A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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MAKING ARTIFICIAL HEART COMPONENTS – SELECTED ASPECTS OF CASTING TECHNOLOGY

WYKONYWANIE ELEMENTÓW SZTUCZNEGO SERCA – WYBRANE ASPEKTY TECHNOLOGII ODLEWNICZEJ

This study shown possibilities of Rapid Prototyping techniques (RP) and metal casting simulation software (MCSS), including non inertial reference systems. RP and MCSS have been used in order to design and produce essential elements for artificial heart. Additionally it has been shown possibilities of Fused Deposition Modeling (FDM) technique and DodJet technology using prototyped elements of rotodynamic pump. MAGMASOFT® software allowed to verify the cast kit heart valves model. Optical scanner Atos III enabled size verification of experimental elements supplied by rapid prototyping together with metal casting elements. Due to the selection of ceramic materials and assessment of molten metal – ceramic reactivity at high temperatures together with pattern materials selection model it was possible to design, manufacture a ceramic mould for titanium based alloys. The casting structure modification has been carried out by means of high isostatic pressure technique (HIP). The quality assessment of the casting materials has been performed using X-ray fluorescence (XRF), ARL 4460 Optical Emission Spectrometer, metallographic techniques and X-ray computed tomography.

Keywords: Ti based alloys, Rapid Prototyping, pattern material, ceramic moulds, castings

W artykule przedstawiono wykorzystanie technik szybkiego prototypowania oraz programów do symulacji przepływów stopów odlewniczych, w tym w nieinercyjnych układach odniesienia, do projektowania, a następnie wykonania elementów sztucznego serca. Zaprezentowano kolejno technikę *Fused Deposition Modeling* (FDM) oraz technologię DodJet na przykładzie wykonania prototypowych elementów pomp wirowych. Program MAGMASOFT® pozwolił zweryfikować projekt zestawu odlewniczego zastawki serca. Zastosowanie skanera optycznego Atos III umożliwiło weryfikację wymiarów doświadczalnych elementów otrzymanych przy wykorzystaniu technik RP oraz elementów odlewanych. Dzięki doborowi materiałów ceramicznych pod kątem oceny ich reakcji z ciekłym metalem oraz doborowi mas modelowych możliwe było opracowanie doświadczalnych form ceramicznych przeznaczonych do odlewania stopów tytanu. Modyfikację struktury odlewów wykonano przy zastosowaniu obróbką techniką HIP. Ocenę jakości wykonanych odlewów przeprowadzono kolejno metodą mikrofluorescencji rentgenowskiej, emisyjnym spektrometrem optycznym, technikami metalograficznymi oraz rentgenowską tomografią komputerową.

1. Introduction

Computer-aided techniques are increasingly used in the development of innovative design solutions. The foundry industry as one of the first has introduced into general practice computer programs such as: MAGMASOFT®, ProCAST, SolidWorks, Solid Edge, Pro/ENGINEER, ANSYS, ABAQUS or Flow-3D. The use of these programs has notably reduced the optimization process of new casting designs and enabled a reliable assessment of proposed solutions as early as at the stage of product design.

Modern computer programs also allow considerable shortening of the design process of components ultimately performed by different techniques, such as plastic forming and machining, or by the rapidly gaining populariy novel technique of printing metal powders, and its the recent industrial version called “additive manufacturing” [1].

The results of research and implementation projects conducted at the Foundry Research Institute in Cracow allowed undertaking studies related to the application of rapid prototyping techniques in the development of the artificial heart components.

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In the whole family of biocompatible materials used in medicine, an important role play parts made of titanium alloys, replacing or supporting the work of elements of the skeletal system carrying high mechanical loads [2]. The main obstacle in a wide-spread use of components made of titanium alloys is the need for high purity processing. The currently applied foundry technologies are based on the method of investment casting, using multi-layer ceramic moulds. The operating parameters of castings are additionally improved by the use of Hot Isostatic Pressing (HIP) [3,4].

When the casting process is completed, the quality inspection of components is carried out by the conventional techniques of metallography and spectrometry. Increasingly, the quality control of castings uses computed tomography, allowing both flaw detection and validation of the correct assembly of components, including parts joined together [5].

2. Making prototype components of centrifugal pumps by Fused Deposition Modeling (FDM)

FDM technique allows fast printing of plastic parts of any open space geometry. The patterns are characterized by a relatively high strength and can be used as ready-made components in prototype devices, thus significantly facilitating the development of construction documents [6,7].

The FDM technique involves the use of a two-nozzle head which applies layers of fused pattern material and support material. Materials in the form of rods are collected from the cassettes located in the lower part of the machine. The rods are unwound and passed to the head, and then heated to a semi-solid state and applied in the form of strands, which quickly freeze to form successive layers of the built pattern. The heads move in the horizontal OX – OY axes, while in the vertical OZ axis moves the work table with the applied backing foil on which the pattern is constructed. Once a single layer is applied, the table is lowered and the head starts printing the next layer.

FDM enables manufacture of components from materials such as:

1. ABS (acrylonitrile butadiene styrene) – for patterns easily processed, characterized by a satisfactory thermal resistance and used in lightly-loaded demonstration elements.
2. ABSi – designed to make transparent functional parts of the outstanding dimensional accuracy, durability and permanent shape stability. This material is characterized by the strength superior to ABS.
3. PC (polycarbonate) – a white or transparent material with the strength and heat resistance higher than ABS. A modification of polycarbonate is called PC-ISO; it is used in medicine, in all those applications where appropriate biocompatibility is required. Patterns can be successfully used as medium-loaded functional parts.
4. PC-ABS – a blend of PC and ABS; a black material having the high strength of polycarbonate and addditionally offering the possibility of the use of soluble supports.
5. PPSF (polyphenylsulfone) – characterized by the highest, in comparison with other materials, strength, hardness and heat resistance (the softening point is approx. 190°C). It offers a relatively high resistance to the effect of gasoline and oils.

The yield of the printing operation can be increased by placing a greater number of elements on the support plate (Fig. 1). After printing, the support material must be separated from the pattern. This can be done either mechanically or by dissolving it in an aqueous solution of a strong base.

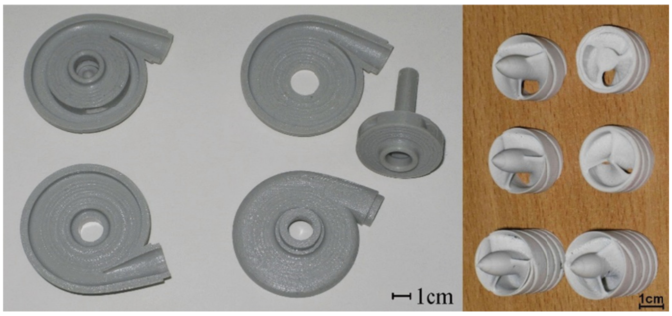

Fig. 1. Parts of centrifugal pump printed by the FDM technique from ABS material

FDM was used as a means to modernize a pneumatic valve operating in an outer chamber of the heart assist device (Fig. 2a). Whilst retaining the previously established operating mode of the valve, some changes were introduced to its design, reducing significantly the volume of individual elements. The prepared design documentation enabled printing all valve elements from polycarbonate (Fig. 2b).

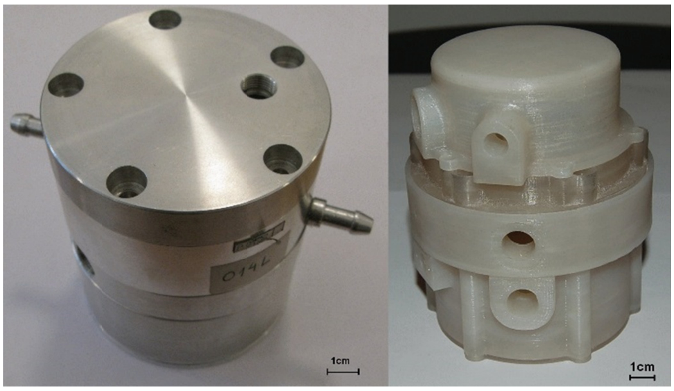

Fig. 2. Complete pneumatic valve operating in an outer chamber of the heart assist device (a) and its parts after modernization made by FDM (b)

The introduced structural changes enabled reducing the total weight of the valve from 1237 g in the case of an AlCu4MnMg alloy to 230 g for the valve made of polycarbonate.

3. Printing parts of centrifugal pumps by the DodJet technology

The traditional technology of precision casting uses wax patterns made in large lot production by injection of wax into a metal die. The metal die is a tool relatively expensive and therefore its manufacture is economically justified only in the case of large batches of the manufactured products.

Prototype patterns made by the DodJet technique enable checking the design assumptions and significantly shorten the time of the casting process development and verification.

The pattern is made by application of the successive layers of material onto the surface of a working table. The table is lowered along the OZ axis after the application of each next layer of material. The pattern base is a polystyrene plate. The determination of the starting point and calibration in the OX and OY axes are executed automatically and precede each subsequent cycle of the printer operation (Fig. 3).

