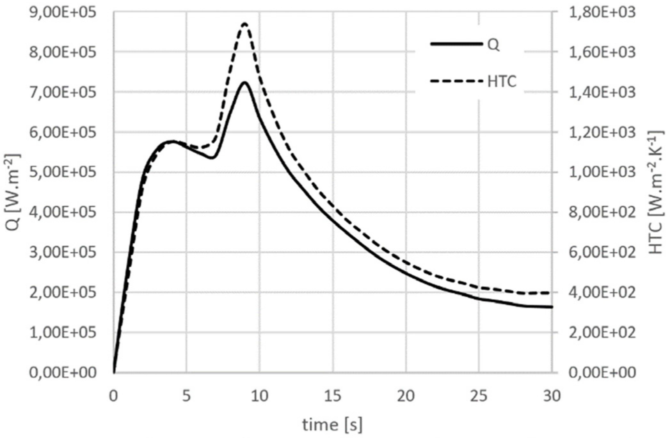

Fig. 6. Heat flux and HTC in gravity casting at pouring temperature 710°C

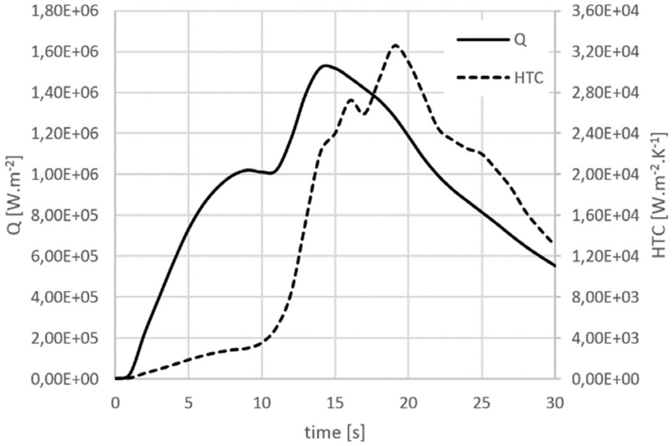

Fig. 7. Heat flux and HTC at pouring temperature 670°C and pressure 50 MPa

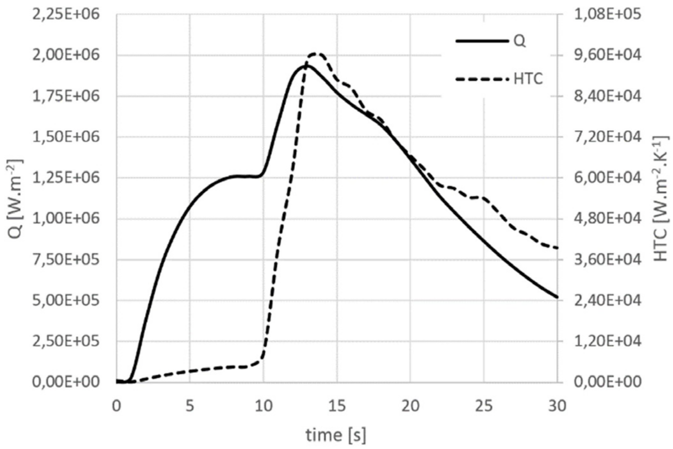

Fig. 8. Heat flux and HTC at pouring temperature 670°C and pressure 100 MPa

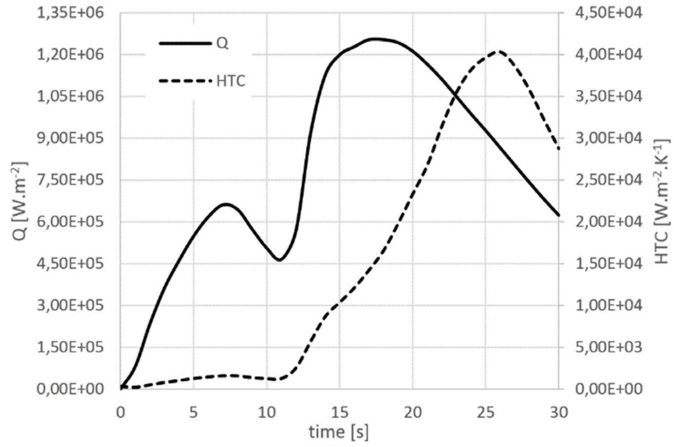

Fig. 9. Heat flux and HTC at pouring temperature 670°C and pressure 150 MPa

The results of the measurements clearly show that there has been a sharp increase in the heat flux and heat transfer coefficient, resulting in faster cooling of the cast. This fact led to a change in the investigated sample structure.

