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CASTING OF TITANIUM ALLOYS IN CENTRIFUGAL INDUCTION FURNACES

PROCES ODLEWANIA STOPÓW TYTANU W INDUKCYJNYCH PIECACH ODŚRODKOWYCH

This paper discusses technical problems related with casting of titanium alloys in centrifugal vacuum furnaces. The potentials of an analysis of the centrifugal casting process carried out in the Flow3D software CFD (Computational Fluid Dynamics) were presented. Simulations were carried out on a model set, which enables casting of two connecting rods for an I.C. engine. Changes in the mould filling process were examined for the three selected spinning velocities of the casting arm. The ranges of the metal flow velocity in mould were calculated as well as metal pressure in mould after reaching a predetermined spinning velocity. The results and the adopted mould geometry enabled determination of the magnitude of stress occurring in mould at the time of filling it with liquid titanium alloy. The paper presents a methodology for testing of the ceramic material strength using a four-point loading arrangement. The strength of the ceramic material was determined on samples heated at different temperatures. The obtained results enabled a thesis to be formulated that for pouring of moulds in a centrifugal vacuum furnace, the layered foundry ceramic moulds can be safely used, and the use of moulds that will provide the directional solidification of metal should be possible as well.
Keywords: Centrifugal casting, innovative casting materials, titanium alloys, liquid ceramic slurries, ceramic mould

W artykule przedstawiono problemy techniczne związane z odlewaniem stopów tytanu w próżniowych piecach odśrodkowych. Zaprezentowano możliwości analizy procesu zalewania wirującej formy przeprowadzonej w programie Flow3D CFD (Computational Fluid Dynamics). Obliczenia symulacyjne prowadzono dla zestawu modelowego umożliwiającego odlanie dwóch korbowodów silnika spalinowego. Analizowano zmiany sposobu wypełniania formy dla trzech wybranych prędkości wirowania ramienia odlewniczego. Obliczono zakresy prędkości przepływu metalu w formie oraz ciśnienia metalu występującego w formie po osiągnięciu założonej prędkości obrotowej. Uzyskane wyniki oraz przyjęta geometria formy pozwoliły na wyznaczenie wielkości naprężeń występujących w formie w momencie wypełnienia jej ciekłym stopem tytanu. Przedstawiono metodykę badania wytrzymałości materiału ceramicznego wykorzystującego czteropunktowy układ obciążający. Wyznaczono wytrzymałość materiału ceramicznego dla próbek wygrzewanych w różnych temperaturach. Otrzymane wyniki pozwalają na przedstawienie tezy, że w podczas zalewania form w próżniowym piecu odśrodkowym będzie można bezpiecznie wykorzystywać warstwowe ceramiczne formy odlewnicze, oraz będzie możliwe zastosowanie form zapewniających założone kierunkowe krzepnięcie metalu.

1. Introduction

The development of an economically viable process for the titanium manufacture has contributed to the creation of a new group of structural materials. Unique physical properties of titanium alloys, especially their low density and high resistance to aggressive corrosive environments, allow their use in products serving the industry of chemicals, aerospace and medicine. The main obstacle to the widespread use of components made of titanium alloys is the need for high purity processing. Metallurgical processes should be carried out reducing as much as possible the risk of absorption by the liquid metal of contaminants, both gaseous and ceramic, originating from the crucible or mould material.

The casting process described in this study has been based on the use of layered ceramic moulds produced on pattern clusters melted out in a steam autoclave. After a high-temperature mould annealing process, casting of titanium takes place in a centrifugal vacuum induction furnace.

The geometry of pattern clusters was developed and validated using a Flow3D computer programme, which allows simulation of phenomena occurring in any arbitrarily selected field of forces, including liquid flow in non-inertia reference systems. During pouring of mould in centrifugal furnaces, the main factor controlling the process is the Coriolis effect and centrifugal force. The ceramic mould making process is designed allowing for the phenomena of both liquid metal – mould filling process (determined by simulation), and liquid metal – mould material high-rate interaction.