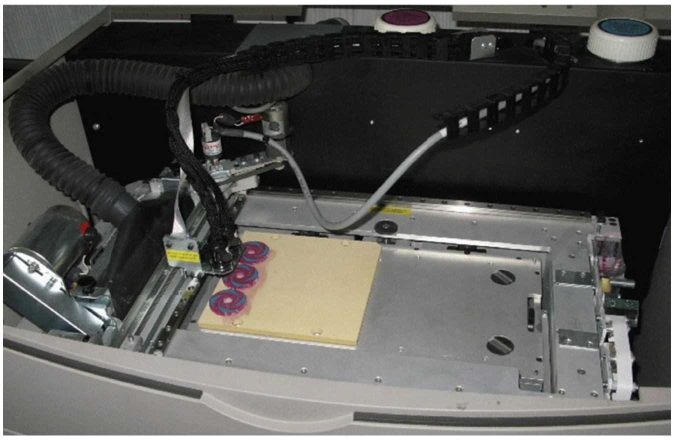

Fig. 3. Printing of centrifugal pump elements on the Solidscape DodJet printer

The pattern material and the support material are applied onto a substrate in the form of liquid droplets. Each of the droplets is composed of a series of "microdroplets" uniform in volume, which is a characteristic feature of the DodJet pressure spray technique. This technology allows placing the droplets in any arbitrarily chosen place of the substrate with a total accuracy of 25.4 μm. The droplets having a diameter of 76.2 μm adhere to each other during wax solidification forming a uniform solid composition. The hardening process takes place quickly enough to allow for mechanical smoothing of the surface. The head sliding cycles are synchronized with the injection-generated droplets. The extent to which the droplets overlap or are distancing from each other is precisely controlled by a computer program. The smooth surface is produced by a repeated several times continuous application of wax along the pattern contour and by filling next the interior part of the pattern along the, alternately, OX axis and OY axis. These operations are performed in every layer of the pattern, which results in internal bonding of the pattern structure, increasing its strength and durability. After filling the surface with the pattern material, the support material is applied, necessary for building of projections or depressions. The support material does not penetrate into the pattern structure, owing to which it is possible to avoid the formation of a "scaffolding" structure, characteristic of other additive methods using only one construction material. The ready wax pattern is encapsulated with support material, which must be rinsed in a preheated solution of organic solvent.

High precision of printing is associated with a relatively long time of this operation. Experimental patterns of parts made during the development of casting technology were printed using the finest print layer of a thickness equal to 12.7 μm (Fig. 4).

Below are compared the pattern printing times and the print thickness applied (*d*):

– centrifugal pump casing (Fig. 5): 51 h d = 25.4 μm
– centrifugal pump impeller 23 h d = 25.4 μm
– axial-flow pump stator (Fig. 6): 55 h d = 12.7 μm
– axial-flow pump impeller: 30.5 h d = 12.7 μm
– valve ring with molten metal feeding allowances 13.5 h d = 12.7 μm.

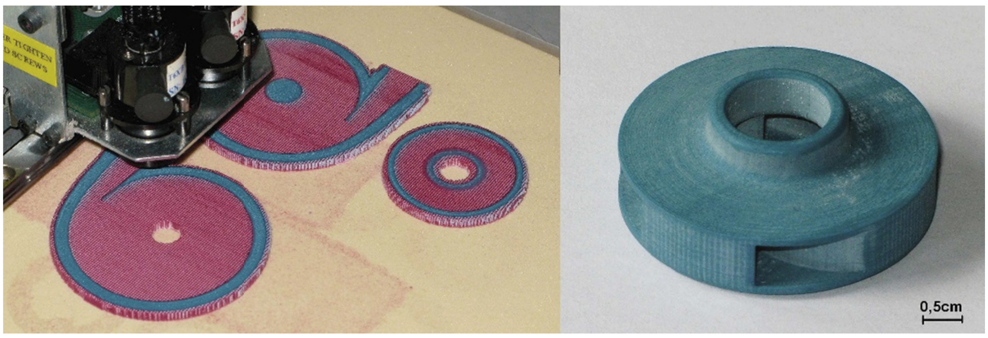

Fig. 4. Wax print of the centrifugal pump casing and impeller

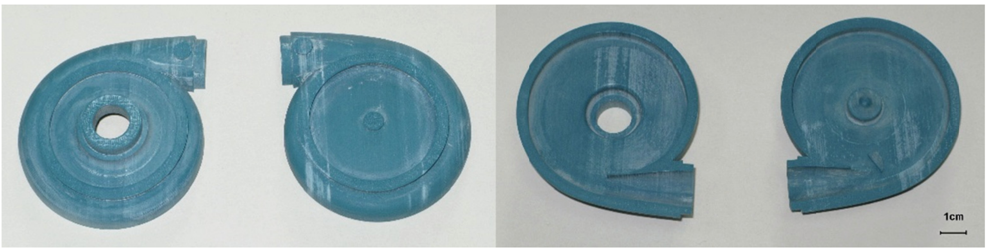

Fig. 5. The centrifugal pump casing after the removal of support material

Fig. 6. Printed axial-flow pump elements: a stator and an impeller (after removal of the support material)

The supplied design documentation was modified introducing elements required by the casting process. Changes were made in the places where these elements could be removed during final machining of the casting.

4. Designing a set of heart valve ring in the MAGMASOFT®

The first step in a computer verification of the casting process is establishing the geometric parameters of the casting with the gating and feeding system supplying metal to the mould. For this purpose, software such as SolidWorks, Solid Edge, Catia or Unigraphics can be used. All these computer programs enable the preparation of 3D documentation in an .stl format. The standard MAGMASOFT® system solves equations of mass and heat flow based on the method of finite differences. Before starting the simulation process, the user defines the parameters of the technological process. The calculations are based on thermophysical data of the TiAl6V4 alloy, supplied by MAGMASOFT® (Table 1).

During the development of mould geometry it is necessary to take into account the casting allowances and location of grips, which allow performing final machining. Of crucial importance is the correct location of hot spots and correct choice of the cas-

TABLE 1

The specific heat, thermal conductivity and density of the TiAl6V4 alloy as a function of temperature (data provided by MAGMASOFT®)

t [°C]	C_p [J/kg·K]	λ [W/m·K]	ρ [kg/m^3]	t [°C]	C_p [J/kg·K]	λ [W/m·K]	ρ [kg/m^3]
1	490	6.3	4423	600	657	15.0	4342
20	499	6.5	4420	995	720	15.0	4295
50	536	6.9	4416	1005	650	15.0	4275
100	565	7.6	4410	1230	700	15.0	4249
150	571	8.4	4404	1660	800	15.0	4200
200	592	9.1	4397	1664	824	15.0	4198
250	600	9.8	4391	1670	860	15.0	4192
300	606	10.5	4384	1675	891	15.0	4179
350	613	11.2	4377	1680	921	15.0	4143
400	619	12.0	4370	1685	952	15.0	4032
450	627	12.7	4363	1688	970	15.0	3996
500	637	13.4	4356	2000	970	15.0	3950
550	648	14.2	4349				

$t_{solidus}$ = 1660°C, $t_{liquidus}$ = 1688°C, heat of melting 300 kJ/kg ting feeding system. By changing the shape or size of the riser it is possible to change the mode of filling the mould with molten metal, as well as the solidification rate and direction. The shape of the valve ring allowed the riser to be placed at the location of the intended technological allowance, indispensable for the final machining of casting. Calculations were performed for the three gradually growing feeding systems. The changes successively introduced to the riser design are indicated in the drawing with an ellipse (Fig. 7).

The results showed that all the tested design solutions connecting the casting with the riser of a gradually increasing volume affected in a similar way the pattern of filling the mould cavity with molten metal, thus enabling the choice of the solution optimum for the final machining of casting (Fig. 8).

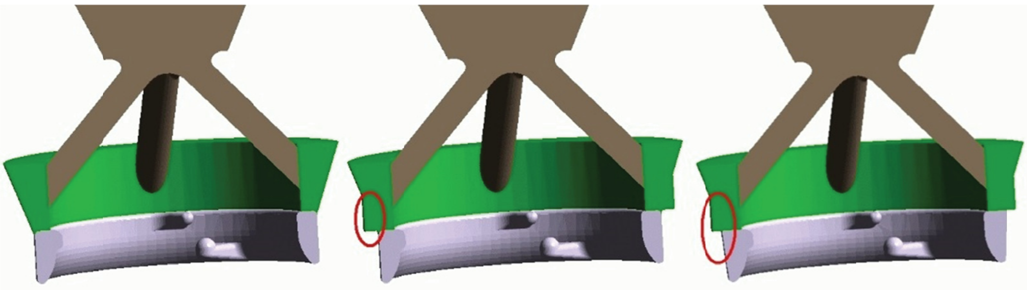

Fig. 7. The geometry of casting and riser used in the calculations (casting of the heart valve)

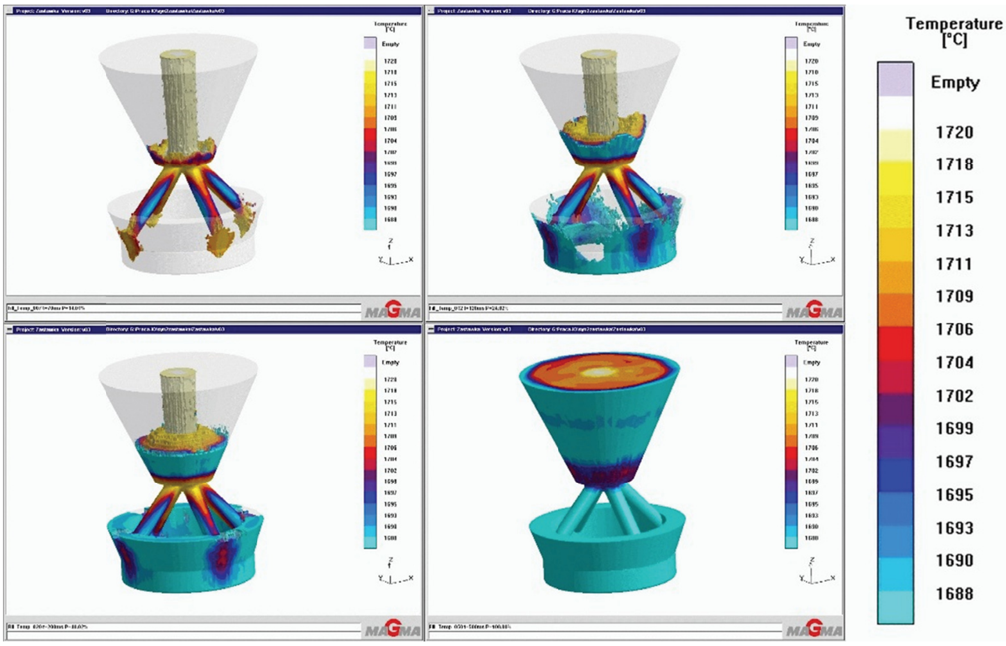

Fig. 8. The spatial distribution of temperature illustrating successive stages of filling the mould cavity with molten metal (casting of the heart valve)

The riser should be designed in such a way as to reduce to minimum the degree of occurrence of the shrinkage porosity defects in casting. If, for some reason, this is not possible, then the solution should be sought which will "move" this defect to those areas of the casting which are not critical for the correct operation of the designed part (Fig. 9).

