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APPLICATION OF NON-DESTRUCTIVE METHODS TO QUALITY ASSESSMENT OF PATTERN ASSEMBLY AND CERAMIC MOULD IN THE INVESTMENT CASTING ELEMENTS OF AIRCRAFT ENGINES

ZASTOSOWANIE NIENISZCZĄCYCH METOD DO OCENY JAKOŚCI WOSKOWYCH ZESTAWÓW MODELOWYCH ORAZ CERAMICZNYCH FORM W PROCESIE ODLEWANIA PRECYZYJNEGO ELEMENTÓW SILNIKÓW LOTNICZYCH

The aim of this paper is manufacturing of turbocharger engine jet blades made of nickel superalloys. Processes for producing molds and casting realized in a production line are special processes. It means that the results are known only after inspection of the finished product. There is lack of the methods and techniques of effective and efficient quality control of the work in stock, above all molds. Therefore, the unknown is the state ceramic mold for the precision casting, which resulting in risk of referral to a defective mold of the casting process and thus give the product does not comply, is eliminated in the final inspection.

One method of reducing this risk is particularly thorough monitoring of all parameters of each process and keeping them in the desired operating point. Operating point is a set of parameters of processes. Such monitoring is possible with the commitment to the methods and techniques to automatically, without human intervention, data collection and processing methods appropriate for use in operational control.

The paper presents results of research on the attitude to the problem of a special process. This change is the introduction to the process efficient and effective form of quality control tools in the course of its preparation. In this case, the method of photogrammetry, thermal imaging and computed tomography were used.

With the infrared camera will be possible to determine the temperature field, the disorder in relation to the pattern indicates the type of defect. Computed tomography and will be used to develop patterns of correlated defects associated with thermal imagers. Photogrammetry is the use of a model set of quality control (comparison of the actual state of the model *.CAD). It also allows the designation of a wall thickness of the mold.

Keywords: special process, investment casting, turbine blades, 3D scan, thermovision, computed tomography

Referat dotyczy procesu wytwarzania łopatek turbosprężarek silników odrzutowych wykonanych z nadstopów niklu. Procesy wytwarzania form i odlewania, realizowane w linii technologicznej są procesami specjalnymi. Oznacza to, że ich wyniki są znane dopiero po kontroli wyrobu gotowego. Brak jest, bowiem metod i technik efektywnej i skutecznej kontroli jakości półproduktu, przede wszystkim formy. Tym samym nieznany jest stan formy przeznaczanej do odlewania, co skutkuje ryzykiem skierowania do procesu odlewania wadliwej formy i tym samym wytworzeniem wyrobu niezgodnego, eliminowanego dopiero podczas końcowej kontroli odbiorczej.

Jedną z metod zmniejszania tego typu ryzyka jest szczególnie gruntowne nadzorowanie wszystkich parametrów poszczególnych procesów i utrzymanie ich w wybranym punkcie pracy. Punkt pracy jest zbiorem parametrów realizacji procesów. Takie nadzorowanie jest możliwe w przypadku zaangażowania do tego celu metod i technik automatycznego, bez udziału człowieka, zbierania danych oraz metod właściwego ich przetwarzania na użytek operacyjnego sterowania.

W artykule przedstawiono wyniki badań nad zmianą podejścia do problemu procesu specjalnego. Zmiana ta polega na wprowadzeniu do procesu efektywnych i skutecznych narzędzi kontroli jakości formy w trakcie jej wytwarzania. W tym celu wykorzystano metody fotogrametrii, termowizji oraz tomografii komputerowej.

Dzięki zastosowaniu kamery termowizyjnej możliwe będzie określenie pola temperatury, którego zaburzenie w stosunku do wzorca wskaże na rodzaj wady. Tomografia komputerowa natomiast będzie służyła do opracowania wzorców wad skorelowanych z obrazami termowizyjnymi. Fotogrametria znajduje natomiast zastosowanie w kontroli jakości zestawu modelowego (porównanie rzeczywistego stanu z modelem *.CAD). Umożliwia także wyznaczenie grubości ścianki formy.