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2. Flow modelling in the Flow3D programme

Numerical analysis is an essential tool supporting the engineer in his work at the early stages of design. It is mainly used to verify the correctness of construction. Calculation algorithms used in the Flow3D software allow solving various problems relating to laminar and turbulent flow. The obtained results help to understand the phenomena arising from the flow of the cast liquid alloy through the gating system, feeding system and mould cavity reproducing the shape of the casting. The mould filling technique is a very important part of the casting process. Too turbulent flow may cause erosion of the mould material, air occlusion inside the alloy melt and, as a consequence, surface defects in the moulded casting and defects in the ready item. The large number of physical models offered by the simulation programme allows simulation of the phenomena occurring during centrifugal casting, including mould filling and solidification of liquid alloy, the formation of porosity, and the occurrence of the segregation and cavitation effects [1].

The first step in calculations is preparing a model geometry in the form of *.stl file, additionally described with a rectangular computing grid. It is used in the Flow3D way to create a computing area, i.e. the determination of a maximum number of the individual model building blocks, which will next determine the accuracy of model approximation and ultimately the accuracy of calculations [2]. The next step is specifying the calculation parameters, i.e. the direction of molten alloy flow, the initial mould and alloy temperature, the time step of calculations, the stability criteria and the selection of parameters tracked and recorded during the simulation. It is possible to obtain data such as the velocity of fluid flow and pressure values, heat flow and the formation of casting defects [1, 3, 4].

The centrifugal force in an obvious way facilitates filling of mould with liquid metal. After filling the cavity, in the system only centripetal force is operating. If its value is too high in the period prior to metal solidification, the risk of mould breaking occurs. The authors have decided to determine the range of the spinning velocity values of the centrifuge arm for which the mould pouring process can be executed in a correct way and, at the same time, a minimum value of the centripetal force can be achieved.

TABLE 1
Time needed to fill the mould with metal compared for various preset arm spinning velocities

Velocity max [rpm]	270	225	170
Start up time [s]	5	4	3
Start of pouring [s]	1.54	1.47	1.46
Instantaneous velocity [rpm]	81	84	79
End of pouring [s]	3.08	2.93	2.92
Instantaneous velocity [rpm]	167	163	164
Time of mould pouring [s]	1.54	1.46	1.46

The maximum spinning velocity of the centrifuge arm is 300 rpm. It was decided to carry out calculations for the centrifuge arm spinning velocity of 270, 225 and 170 rpm.

Analysis of the centrifugal casting parameters showed that the mould filling process always starts at the same spinning velocity of the casting arm. This speed is determined by the distance from the crucible axis of rotation, its deviation from the vertical axis and the speed that enables liquid metal to reach the spout level in a ceramic crucible. A similar time of filling the mould with molten metal can be achieved by reducing the time necessary to reach the preset maximum spinning velocity.

Since in each case similar results of the simulation were obtained, below a visualisation has been done for the results of computer simulation made on the example of cast connecting rod for an I.C. engine operating in Fiat 126p car, as obtained for the lowest target spinning velocity of the casting arm (Fig. 1).

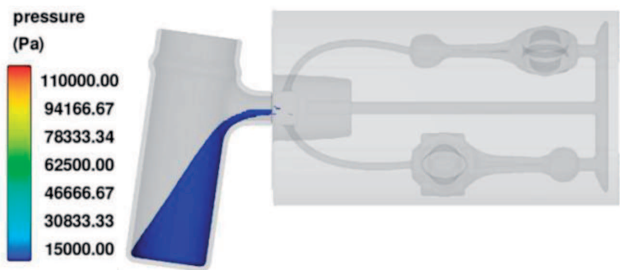

Fig. 1. Visualisation of metal working pressure in a pouring system at the beginning of the process of filling the mould with metal for the target spinning velocity of 170 rpm