The metal solidification process is compatible with the assumed mould geometry. The last stages of the solidification process include the riser and the gating system. Solidification of metal in the gating system has no significant effect on the processes occurring in a clearly separated casting – riser system. The final step in the calculations is the assessment of metal porosity rising in different areas of the casting. In the case under discussion, this evaluation was performed for each of the examined casting geometries (Fig. 10).

In all calculations, a correct, pore-free casting structure was obtained in "fingers" supporting the carbon disk in valve. In each case, porosity occurred in the ring. A small porosity can be removed in the process of hot isostatic pressing (HIP).

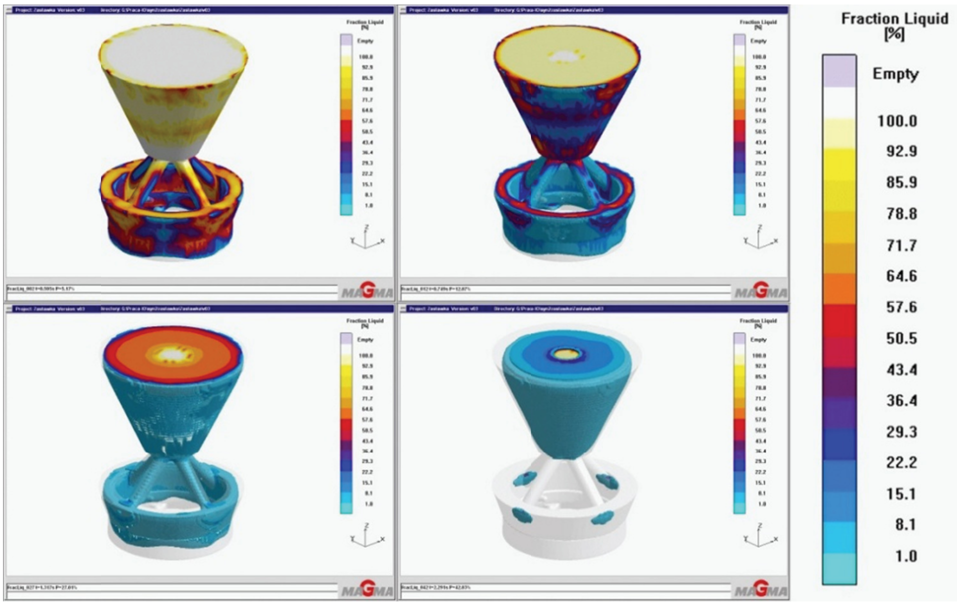

Fig. 9. The spatial distribution of temperature showing successive stages of metal solidification in mould on the example of a heart valve casting

Fig. 10. The spatial distribution of shrinkage porosity occurring in casting and riser of different geometries on the example of a heart valve ring

5. Dimensional verification of printed patterns using the Atos III optical 3D scanner

The dimensional verification of parts was performed with an optical 3D scanner. Spatial scanning was used in the quality assessment of prototypes made of plastics and wax, and in the final assessment of parts cast from titanium alloys.

Spatial scanning enables non-contact determination of three-dimensional coordinates of the real objects of measurement. It is possible to generate the spatial (3D) documentation of objects of practically any surface geometry. The technique of spatial scanning is particularly useful in the preparation of documentation of objects made of soft materials prone to mechanical damage.

Optical scanner projector illuminates the object to be measured with a set of lines of the white light of a specified density. The large number of lines gives a more accurate image of the object. The measurement uses the data from two digital cameras recording the image of the structured light fringes lying on the surface of the object.

For calculations are used only those images of the fragments of surfaces that at the moment of being illuminated are visible through both digital cameras. A complete spatial image is made up of a sequence of images at selected positions of the object. Joining ("bonding") of individual images is possible by analysis of the position of reference points pasted on the scanned object.

The data obtained form a spatial cloud of points, which must be converted to a grid of adjacent triangles. The created polygonal mesh is subjected to re-calculation to remove the reference points, fill surface discontinuities and make it smooth. The end result is an object documentation prepared in .stl format.

The data obtained allow preparing a complete technical documentation, including sections made along any arbitrarily selected plane. It is possible to compare the object with a construction model, to compare two objects, and draw spatial maps of dimensional deviations (Fig. 11).

Structural requirements for the heart valve ring, including variable periodic loads, place particularly high demands during the development of the technological process.

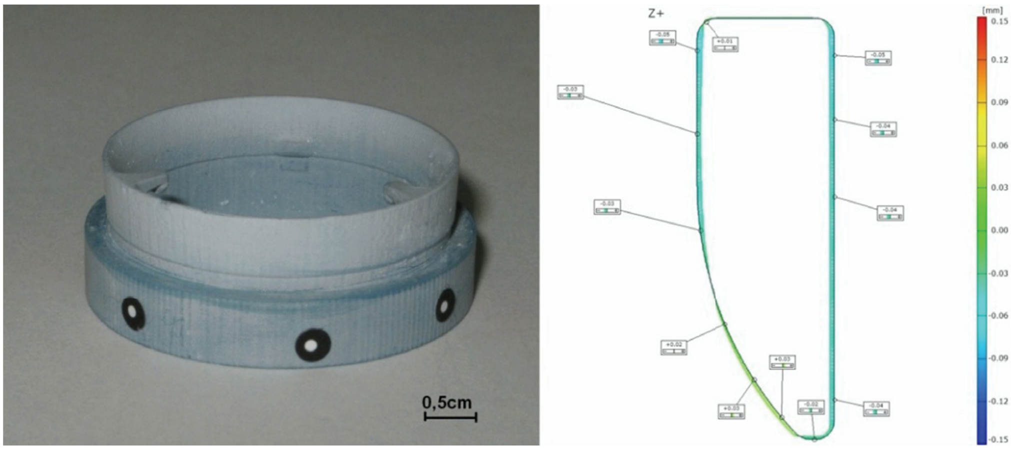

Fig. 11. Element of the heart valve ring and comparison of model with operation drawing

In this case, prints were made for different sizes of the heart valve rings and for different sizes and positions of the feeding system (Fig. 12). The printed patterns were used in the development and assembly of experimental casting sets of the geometry tested with the use of Flow-3D software.

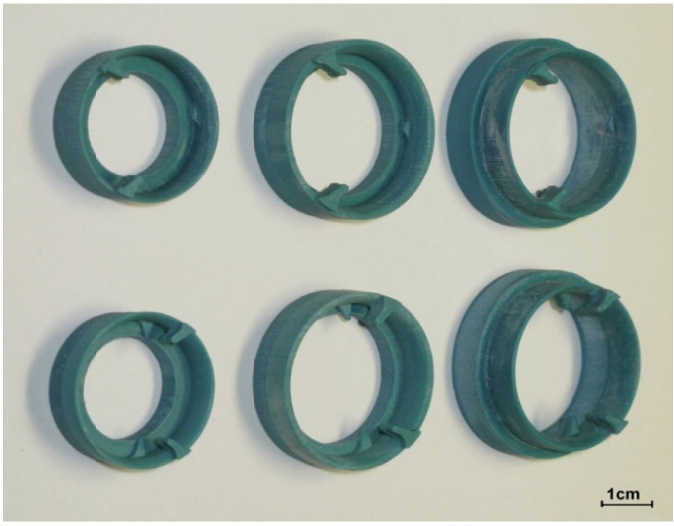

Fig. 12. Different versions of the heart valve rings obtained from a DodJet printer

6. Numerical calculations of molten titanium alloy flow in a rotating reference system carried out with the use of Flow-3D software

The use of centrifugal force in the process of filling the mould cavity with molten metal can significantly speed up this process, and consequently improve the accuracy of castings [8,9]. The value of centripetal acceleration of 20 g is obtained at the crucible outlet distant from the axis of rotation by 0.24 m and at the arm rotational speed equal to 270 rpm/min. In the case of castings made in a SuperCast centrifugal vacuum furnace, the maximum length of the ceramic mould is 0.34 m. This value is comparable with the distance of the gating system from the axis of rotation. In such a case, the process of filling the mould cavity with molten metal depends mainly on the effects associated with Coriolis force.

The rich database of the Flow-3D software relating to the field of forces generated in a variety of physical phenomena allows performing accurate simulation of the dynamic process of fluid flow in a spinning mould.