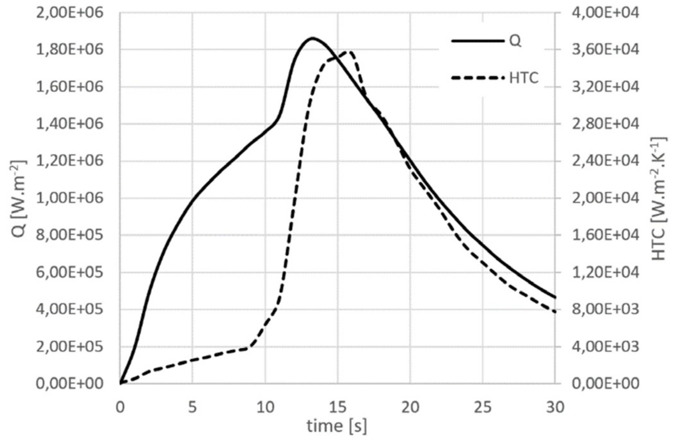

Fig. 10. Heat flux and HTC at pouring temperature 690°C and pressure 50 MPa

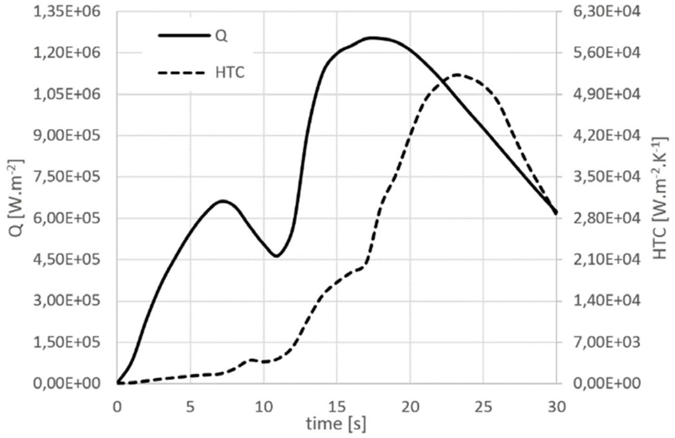

Fig. 11. Heat flux and HTC at pouring temperature 690°C and pressure 100 MPa

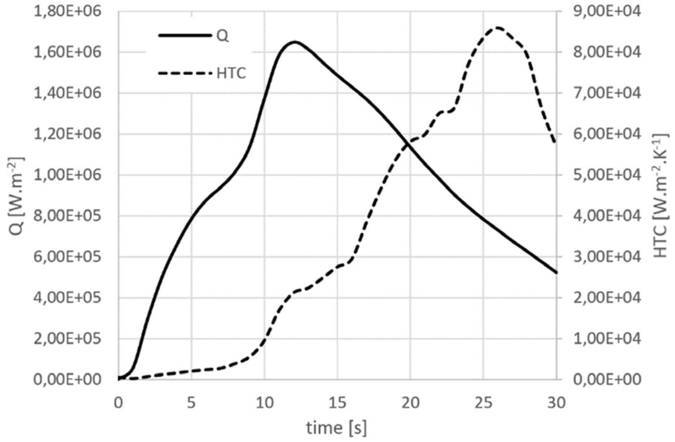

Fig. 12. Heat flux and HTC at pouring temperature 690°C and pressure 150 MPa

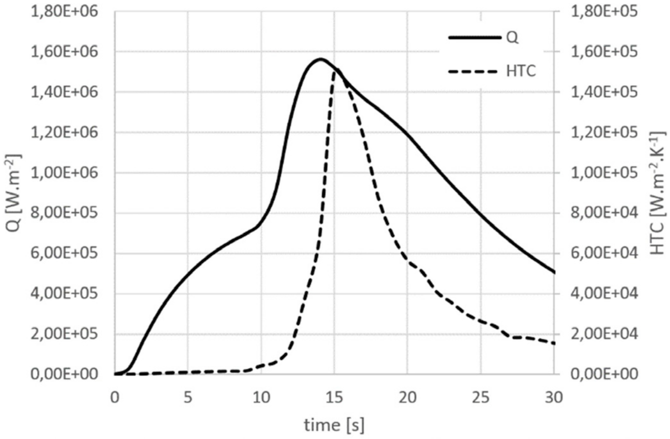

Fig. 13. Heat flux and HTC at pouring temperature 710°C and pressure 50 MPa

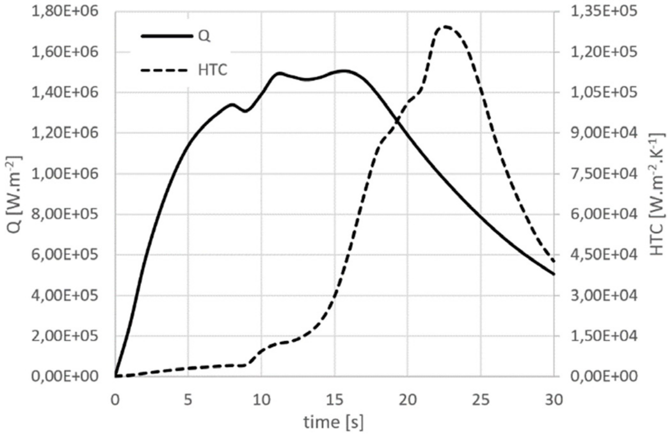

Fig. 14. Heat flux and HTC at pouring temperature 710°C and pressure 100 MPa

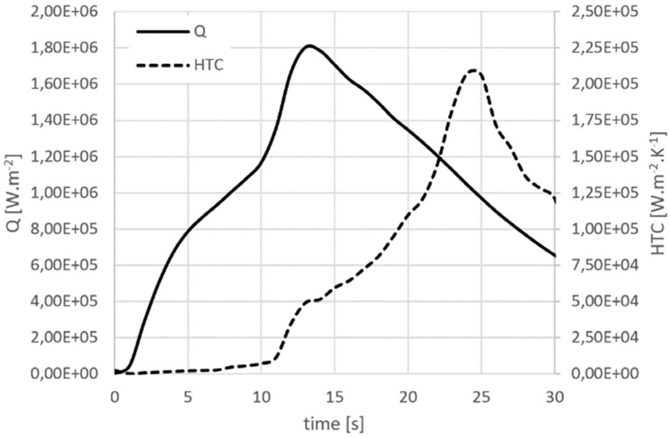

Fig. 15. Heat flux and HTC at pouring temperature 710°C and pressure 150 MPa

3.2. Microstructure evaluation