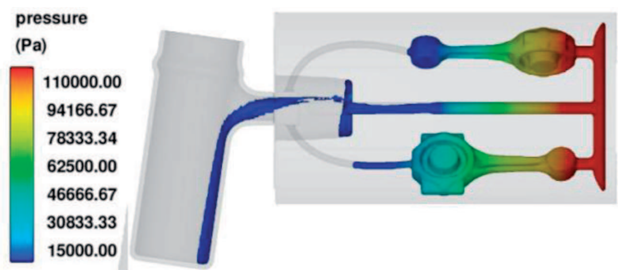

Fig. 2. Visualisation of metal working pressure in a pouring system at the end of the process of filling the mould with metal for the target spinning velocity of 170 rpm

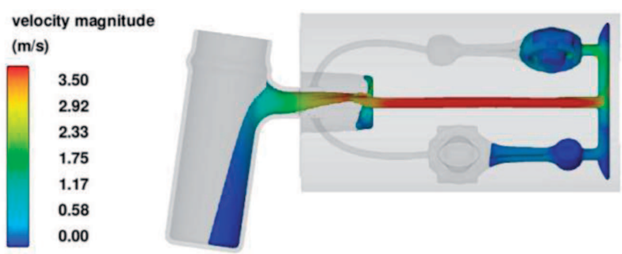

Fig. 3. Visualisation of molten metal velocity magnitude for the target spinning velocity of 170 rpm after having reached the spinning velocity of 130 rpm

The preset rotating arm velocity determines the maximum metal pressure acting on the bottom part of the ceramic mould (Fig. 2, 3). If the obtained ceramic mould strength considerably exceeds the value of the forces occurring in the rotating pouring system, then, in the casting process, self-supported moulds can be used without the need to fill with a ceramic material the space between the mould and the metal sleeve. This will reduce the total weight of the ceramic material and will enable better utilisation of the mould geometry to ensure an optimum cooling process.

3. Testing the layered ceramic material strength

Strength of ceramic materials is a characteristic property connected with the grain size, the size distribution, the method of sample preparation and the research technique related with the measurement methodology. The strength of the prepared ceramic samples was tested using a measuring device developed by the Foundry Research Institute, based on the four-point loading arrangement (Fig. 4) of a ceramic specimen with 20×7×60 mm dimensions. A uniform load provided between the central supports greatly facilitates finding the critical defects that may occur at random in the sample. The study used four series of samples of the layered ceramic mould materials made of zirconia stabilised with yttrium oxide (Fig. 5). The successive series of samples were annealed at temperatures of 1000, 1127, 1253, and 1380°C. The mechanical strength of the mould material was determined at 500°C [5, 7].

Fig. 4. The four-point strength measurement

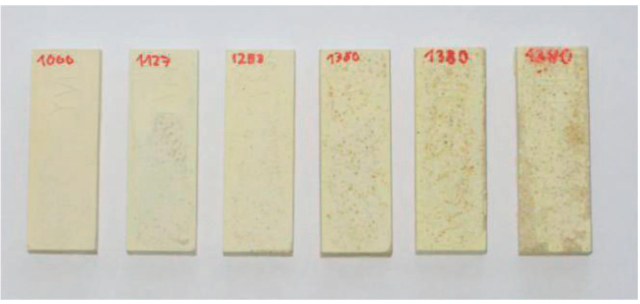

Fig. 5. Samples ready for the strength measurement

In the system described above, the strength of the ceramic material is determined from the following formula:

$$\sigma_f = \frac{3}{2}\frac{F_f\,(L-l)}{d\cdot h^2} \tag{1}$$

where:

σ_f – sample strength (rupture stress at bending) [Pa];
F_f – breaking load [N];
L – distance between supports [m];
l – load spacing [m];
d – sample width [m];
h – sample height [m];