1. Introduction

Investment casting in multi-layer ceramic moulds allows manufacturing geometrically complex shapes of aircraft parts, such as: blades, segments of turbine, vane clusters, housing and others. However, current investigations and production experiences indicate that this method does not provide conditions to obtain castings of a fully repeatable quality. This quality is

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determined by the shape, size, surface conditions, edge condition, the level of internal defects. It should be emphasized that a lack of the total repeatable, means an occurrence of defected castings, causes only a yield decrease (and has negative economic consequences), but does not influence the quality of the product supplied for assembling in engines. It happens due to the 100-percent acceptance inspection. The production process of aircraft engines is a complex process, in which several material-technological and organizational factors influence the final quality.

Moulds are made in a multi-operational process of depositing ceramic coatings on wax sets of patterns, wax melting, washing, drying and mould burning [1]. Depositing of ceramic coatings is done either manually or by robots. After burning, moulds are insulated, heated to a high temperature and poured with liquid metal under vacuum conditions. Each of these processes and their cycle has character of a special process, which means that their result can be assessed only at the end, as the bases of the multi-criteria inspection of the final product.

Thus produced critical parts of the aircraft are decisive to flight safety and therefore can not be subject to geometrical defects, surface and internal defects casting. The requirements for this level puts all companies producing aircraft engines with the highest world standards. Early detection of defects in the mold, it is primarily a problem of eliminating losses. Faulty form should be as early discontinued. Reducing the production defective is yet another aspect of the economy outside directly associated with yield. This is a desire to reduce the risk of error of the second kind, ie the recognition of the defective product for the product line. Without a doubt, the production of a greater number of defects, even under 100 percent control creates conditions for increased risk of such a mistake.

Currently there is a lack of efficient methods and techniques of a mould quality control during its successive production phases, as well as after its finishing and treatment. To this effect, moulds in an unknown state are passed over to the final operation of pouring with liquid metal. In practice, it causes high losses due to a small yield or reparation costs.

Significant losses are also caused by unnecessary costs of producing faulty moulds. The more so, since till now there is none cause and effect, accurate, quantitative description of individual processes and their combination, which would be able to forecast the casting result on the bases of the set of parameters obtained at the model set of patterns and mould preparation.

Obvious obstacle is the lack of the possibility of controlling individual processes, especially the mould state, during successive production stages.

The concept of the application non-destructive methods for interoperation quality control of multi-layer ceramic moulds in the process of investment casting of turbo-compressor blades for aircraft jet engine is presented in this paper. Methods of photogrammetry, thermovision and tomography were applied. The obtained results indicate that photogrammetry will find its application in the quality control of wax pattern assembly (comparison of the real state with the model *.CAD) and will allow to determine the mould wall thickness. Due to applying the thermovision camera it will be possible to determine the temperature field, the disturbance of which – in relation to the standard – will indicate the kind of defect.

Computed tomography will allow for developing fault standards correlated with thermovision pictures. An implementation of this type of control will enable the early discovery of a defected mould, its elimination from the production and in consequence the significant decrease of production costs.

2. The essence of NDT methods applied in assessment wax pattern assembly and ceramic mould

2.1. The essence of photogrammetric method

Photogrammetry deals with obtaining information on physical objects and their surroundings by recording, measuring and interpretation of pictures and photographs. Recording of the same point in several photographs performed from various positions allows to determine point space location. The photogrammetry application requires taking some photos from various, known positions for the same scene.

Photogrammetric digitalizing 3D systems should be considered as the subsystem of the 3D scanning and as the photogrammetric subsystem.

The 3D scanning subsystem is the stereoscopic optical system, containing two cameras equipped with the CCD matrices and projector with the LED lighting. Three triangulation angles – between cameras and between cameras and a projector are used in the pictures processing. A measuring accuracy depends, among others, on the measuring field, geometric parameters of the stereoscopic optic system, parameters of cameras and objectives. The software offered by leading producers of systems[2,3], allows the automated realization of the majority of the basic functions of data processing, including: calibration, transformation, control of locations and controlling of the measuring head. The projection quality during each measurement, calculation of the proper lighting, calculation 3D coordinates, joining individual measurements based on reference points, calculation of triangle networks (traversing from point clouds 'holes closing), calculation of parallel and perpendicular cross-sections, notation in the global coordination system: 3-2-1 as well as operations of: cutting, projection, averaging, are also automated. This software assures also the direct data exchange with the CAD/CAM programs.