The use of the *fit to geometry* option allows the user to choose the mesh best fitted to the geometry of the model. The number of elements in the mesh should be such as to enable exact mapping of the model during calculations (Fig. 13).

After analysing the accuracy of the selected grid, a mathematical model of the phenomenon used by the calculation algorithm during simulation should be determined. The Flow-3D software is equipped with physical models allowing the simulation of phenomena, which occur during mould pouring and metal solidification. In the case of centrifugal casting, the following physical models described in the software library are used:

1. *Air entrainment* – describes the closure of air by the liquid casting alloy.
2. *Defect tracking* – analyzes the defects arising under the influence of flow turbulence.
3. *Heat transfer* – calculates heat transfer in the molten alloy – mould system.
4. *Non-inertial reference frame* – calculates the motion of an object in space.
5. *Surface tension* – examines the effect of surface tension on the analysed process.
6. *Viscosity and turbulence* – examines the flow behaviour in a gating system.

The calculations allowed visual representation of the molten alloy velocity and pressure upon filling the foundry mould and the occurrence of potential structural defects (Figs. 14-16).

Based on the obtained results, a method for filling the mould cavity with molten metal was determined for different geometries of the foundry patterns. Verification of the adopted solution was possible at the design stage of a pattern set, which greatly facilitated further development of the casting technology.

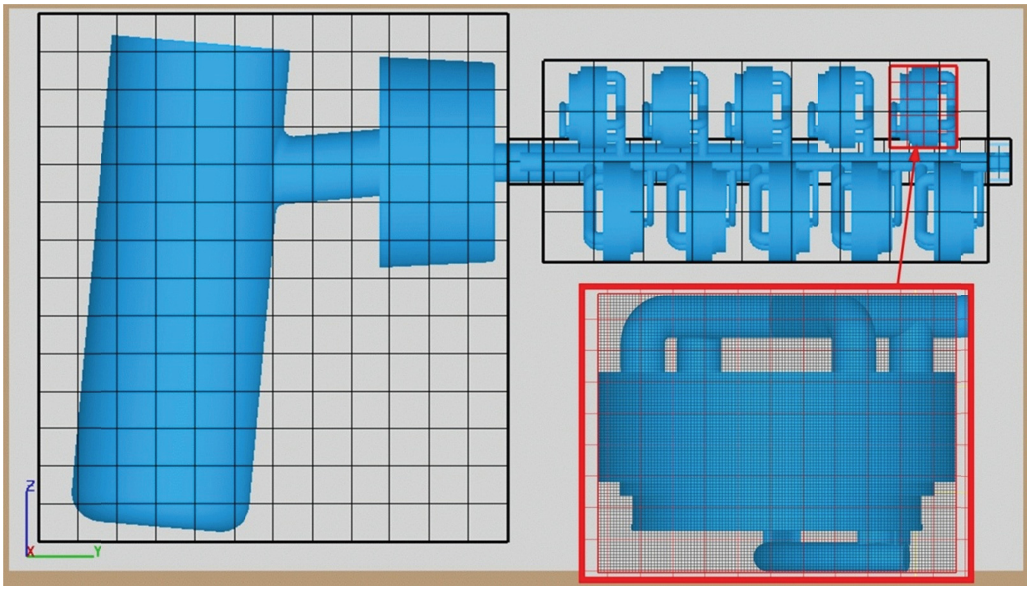

Fig. 13. Flow diagram used in simulation showing the division of the analyzed volume into fragments with increasing accuracy of calculations (casting of the heart valve)

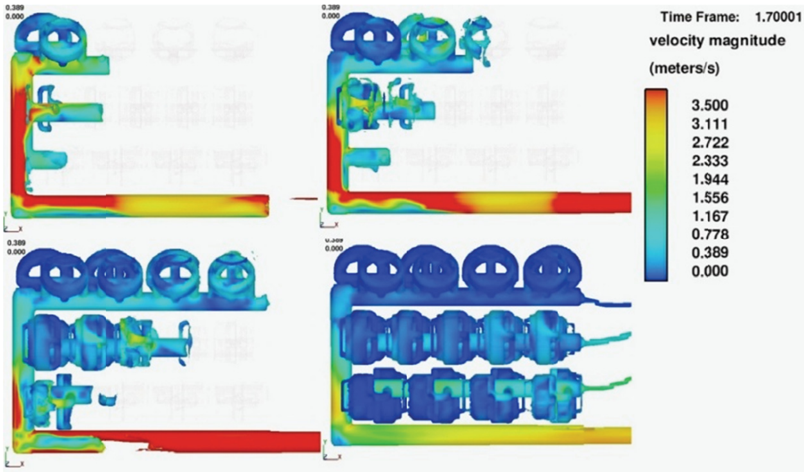

Fig. 14. Selected fragments of calculations of the metal flow rate during the process of centrifugal mould pouring (casting of the heart valve)

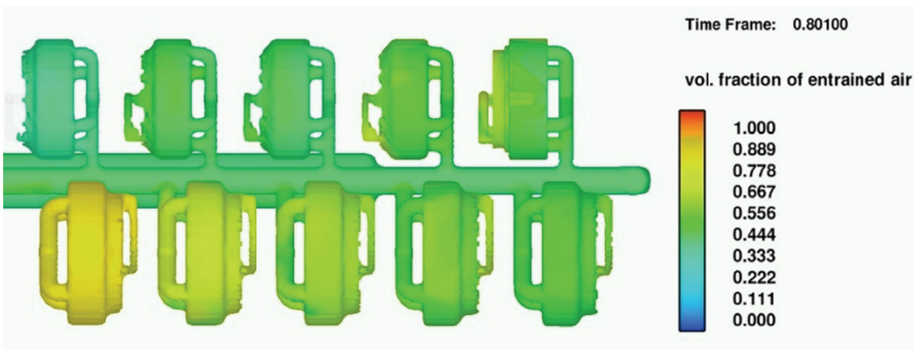

Fig. 15. The calculated distribution of the gas pressure in molten alloy after 2 seconds from the start of the mould pouring process (casting of the heart valve)

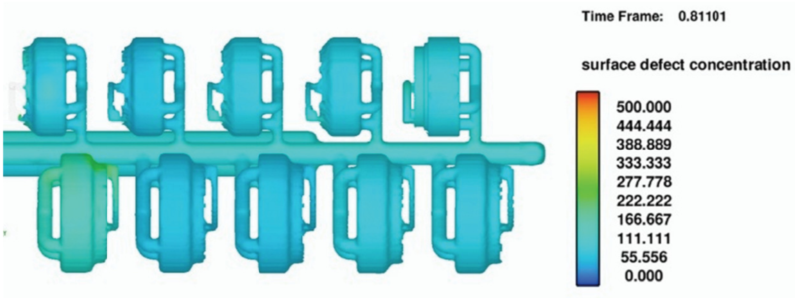

Fig. 16. The calculated distribution of the concentration of surface defects after 2 seconds from the start of the mould pouring process (casting of the heart valve)

7. Choice of ceramic materials and studies of the ceramic mould material – molten metal interactions

When the foundry process involves casting of titanium alloys, one should be aware of the high melting point of these alloys combined with high chemical activity of molten metal [10]. Liquid titanium dissolves the majority of materials used for the ceramic crucibles and moulds. Literature data indicate that ceramic moulds can be made from the ceramic materials based on the following metal oxides: Al_2O_3, TiO_2, Y_2O_3, ZrO_2, CaO and MgO [11,12].

From selected ceramic materials, ceramic pellets with a 17 mm diameter were made (Fig. 17), using both ceramic powder and pure material obtained from the evaporation of colloidal binders based on the following oxides: CeO_2, Y_2O_3 and ZrO_2. The pellets made in silicone moulds were dried and then fired at 1250°C.

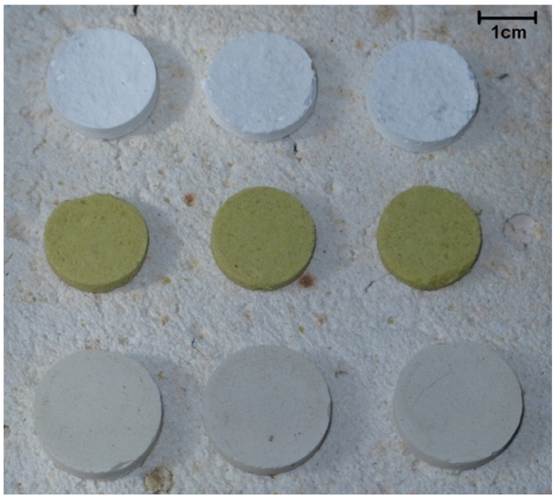

Fig. 17. Experimental ceramic samples made of Y_2O_3, CeO_2 and ZrO_2

The effect of moulding material composition on its physico-chemical interaction with liquid titanium was investigated by the sessile drop method, which allows tracing and recording the course of the joint heating of a couple of test materials (ceramic samples and samples of pure titanium). The method allows the determination of the kinetics of the solid substrate wetting by molten metal and measurement of the contact angle at any time instant of the tested process (Figs. 18-19).