It is apparent from the microstructure evaluation that the applied pressure had the greatest impact on refinement and regularisation of the structure. Figs. 16 and 17 show the microstructure of the sample cast without applying pressure.

Figs. 18 and 19 show a squeeze-casting sample, cast under pressure of 150 MPa, which exhibited a finer-grain structure compared with the gravity cast sample. There has also been regularisation of eutectic silicon exclusion throughout the structure, wherein we observed no eutectic agglomerates compared with the gravity cast sample. In the sample, we observed no significant

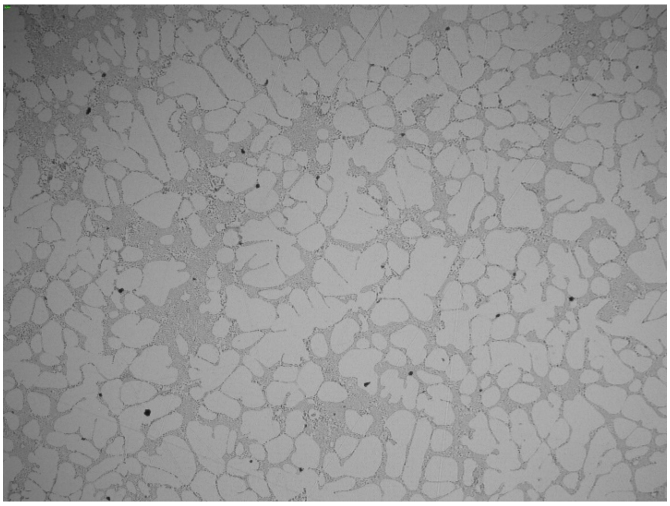

Fig. 16. Microstructure of the sample cast without applying pressure, zoom 100×, etching 0.5% HF