The detector of the photogrammetric subsystem contains the digital photo camera of a resolution of at least 20 million of pixels with equipment assuring the proper picture quality and data processing scale. The software of the photogrammetric subsystem is joint with the software of the 3D scanning subsystem and allows the automated detector calibration, defining the global reference networks and optical space scanner, the possibility of measuring static deformations, possibility of data comparing with the CAD model, functions of location and shape.

Photogrammetric techniques allow scanning (measuring points coordinates) elements of various dimensions, from some millimeters to several dozen of meters. Their action is based on the triangulation rule. Two cameras observe the spectral line pathways on the measured object and for each

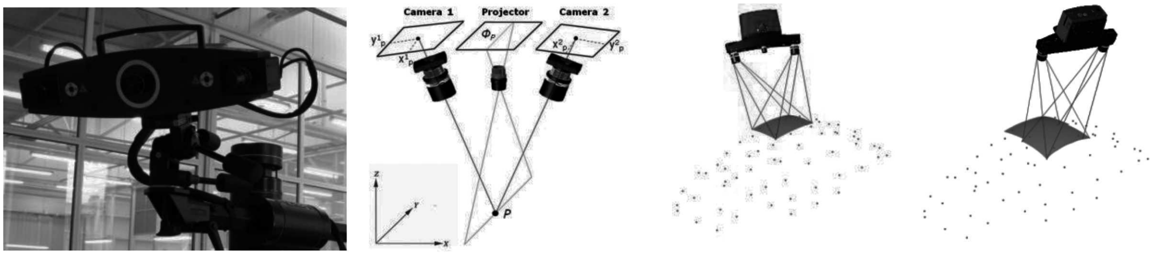

Fig. 1. 3D scanner – essence of activity [2]

camera pixel the coordination point is calculated. Such measurement is taken very precisely. The total analysis of the performed measurement, consisting of: dimensioning of details, comparing with the CAD data, creating the colored map of deviations, inspection of cross-sections is possible due to the proper software. The 3D scanner and the measuring essence are presented in Figure 1.

The photogrammetric method found wide range of applications, among others, in automotive, aircraft, railway, shipbuilding and building industries.

Information concerning photogrammetry and its detailed description together with the application possibility are presented in papers [2-7].

2.2. The essence of thermovision method

Thermovision is recording of an infrared radiation emitted by objects being in its visual field. An object temperature influences its radiation intensity. A visible radiation occurs when a source is at a temperature above 950K. At first a red part of the spectrum widens, then at a temperature near 1500K the red, yellow and green parts occur, and at a temperature near 1800K already the whole visible range is seen. The electromagnetic spectrum extends also to the infrared (IR) and ultraviolet (UV). The infrared is represented at low temperatures (<950K), while ultraviolet at high temperatures.

An electromagnetic spectrum is divided into several wave length ranges called zones (Fig. 2). These zones are discriminated by methods applied for the radiation detection. There is none essential difference between radiations of various spectrum bands. All of them are subjected to the same laws, the only difference being their wave length.

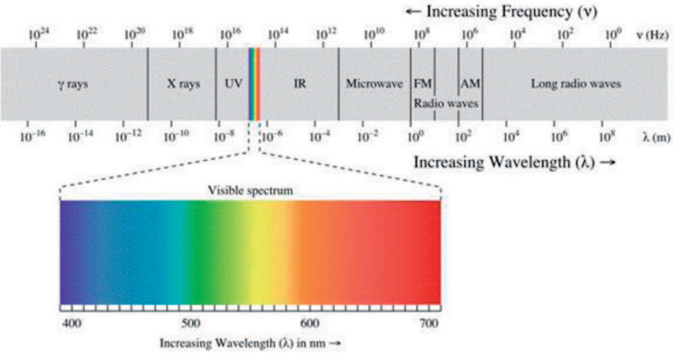

Fig. 2. Electromagnetic spectrum [8]

Each body of a temperature higher than the absolute zero is a radiation source in an infrared band and its intensity depends on a temperature and properties of its surface. The bases of thermovision operations constitutes the Stefan-Boltzmann law, which states that the total radiation energy (visible and invisible) emitted by the black body surface unit in the time unit is expressed by the equation:

$$E = \sigma T^4 \tag{1}$$

where: σ =5.669·10-8 W/m^{2}K^4 – Stefan-Boltzmann constant.