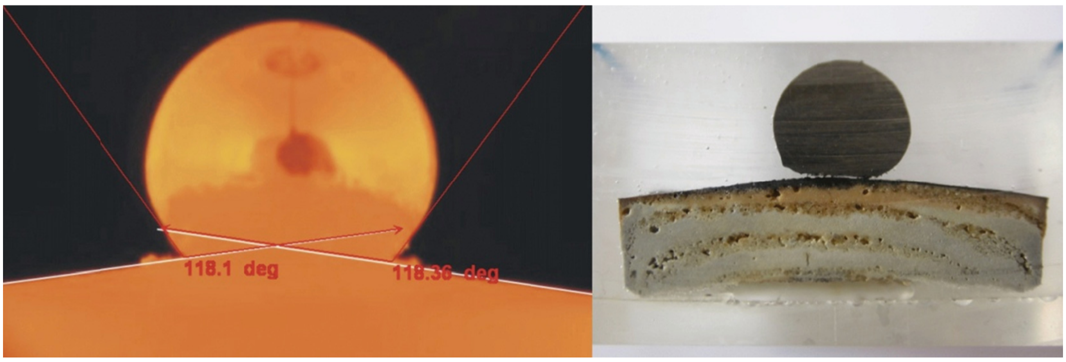

Fig. 18. Visualization of physico-chemical interactions occurring in the Ti/ZrO_2 system examined by the sessile drop method. The zirconia substrate was prepared with the use of a colloidal binder based on SiO_2

The conducted studies showed that using the ZrO_2 flour it is possible to make layer moulds for casting of titanium alloys.

To confirm the obtained results of studies, for large metal samples, experimental ceramic crucibles of 50 mm diameter were made by the technology of layer ceramic moulds. The crucible firing temperature was determined from the results of the scratch test, which consisted in scratching the surface of the thin samples of ceramic material with corundum tip. The scratch test was performed on samples preheated in the temperature range of 1150-1750°C (Fig. 20).

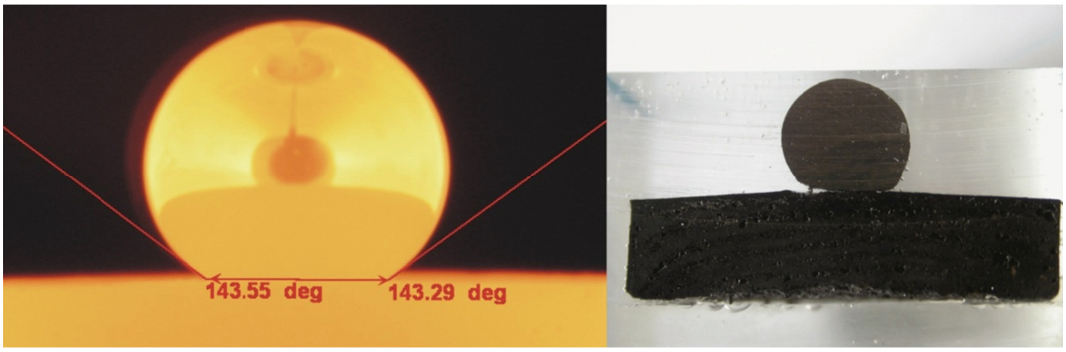

Fig. 19. Visualization of physico-chemical interactions occurring in the Ti/ZrO_2 system examined by the sessile drop method. The zirconia substrate was prepared with the use of a colloidal binder based on Y_2O_3

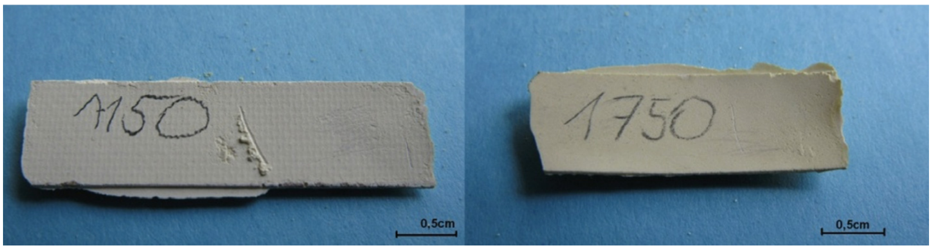

Fig. 20. The photograph of samples preheated at 1150 and 1750°C after the "scratch test"

Based on the obtained results, the temperature range for firing of ceramic samples was established at 1200 to 1400°C.

Samples were fired under the conditions of temperature increase preset at a rate of 10°C/min over the entire test range. The ceramic mould enters into direct contact with the intense metal flow and therefore its surface should form a compact layer sufficiently resistant to mechanical loads to prevent some of the mould elements from being "pushed" into the liquid metal.

The prepared experimental set consisted of titanium feedstock contained in a 50 mm diameter crucible. This crucible was, in turn, placed in a larger crucible casing adapted to operation in a Titancast 700 vacuum furnace. The composition of the starting alloy and of the remelted metal was determined with a Niton XL3t spectrometer using the X-ray microfluorescence phenomenon.

After remelting of titanium in a ceramic crucible, partial dissolution of zirconia in the titanium alloy melt was observed.

	%	±	Error		%	±	Error
Sb	0	:	N/A	Sb	0	:	N/A
Sn	0	:	N/A	Sn	0.017	±	0.006
Pd	0	:	N/A	Pd	0	:	N/A
Ag	0	:	N/A	Ag	0	:	N/A
Ru	0	:	N/A	Ru	0	:	N/A
Mo	0	:	N/A	Mo	0	:	N/A
Nb	0	:	N/A	Nb	0	:	N/A
Zr	0	:	N/A	Zr	0.389	±	0.005
Bi	0	:	N/A	Bi	0	:	N/A
Pb	0	:	N/A	Pb	0	:	N/A
Se	0	:	N/A	Se	0	:	N/A
W	0	:	N/A	W	0	:	N/A
Zn	0	:	N/A	Zn	0	:	N/A
Cu	0	:	N/A	Cu	0	:	N/A
Ni	0	:	N/A	Ni	0	:	N/A
Co	0	:	N/A	Co	0	:	N/A
Fe	0.035	±	0.012	Fe	0.032	±	0.014
Mn	0	:	N/A	Mn	0	:	N/A
Cr	0	:	N/A	Cr	0	:	N/A
V	0	:	N/A	V	0.238	±	0.055
Ti	99.819	±	0.073	Ti	99.208	±	0.080
Al	0	:	N/A	Al	0	:	N/A
S	0	:	N/A	S	0	:	N/A
P	0	:	N/A	P	0	:	N/A
Si	0	:	N/A	Si	0	:	N/A
Mg	0	:	N/A	Mg	0	:	N/A

Fig. 21. Titanium before and after remelting in the experimental ZrO_2 crucible and the results of chemical analysis of the titanium feedstock and metal remelted in the crucible using Niton XL3t spectrometer

8. Choice of materials for foundry patterns

The basic material used in the studies was zirconia of different granulations. The stabilizers tested were oxides of magnesium, calcium, yttrium and hafnium. The experimental ceramic moulds were made using colloidal aqueous binders based on zirconium, cerium and yttrium. Studies covered reactions which take place on the surface of ceramic mould when different types of pattern materials are melted out (Fig. 22).

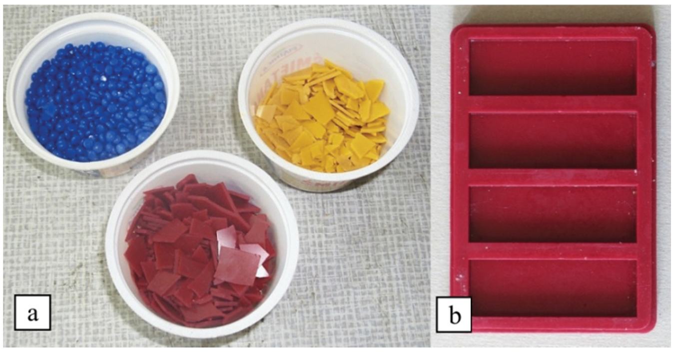

Fig. 22. Samples of different pattern materials (a) and moulded specimen of the Castaldo red wax (b)

The study used liquid ceramic slurries made from pure zirconia flour and flours stabilized with oxides of magnesium, calcium, yttrium and hafnium. The flours were mixed with aqueous colloidal binders of zirconium, cerium or yttrium, and were next poured into the prepared test moulds made from a variety of pattern materials. The surface of the poured liquid ceramic slurry was sprinkled with ZrO_2 sand to remove excess binder. Samples were dried in the open air and then wax was melted out in an air drier at a temperature of 300°C. By this procedure, samples measuring 60×20×6 mm were obtained (Fig. 23).

The next step involved firing of test samples raising the temperature at a rate of 10°C/min to a value of 1200°C. At this temperature, the samples were kept for 30 minutes, and then were cooled together with the furnace at a rate of 10°C/min to ambient temperature.

The moulding material of the highest quality, yielding moreover, which is most important, the highest mould surface quality, has proved to be the zirconia flour in combination with zirconium binder.

During melting out of pattern materials, it was found that some of them could damage the surface of the ceramic mould. This was due to the additives stabilizing the dimensions and, unfortunately, to a relatively low strength of the raw ceramic material.

In the case of items small in size, a D-VWI vacuum machine was used for the injection of pattern material, which significantly speeded up the execution of a series of wax patterns in specially designed flexible silicone rubber matrix moulds. In the first stage of the process, the interior of the matrix mould made of silicone rubber, placed in an outer tray, is emptied of air and then wax is injected into the mould cavity. The software monitoring the operation of the injection machine allows adjustment of the wax temperature, the time of maintaining vacuum and pressure, and the time of wax injection into the mould.