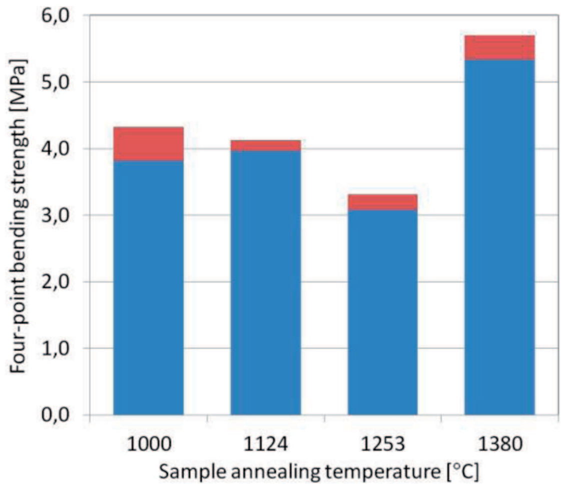

Fig. 6. The strength values and standard deviation calculated for the four-point bending test of ceramic samples

If we assume that:

$$R_m = \frac{\sigma_f}{1.7} \tag{2}$$

determined tensile strength R_m is about 3.3 MPa

Lower strength of the ceramic material observed in samples annealed at 1253°C is due to the crystallographic transformation of zirconia occurring at a temperature above 1170°C followed by an increase in material volume (Fig. 6).

4. Testing the layered ceramic mould strength

The self-supported ceramic layered mould is formed by alternate application onto a pattern set of coatings of the liquid ceramic slurry and sand with a grain size of 0.1÷1 mm. The number of the applied layers determines the mould wall thickness. Generally, to provide sufficient mould strength, from 6 to 8 layers are applied (Fig. 7). The wall thickness is in the range of 7 to 10 mm. Due to the complex geometry of ceramic moulds, the required strength varies in different areas of the mould. The highest strength the mould should achieve in the zone where the highest pressure is operating, and thus at a point most distant from the axis of rotation. It should also be borne in mind that too high strength of the ceramic mould will make cleaning of castings much more difficult.

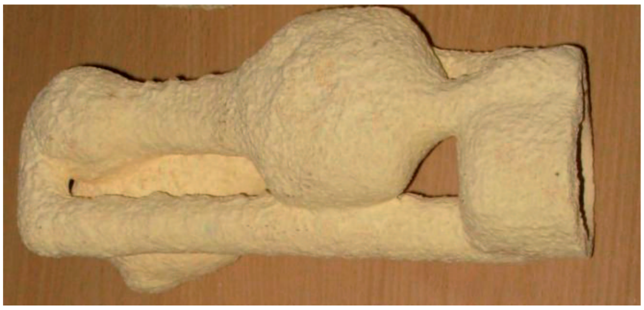

Fig. 7. Layered ceramic mould reproducing two connecting rods for an I.C. engine

The design of mould geometry is based on the bottom pouring system, wherein the lower part of the ceramic mould comprises a set of the cylindrical feeding channels.

Let us presume that these channels form a cylindrical tank with a radius r (diameter $\varphi = 0.01$ m), and the wall thickness $g = 0.007$ m. The maximum pressure of metal determined by computer simulation is $p = 0.11$ MPa.

The circumferential stress occurring in a long cylindrical vessel is:

$$\sigma_1 = \frac{pr}{g} = \frac{p\varphi}{2g} \qquad (3)$$

The calculated stress acting on the tank perimeter will be $\sigma_1 = 0.079$ MPa, and so it will be much lower than the calculated strength of the ceramic samples.

5. Summary

Self-supported ceramic layered moulds can be safely used in the centrifugal casting process. It is not necessary to fill the space between the clamping sleeve and the casting mould with a ceramic material significantly changing the cooling parameters of the entire system.

It is possible to design a pattern set geometry in such a way as to provide for a specific group of castings the process of directional solidification. It is enough to place the casting part cooling down most rapidly close to the surface of the covering sleeve. A central element with the intentionally increased thermal capacity will, in turn, ensure maintaining proper temperature on the other side of the casting. The necessary temperature gradient will be created during melting of the metal with the preheated foundry set placed in a chamber of the centrifugal furnace.

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