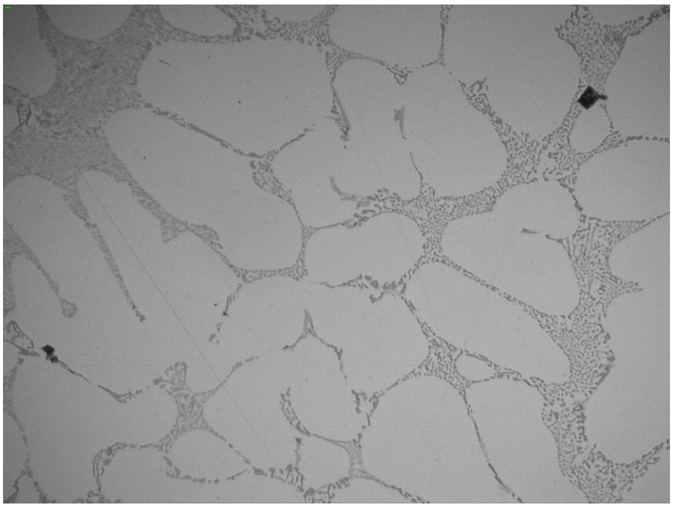

Fig. 17. Microstructure of the sample cast without applying pressure, zoom 400×, etching 0.5% HF

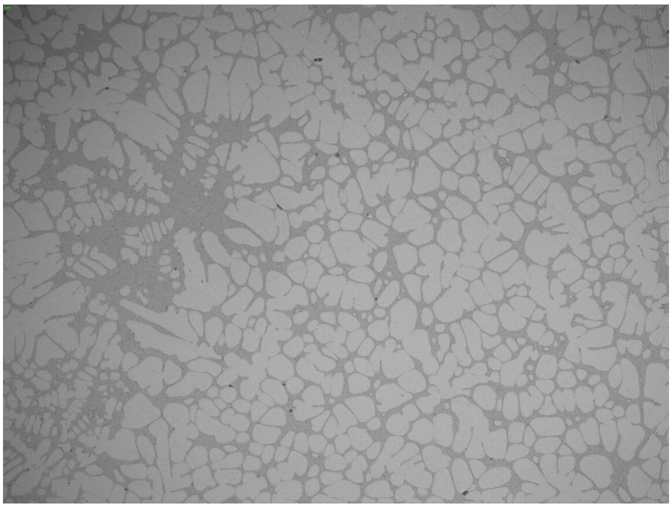

Fig. 18. Microstructure of the sample cast under pressure with value 150 MPa, zoom 100×, etching 0.5% HF

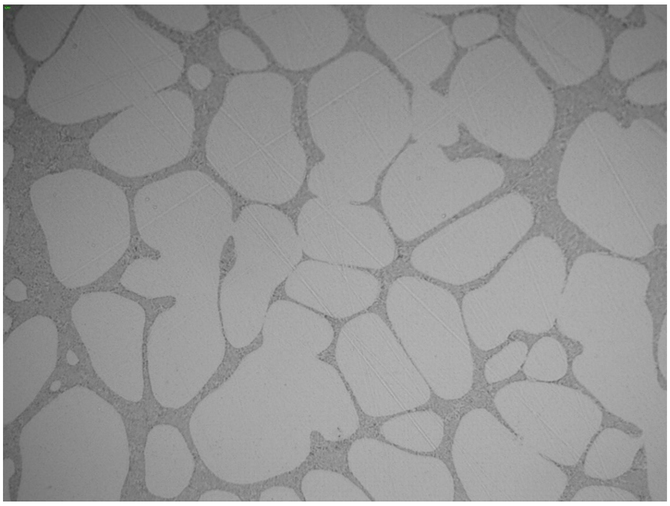

Fig. 19. Microstructure of the sample cast under pressure with value 150 MPa, zoom 400×, etching 0.5% HF

change in the eutectic silicon morphology. This was caused the fact that the primary alloy was inoculated with Ti.

3.3. Mechanical properties

The cast samples were tested for mechanical properties – in particular, we evaluated the strength and elongation. Under the effect of pressure applied during casting there was a significant increase in the material strength and elongation – both the properties increased with increasing applied pressure. Casting temperature variation had no significant effect on changes in the material mechanical properties. The highest increase in strength (by up to 25%) was observed in the sample cast at 670°C and applied pressure of 150 MPa. The strength of this sample was 202 MPa. Fig. 20 shows the strength values for each sample.

Elongation of the material exhibited a similar tendency. The highest elongation was observed in the sample cast at 670°C and applied pressure of 150 MPa. The value of elongation in that sample was 16%. Fig. 21 shows the elongation values for each sample.