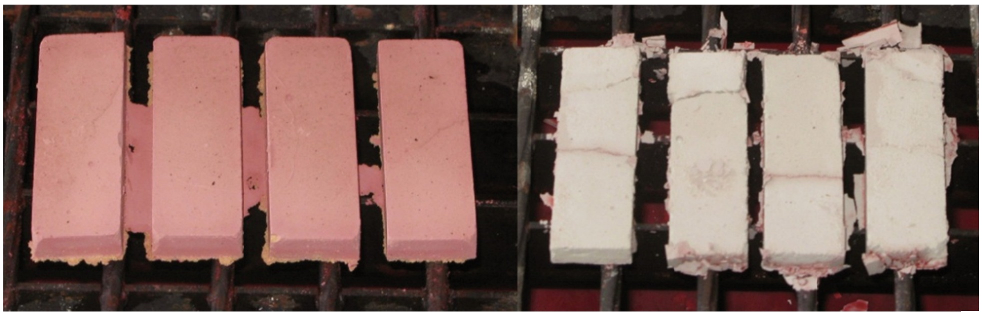

Fig. 23. Samples of ceramic slurries after melting out of the pattern material

9. Casting test pieces from aluminium alloys

Using wax patterns previously made, several different sets of castings weighing approx. 100 g each were poured. Owing to this, 250 g of aluminium alloy was melted in a Titancast 700 furnace filling the crucible to a maximum level. The first experimental castings were made from an AlSi7Mg alloy (Figs. 24-25).

During casting of aluminium parts, different designs of the feeding systems were tested and the effectiveness of vent channels was checked. In the casting process, block moulds made from the chemically-bonded ceramic materials were used. Particular attention was paid to the process of casting rings of the heart valves according to the documentation provided by the Zbigniew Religa Foundation for the Development of Cardiac Surgery in Zabrze.

Castings were made from the three different aluminium alloys. The commonly known AlSi7Mg alloy was used as the first one, followed by an alloy with low silicon content and specially prepared aluminium-magnesium alloy modified with titanium (Fig. 26).

The next trials were associated with the choice of alloy and casting pouring geometry to ensure the best conditions for filling the mould cavity with molten metal.

Fig. 24. Wax pattern sets made from different types of pattern materials (casting of the heart valve)

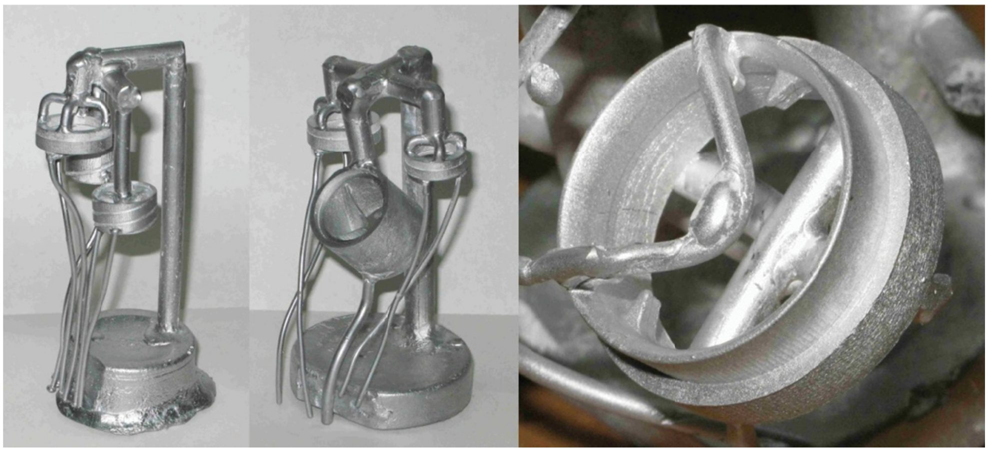

Fig. 25. Experimental castings of the heart valve made from an AlSi7Mg alloy

Fig. 26. Different designs of the heart valve castings

10. Making experimental ceramic moulds for casting of titanium alloys

Wax pattern sets were prepared using elements printed by the DodJet technique on a Solidscape printer and parts made from the Castaldo wax. The volume of the entire set depended on the titanium volume prepared for melting and amounted to approx. 180 cm^3.

The design of pattern sets allowed for the results of calculations made earlier in the Flow-3D program for the centrifugal mould pouring. All sets included elements to make specimens for the strength testing. After the completion of pattern-making operations, each set was weighed and after careful degreasing was coated with a surfactant to facilitate wetting of the wax surface with an aqueous suspension of the ceramic material.

Final quality of the titanium casting surface is mainly dependent on the properties of the suspension applied as a first layer of the ceramic mould. When the liquid slurry is prepared, it is important to carefully control its viscosity with the increasing addition of ceramic flour.

In studies of the technology of making layer moulds, the relatively laborious measurement of dynamic viscosity can be replaced with the measurement of kinematic viscosity, which consists in the determination of outflow time measured with a Ford cup. It is important to observe in the measurement a relatively rapid increase in the outflow time, when the volume fraction of the ceramic flour exceeds 42%. This means that the viscosity of the suspension allows obtaining the first layer of the ceramic mould characterized by the required high quality. In the case under discussion, the liquid ceramic slurry prepared for the first layer of the mould was characterized by an outflow time of 30 seconds (Ford cup, $\phi = 4$ mm) (Fig. 27). After coating the pattern set with liquid ceramic slurry, its surface was sprinkled with zirconia sand with the grain size of 0.1÷0.3 mm (Fig. 28).

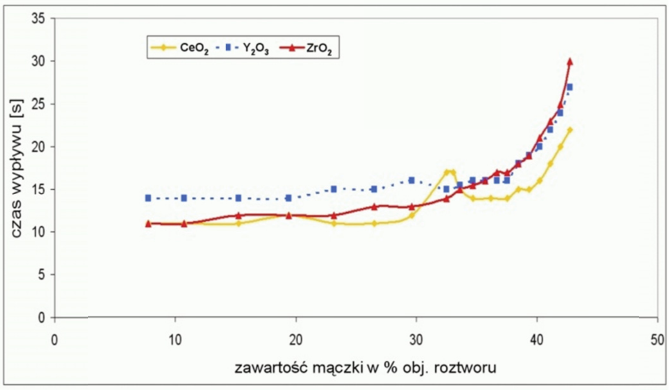

Fig. 27. Outflow time vs ceramic flour volume fraction in a dispersed system for the three tested solutions of colloidal binders

After the application of the first layer, the liquid ceramic slurry was made thinner adding a small amount of binder to obtain the outflow time of 20 s. After immersion in this slurry of the dry pattern set, it was coated with sand of 0,5÷1 mm grain size (Fig. 29).

After final drying for a time of approx. 24 h, the ceramic material covering the gating system of the ceramic mould was removed, the wax pattern material was melted out in a water autoclave at a temperature of 130°C. After de-waxing, the ceramic moulds were fired in a chamber furnace (Fig. 30).

The rate of temperature increase was 10°C/min up to the level of 1200°C. The mould was held at this temperature for 30 minutes and then was cooled with the furnace at a rate of 10°C/min to ambient temperature.

Castings were characterized by certain level of surface roughness reflecting the mould surface quality. Due to the presence of thermal phenomena degrading the surface of the ceramic mould when filled with molten metal, castings will always have certain level of roughness greater than the surface of the mould itself. The measured roughness of the mould surface indicates the expected casting surface quality (Figs. 31-32).

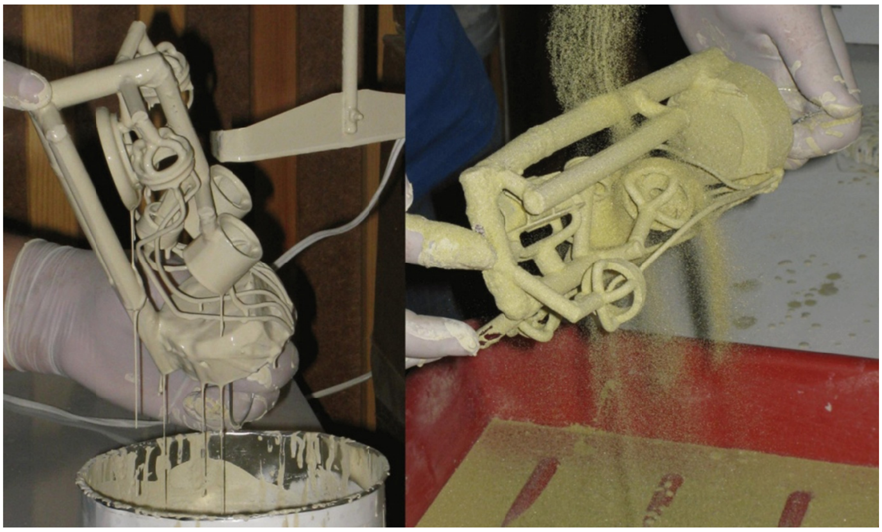

Fig. 28. Successive steps in the process of making the first layer of a ceramic mould (castings of the heart valve and hydraulic drive unit components)

Fig. 29. Successive layers of the ceramic mould applied in a tumbling device (castings of the heart valve and hydraulic drive unit components)

Fig. 30. Raw ceramic moulds before and after de-waxing

Fig. 31. Measurement of the ceramic mould surface roughness using a Hommel Tester T500 device

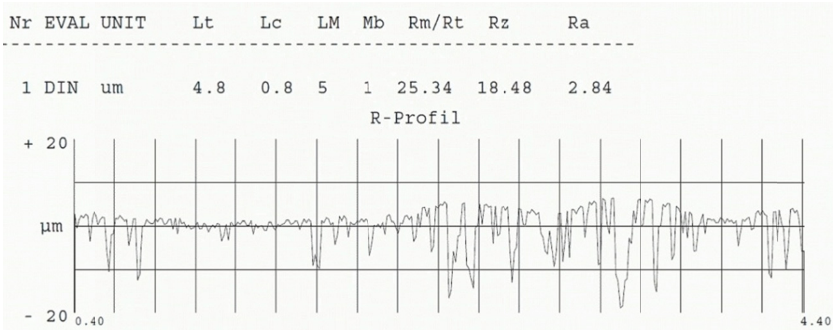

Fig. 32. An example of the measured roughness profile of the mould surface

11. Making experimental titanium alloy castings

Due to high forces acting on the mould during centrifugal pouring, the idea of making castings in self-supported moulds was abandoned. Finished moulds were placed in sleeves made of perforated stainless steel filled with Shaw refractory material. After preliminary drying, moulds were fired at 1000°C, and then cooled to pouring temperature. The prepared metal feedstock (TiAl6V4 alloy) was placed in a crucible and carefully dried at 200°C (Fig. 33).