The black body is an object, which absorbs the whole radiation incidence regardless of wave lengths. A seemingly improper name ‘black body’ used for the object emitting radiation is explained by the Kirchoff’s law, which states that a body which is able to absorb radiation of any length is also able to emit this radiation. In practice, a notion of the grey body is also used. It emits (or absorbs) less energy than the black body, since it depends on the emission (absorption) coefficient of the given surface, which is a function of its chemical composition and state. Thus, the thermovision application is based on recording, by means of a special camera, the infrared part of the spectrum emitted by the body and transferring it into the colored map of temperatures distribution (temperature field).

The emissivity (emission factor) is an indicator of the given object ability for the energy radiation. It is defined as the ratio of the energy radiated by the object at the determined temperature to the energy emitted by the black body at the same temperature. The emission factor value depends on the material kind, finishing and geometry of its surface, material temperature, observation wave length and the observation angle. The emission factor of the black body equals 1.0. The emission factor of a majority of organic substances (textiles, plastics, wood, etc.) equals approximately 0.95, however for metals of smooth, polished surface the emission factor is much lower than 1.0. A high emissivity value of the object indicates that it is well ‘measurable’ by the camera. If the emission factor is close to zero, it means that the object is difficult for measuring by the camera. This is related to the influence of the radiation of the surroundings reflected from the object.

Thermovision cameras are devices used for measuring the objects temperature fields. A picture creation is based on recording the radiation emitted by the observed object and transforming it into the coloured temperature map.

An accuracy or uncertainty of the thermovision measurement result should be considered from several aspects. A basic parameter constitutes the object emissivity. The temperature distribution of the investigated object depends not only on properties which are analysed e.g. thickness changes, structure, defects etc., but also on the object placement, influencing e.g. a cooling intensity of individual segments. Generally errors of the method, calibration and electronic path are singled out. In the current thermovision systems the most modern technology, minimizing these errors, is applied. On the basis of the discovered temperature differences the thermovision cameras create a clear picture. Adequate algorithms enable reading from these pictures the proper temperature values and generally allow to determine the temperature field.

The infrared energy originated from the object is focused by optical elements on the infrared detector. This detector sends information to the electronic sensor to transform the picture. The data from the detector are electronically transferred into the picture, which can be seen either in the viewfinder, or standard video monitor or on the LCD screen. The software allows adjusting picture parameters such as: a color palette, temperature level and range. Infrared imaging became one of the most valuable tools of the technical state survey of the production system elements. Discovering anomalies, often invisible to the naked eye, thermovision allows to undertake remedial measures before the costly system failure.

The thermovision method is applied, among others, in building, automotive, aircraft and railway industries as well as in material investigations.

Information concerning thermovision, details of its essence as well as practical applications are presented in papers [9-14].

2.3. The essence of computed tomography method

A computed tomography is a kind of the X-ray spectroscopy. It allows to obtain tomographic pictures (cross-sectional profiles) of the investigated object. It uses the composition of the object projection performed from various directions to create cross-sectional profiles (2D) and then, after their combination, obtaining space pictures (3D).

Creating of tomograms is based on measuring the radiation component not absorbed by the object, which is divided into small cells called voxels, in which the linear absorption coefficient is the same. The cross-sectional profile formed in such way is the quantitative map of the linear absorption coefficient of the radiation, measured in voxels, being included in the scanned layer. The tomographic measurement, at a significant simplification, is based on directing the radiation beam X on the object and recording its intensity on the other side in the detector. The X-ray radiation passing through the investigated object becomes weaker, which is the function of the radiation energy, kind and thickness of the investigated material.