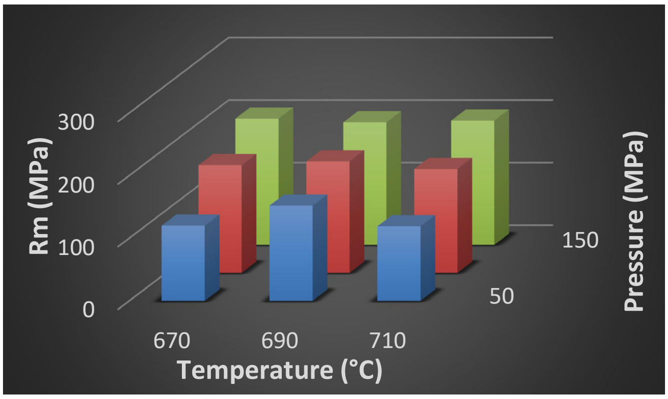

Fig. 20. Effect of change in casting parameters on the strength of the experimental material

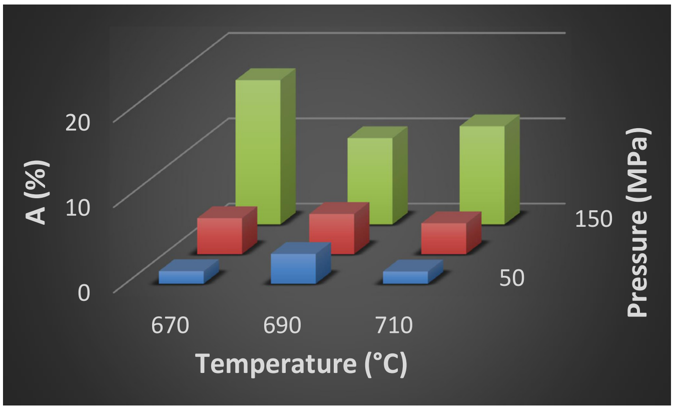

Fig. 21. Effect of change in casting parameters on the elongation of the experimental material

4. Conclusion

Heat flux in the gravity cast sample increased within 5 seconds after pouring. Shrinking of the casting resulted in the formation of a gap at the casting-mould interface. The formed gap caused reduced heat flux from the casting. In the unaffected sample, the heat flux at the onset of pouring increased to the value of $5.75.10^5$ W.m^{-2}. At time 7 seconds after pouring, heat flux through the gap started to apply. The heat flux value increased up to $7.22.10^5$ W.m^{-2}. Heat transfer coefficient reached the value of $1.15.10^3$ W.m^{-2}.K^{-1} at the onset of pouring, only to increase to the value of $1.74.10^3$ W.m^{-2}.K^{-1} when applying heat transfer through the gap. For technological reasons, pressure was applied 10 seconds after filling the mould. All samples affected by pressure experienced a significant increase in both the heat flux and heat transfer coefficient at the casting-mould interface. Due to the effect of increased pressure, the heat flux increased by between $5.5.10^5$ W.m^{-2} and $8.5.10^5$ W.m^{-2} compared with the value before the application of pressure. This increase represented a change in the range of 42 to 78%. Direct correlation between the observed changes was not confirmed. However, with increasing casting temperature also the variation increased, which was caused by thermocouple response. Heat transfer coefficient kept changing due to the effect of applied pressure – HTC increased with increasing pressure. At the casting temperature of 670°C, the increase in HTC was 80-fold at 50 MPa, 120-fold at 100 MPa, and 133-fold at 150 MPa. At the casting temperature of 690°C, the increase in heat transfer coefficient, compared with the stage without affecting, was 90-fold at 50 MPa, 148-fold at 100 MPa, and 286-fold at 150 MPa. At the casting temperature of 710°C, the increase in HTC was 187-fold at 50 MPa, 317-fold at 100 MPa, and 525-fold at 150 MPa. Heat transfer at the casting-mould interface significantly increases with the increasing difference in heat contents of the poured material and the mould, and also with the increasing applied pressure. It is apparent from the microstructure evaluation that the applied pressure had the greatest impact on the structure refinement and regularisation. Increased pressure and cooling rate resulted in reduced proportion of eutectic in the structure, increased amount of silicon in eutectic, and reduced size of α-phase dendrites. The most notable changes in the structure compared with the gravity cast sample occurred in the sample poured at 690°C and applied pressure 150 MPa. In this sample, we observed no effect of pressure on changes in the eutectic silicon morphology due to inoculation of the primary alloy with Ti. Under the effect of pressure applied during casting, there was a significant increase in strength and elongation of the material compared with the gravity cast sample. Changing the casting temperature had no significant impact on changes in the material mechanical properties. The highest values of strength (202 MPa) and elongation (16%) were observed in the sample cast at 670°C and applied pressure 150 MPa.

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