The feedstock melting process and mould pouring were performed in a SuperCast centrifugal vacuum induction furnace from Linn High Therm using argon with a purity of 5.0 at a pressure of 600 mbar. The preset speed of rotating arm was 270 rpm. Time taken to reach this speed was 3 s (Fig. 34).

In the furnace chamber, the preheated crucible was placed, first, and then hot metal sleeve with the ceramic mould. After closing the furnace chamber and rinsing it with pure argon, the process of melting began. Monitoring and control of the entire process were executed watching the images obtained from a CCD camera connected with an optical pyrometer. When the pouring temperature was reached, the coil of the generator was lowered and chamber spinning process was put into operation, allowing the flow of molten metal from the crucible into the ceramic mould. With the spinning process completed, the chamber of the furnace was filled with argon until the value of atmospheric pressure was reached. Then the chamber could be safely opened and the metal sleeve poured with titanium alloy was taken out. The mould was left to cool down spontaneously, and then the ceramic casing was removed together with the mould material (Fig. 35).

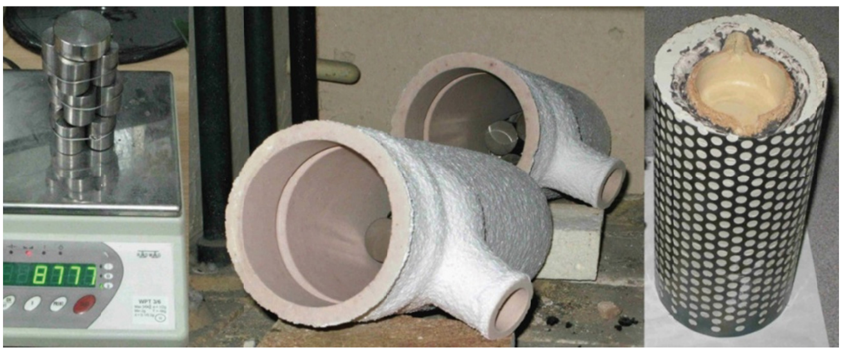

Fig. 33. Weighing of titanium feedstock, drying of crucible with feedstock placed inside, and ceramic mould ready for pouring with molten metal

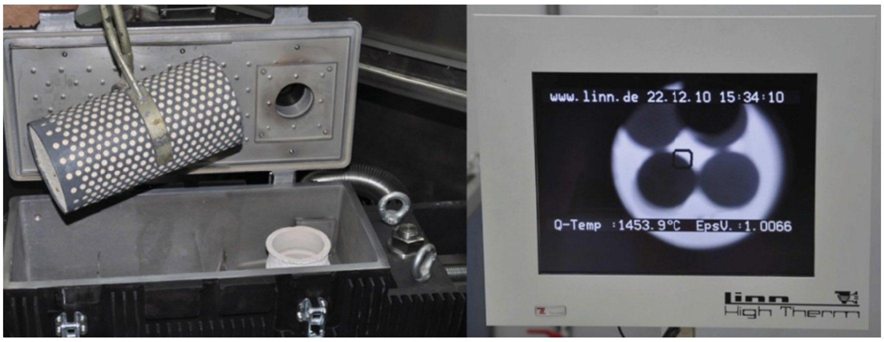

Fig. 34. Loading of the centrifugal furnace chamber and watching the titanium melting process with precise non-contact temperature measurement (right)

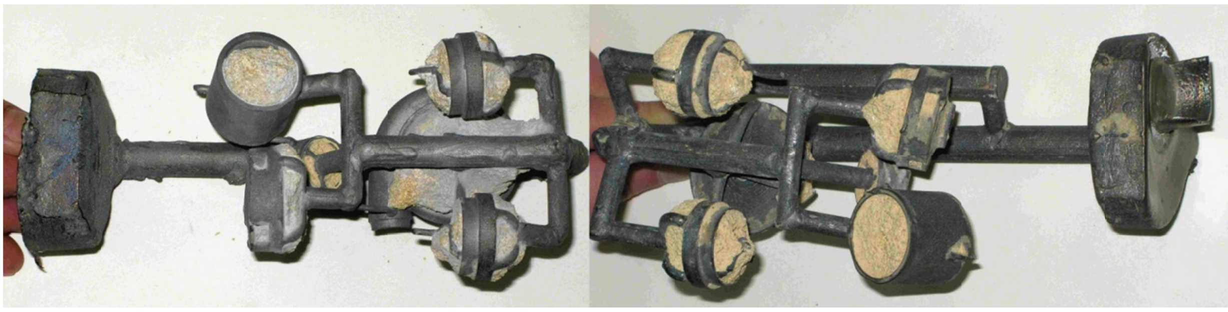

Fig. 35. Titanium castings after the initial removal of ceramic material (castings of the heart valve and hydraulic drive unit components)

12. Structure modification by HIP

Regardless of the casting technique applied, some adverse changes always happen in the structure of the final cast component. These are in most cases the defects in the form of gas and shrinkage microporosity. The result is a decrease of the casting strength, and defects that appear on the surface of the finished product after machining disqualifying this product, specifically from being used in responsible applications.

To remove the above mentioned defects, it was decided to apply the hot isostatic pressing that combines the process of heat treatment with high-pressure pressing.

Selected castings, after determining the heterogeneity of structure by computer tomography, were subjected to HIP (Fig. 36).

Fig. 36. The device for hot isostatic pressing of castings – HIP

13. Casting quality verification

The following photos show the resulting cast components of centrifugal pumps and chamber valve rings made according to different design solutions for the heart assist device (Figs. 37-38).

On the knocked out and sand blasted castings, tags were pasted for the 3D imaging with ATOS III optical scanner (Fig. 39).

The file in .stl format obtained as a result of scanning allowed comparing the dimensions of the scanned item with its CAD design drawing (Fig. 40).

The described technique of 3D scanning, besides the possibility of obtaining the required dimensions in any arbitrarily selected measurement plane, also provides an option which enables exact determination of the casting contraction. For the casting under consideration, the casting contraction determined by this technique was 1%, while the dimensional deviations did not exceed 0.1 mm (Fig. 41).

The tensile strength of the cast samples included in each paterrn set was above 800 MPa. Using prepared specimens, images of metallographic structures were taken (Fig. 42).

Non-destructive testing of the valve ring was performed on a computer-assisted Nanotom L80 X-ray tomograph achieving the measurement resolution of 0.5 μm.

To compare the component made by casting technique, studies also covered a heart valve ring made by the CNC machining.

Fig. 37. Titanium castings of centrifugal pump components for the hydraulic drive unit of the artificial heart

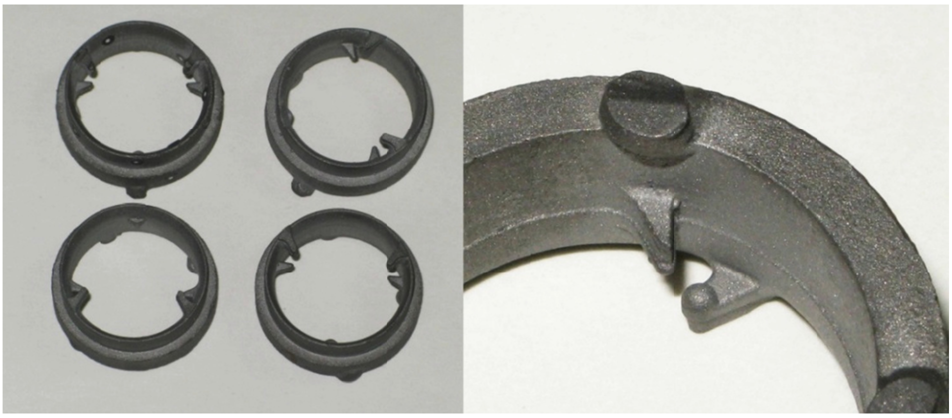

Fig. 38. Titanium castings of the heart valve ring and fragment of the valve disc holders as seen under a magnification