Two kinds of projection systems are the most often used in the computer tomography:

– system with a parallel radiation beam (2D tomograph) (Fig.3a),

– system with a conical radiation beam (3D tomograph) (Fig. 3b).

The system with a parallel radiation beam consists of the flat X-ray beam, which is emitted in the direction of the investigated object. On the other side of the system lamp-object there is the linear detector responsible for recording the measuring signal. The investigated object is angularly and linearly shifted in x, y, z directions or the system lamp–detector is relocated.

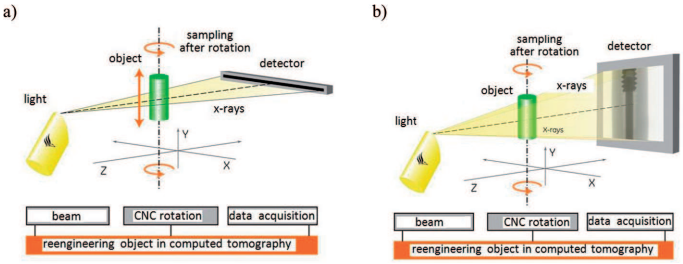

Fig. 3. Projection system with a parallel radiation beam (a), a conical radiation beam (b) [15]

The system with a conical radiation beam, in a similar fashion as the previous system, consists of the lamp and matrix detector. The difference is based on the emitted radiation beam, which is formed in a cone and on the detector kind. The representation accuracy depends on the number of projections performed for the detail. The method applying a conical radiation beam is currently the most often used in the industrial computed tomography. It is characterized by a high speed of the picture reconstructure and a simpler system structure.

The computed tomography, apart from a wide application in medicine, is also used in technique, especially in material investigations and in determinations geometrical features of products, which measuring by other methods is either inaccurate or just impossible.

Tomographic images contain information on a location and density of the object absorbing features and are further used for reconstruction of space data. Even small differences in density, porosity, discontinuity etc. inside the object, can be imaged and measured with the accuracy sufficient for the majority of engineering problems. The immobile X-ray lamp is used in metrology and material investigations. The investigated object is being turned. Due to a high radiation hardness the measurements of very complex objects of not easily accessible, or even invisible, surfaces are possible. Computer X-ray tomography is applied as a tool for 3D microanalyses, identification of inner faults, delaminations, inclusions and for measuring geometrical values.

Equipment for various applications is currently available, including faults inspection and structure analysis as well as 2D and 3D metrology. It enables distinguishing of objects already from dimensions 200-300nm with a resolution (voxel) from 0.5 μm. The measurement minimal error is 1 μm.

Equipment solutions are characterized by unique software modules enabling a noise and disturbance reduction, filtration of effects resulting from physics laws and automated geometrical calibration. Applications are adjusted both for samples weakly and strongly (metals) absorbing radiation.

Information and the detailed description of the essence of tomography and its applications are presented in papers [15-23].

3. Experimental Setup

3.1. Investigations carried out by means of photogrammetric method

The essence of photogrammetric investigations was assessment of the individual wax model and the wax pattern assembly with the *.CAD model. In addition, the comparison of the wax pattern assembly scanning results with the mould scanning results allowed to determine the wall thickness distribution of individual elements.

The wax pattern assembly (Fig. 4), produced under industrial conditions, was used in investigations and subjected to the photogrammetric scanning.

Fig. 4. Part of pattern assembly

Investigations were performed by photogrammetric system: ATOS Triple Scan of the GOM Company [2] (Fig. 5). The device was equipped with two independent cameras of a resolution of 8 million pixels each. The measuring field, it means the maximum area encompassed in one scan, was 300×220 mm, while the physical distance between points was at the level: 0.01-0.61 mm. Result of settings of metering equipment and room conditions (temperature, humidity, light conditions) was a single scan accuracy of 0.05 mm.