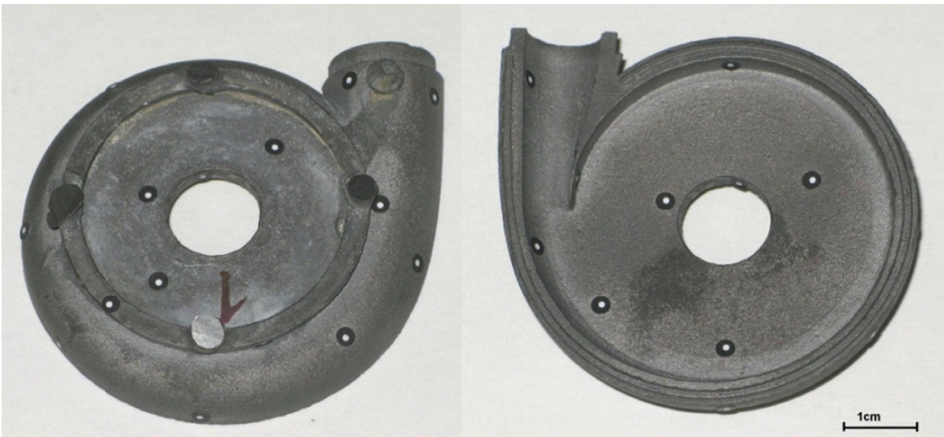

Fig. 39. A titanium casting of the centrifugal pump casing ready for 3D imaging

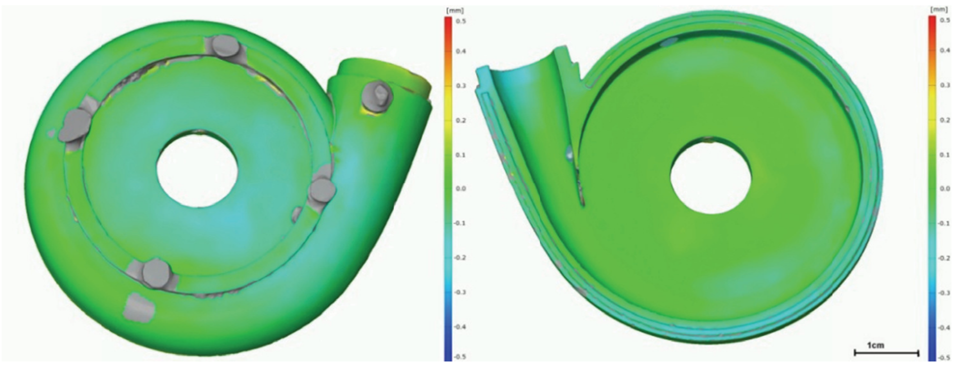

Fig. 40. Directory of dimensional deviations obtained for a casting of the centrifugal pump casing

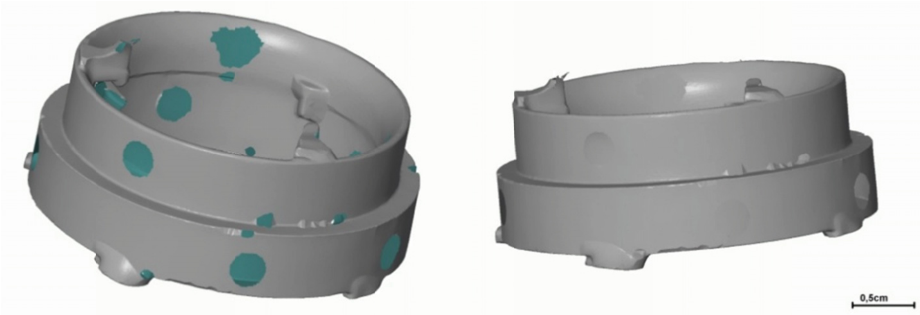

Fig. 41. The results of the transitional stage of the 3D scanning of the heart valve ring

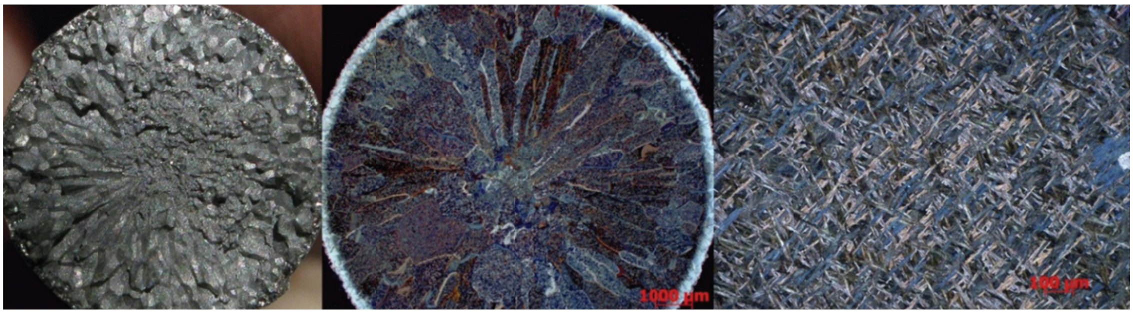

Fig. 42. Photograph of the test sample fracture (a) and sample microstructure as seen under the optical microscope at a magnification of 12,5× (b) and 100× (c)

Below are the results obtained by various graphic imaging techniques (Fig. 43).

The final result of computer-assisted X-ray tomography is a virtual 3D image of the scanned object that allows examination of successive layers of the casting in any arbitrary plane. Possible is location of structural defects, enlargement of the area of their occurrence and rotation with respect to the selected axis (Figs. 44-45).

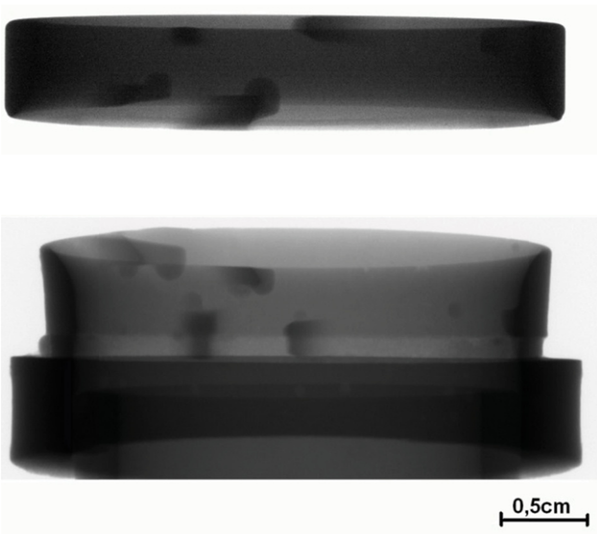

Fig. 43. The results of computer-assisted X-ray tomography of the heart valve rings made by machining (top) and casting (bottom)

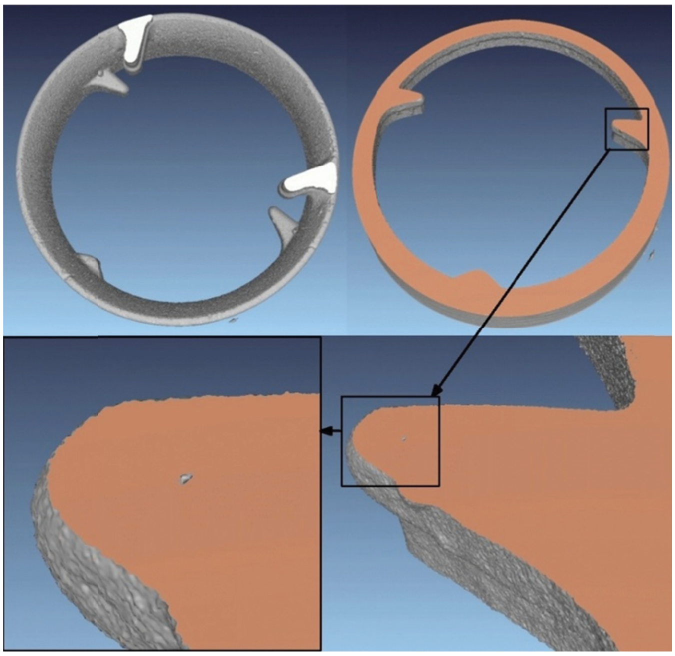

Fig. 44. A spatial model of the heart valve ring developed for the detection of structural defects in casting

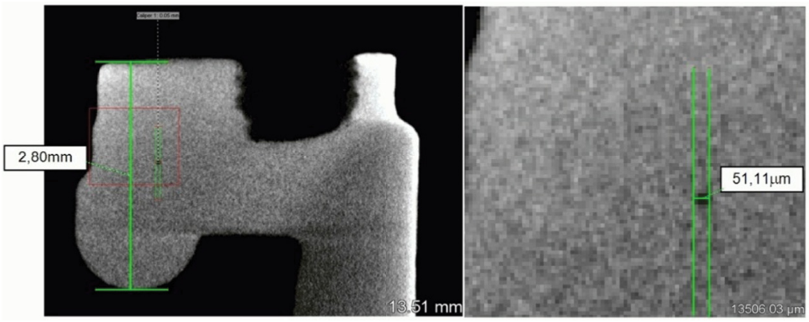

Fig. 45. Vertical section of casting in the place where a structural defect was detected

14. Summary

As a result of studies conducted at the Foundry Research Institute under the "Polish Artificial Heart" programme:

a) a computer-aided casting design was developed and a physical model of the cast components of a propulsion system was made,
b) pattern materials and ceramic materials were selected,
c) a technological process was developed to cast the components of a propulsion system,
d) test castings of the propulsion system components were made,
e) a technique of melting and mould pouring in a vacuum induction furnace for centrifugal casting was developed.

During practical implementation of the study, patterns for visualization of the currently offered design solutions were printed.

Based on the results of computer simulations using 3D Flow software, the casting process parameters were verified.

The developed technology of ceramic layer moulds made of zirconia enables making castings from titanium alloys in a SuperCast vacuum induction furnace for centrifugal casting.

For centrifugal pumps, patterns were made of both the pump casing and impeller. The centrifugal pump impeller was made in two variants, i.e. with closed and open channels intended for mounting of the drive magnets.

A technique of casting quality control was developed including:

a) testing of mechanical strength on samples included in each pattern set,
b) determination of alloy composition using Niton XL3t 900S GOLDD X-ray microfluorescence analyzer and LECO GDS 850A optical emission spectrometer with glow discharge,
c) a method for the determination of metallographic microstructure in polarized light.

At the final stage of the quality control process, the level of microporosity was examined using sequentially a digital X-ray apparatus and CT scanner.

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