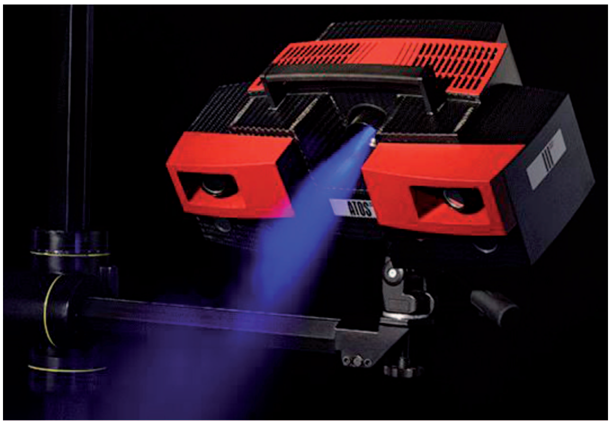

Fig. 5. Photogrammetric system ATOS Triple Scan [2]

Images obtained in the photogrammetric scan were superposed on the *.CAD (Fig. 6) model to estimate the quality of the set of patterns, it means: shape, dimensions and layout of individual wax models. The software GOM Inspect was used for images processing.

At next step, wax pattern assembly was directed to the process of depositing multi-layered ceramic coatings. The successive operations were: moulds drying in a dryer, wax melting in an autoclave and moulds burning in a pusher furnace. After these operations the moulds (Fig. 7) were again photogrammetrically scanned.

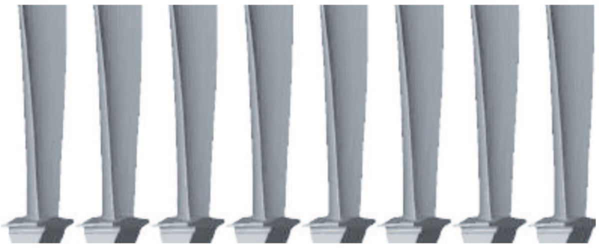

Fig. 6. *.CAD model of pattern assembly

Fig. 7. Part of ceramic mould

After the proper processing, images of the wax pattern assembly and the ceramic mould were superimposed on each other by means of the GOM Inspect program. As the result of such composition of images the wall thickness of the mould was obtained. The results are presented in forms of photograms.

3.2. Investigations carried out by means of thermovision method

The investigation essence in thermovision was the quality assessment of the ceramic mould, based on the identification of external surface defects as well as internal defects such as: cracks, structural defects and diversification of mould walls thickness.

Fig. 8. Thermovision camera FLIR SC8000 [14]

The thermovision camera: SC8000 of the FLIR company (Fig. 8) was used in investigations. It was equipped with the InSb cooled detector, allowing to obtain sharp thermograms of a resolution: 1280×1024 pixels at a frequency of 100 Hz. Due to that feature, it was possible to collect four times more thermal data than offered by standard images of a resolution: 640×512.

Investigations were carried out in two independent series, in dependence of a medium filling the mould for its excitation:

– mould pouring with water at a temperature of 90°C,

– mould heating (by the dryer of the Streuers Company) at a temperature of 200°C for 30min.

The continuous temperature changes measurements of the external mould surface were performed during each stage. The ThermaCAM Researcher software applied for thermograms editing, allowed depositing temperature-measuring points on each place on the external surface of the tested mould. The obtained results are presented as thermograms with the temperature fields.

3.3. Investigations carried out by means of computed tomography method

The essence of the tomographic investigations was the complex quality assessment of the ceramic mould based on the identification of its external surface defects as well as inner defect such as: cracks, structural defects, porosities, diversification of grain sizes on the mould wall cross-section and diversification of wall thickness. It is especially important that - due to this method - it was possible to assess the quality of the inner mould surface, since the identification of its state is not possible by other methods.

Tomograph V|tome|×L 300 of GE Measurement & Control Solutions company (Fig. 9) was used in investigations. Operation parameters of the device were:

– individual voxel size: 14.633 μm,

– resolution: 1980×1000,

– lamp power: 240 kV,

– number of individual images in tomogram: 2200.

Fig. 9. Tomograph V|tome|×L 300 [21]

One ceramic mould was chosen for testing. The obtained results of the outer and inner surface, cross-sections and wall thickness are presented in tomograms with the application of the myVGL 2.1 Volume Graphics GmbH. company program.

4. Results

4.1. Investigations results obtained by photogrammetric method

The photogrammetrically scanned image of the wax pattern assembly superimposed on the *.CAD model is presented in Fig. 10.

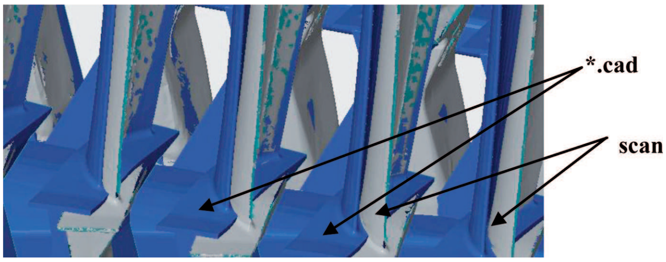

Fig. 10. Comparison of the scanned image of the pattern assembly with the *.CAD model

Brighter (grey) areas are the effects of the scanning while darker (blue) areas correspond to the *.CAD model. The results superimposed on each other indicate the improper quality of the wax set of patterns in a form of shifting individual blades in relation to the model. Examples of positive and negative deviations are presented in a photogram (Fig. 11).

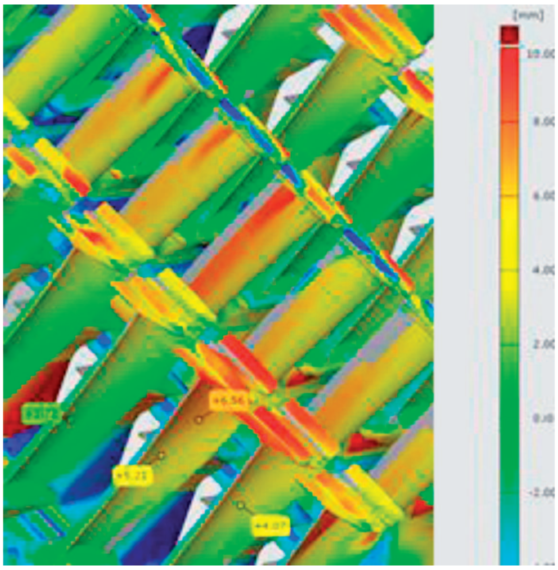

Fig. 11. Map of deviations of the pattern assembly in relation to the *.CAD model

The observation results of the ceramic mould image (grey areas) superimposed on the wax set of patterns image (blue areas), obtained as a result of photogrammetric scanning are presented in Fig. 12.

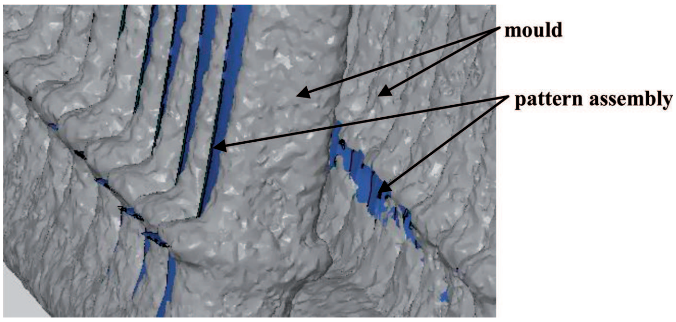

Fig. 12. Comparison of the image of the pattern assembly with the superimposed image of the scanned mould

These results indicate that during the ceramic mould production the wax set of patterns undergoes a certain deformation. The most probably it is caused by a high density and viscosity of the material, intended for the ceramic mould production and influencing an easily deformable wax. The results of the identification of the mould walls geometry and thickness, by means of using the so-called cross-sectional inspections are presented in Fig. 13.

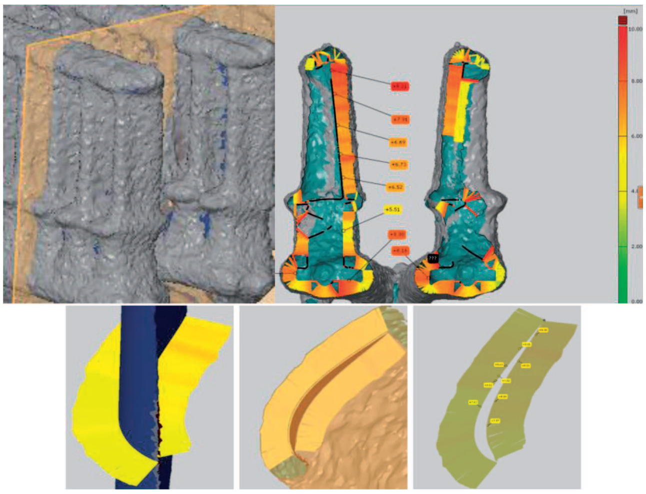

Fig. 13. Identification of the mould walls geometry and thickness with an application of cross-sectional inspections

The results indicate the diversified thickness of the mould walls within a range: 4-10 mm. Such a high dispersion of the wall thickness of the mold may influence the formation of cracks during pouring the liquid metal or the occurrence of defects in the finished product, due to varying heat dissipation rate of the mold wall.

4.2. Investigations results obtained by thermovision method

The obtained results of temperature fields for the mould poured with water at a temperature of 90°C are presented in Fig. 14 as thermograms.

Thermograms present diversified temperature fields on the mould surface after 5 seconds of being poured with water (Fig. 14a), after 30 seconds (Fig. 14b) and after 60 seconds (Fig. 14c).

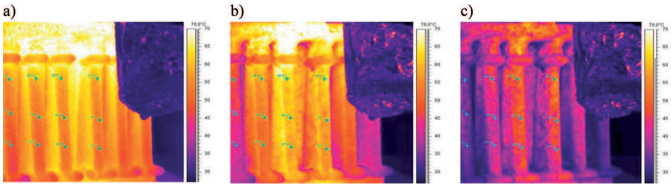

Fig. 14. Distribution of temperature fields on the mould surface poured with water: a) after 5 seconds, b) after 30 seconds, c) after 60 seconds

The temperature range of the mould surface is between 30°C and 90°C. It can be observed, that the liquid propagation inside the mould as a time function is manifested by diversification of the temperature fields. The essential fact is, that the smaller wall thickness the higher temperature in this point on the mould surface than in areas around this point.

The results of temperature fields obtained for the mould heated, at a temperature of 200°C for 30 minutes in the dryer, are presented in a thermogram form in Fig. 15.

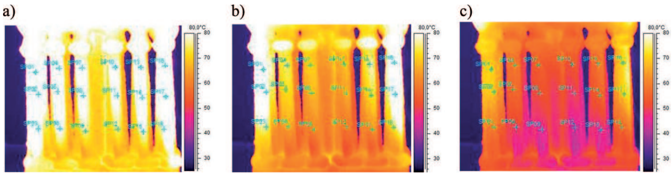

Fig. 15. Distribution of the temperature fields on the mould surface after heating in the dryer and then cooling for: a) 10 seconds, b) 60 seconds, c) 180 seconds

Thermograms present diversified temperature fields on the surface of the mould removed from the dryer after 10 seconds (Fig. 15a), 60 seconds (Fig. 15b) and 180 seconds (Fig. 15c). Temperatures of the mould surface are from 30°C to 180°C. Similar as in the case of the mould poured with water, it can be observed that the characteristic temperature fields depend on the mould wall thickness.

4.3. Investigations results obtained by computed tomography method

The results of the observation of the mould part with the visible external surface, the mould wall cross-section and the inner surface are presented in a form of a tomogram in Fig. 16a. The results of the observation of the mould external surface indicate its high irregularity (Fig. 16b).

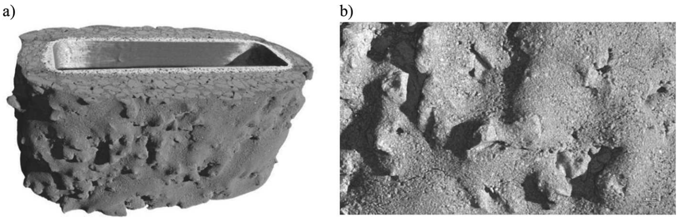

Fig. 16. 3D image of the part of the tested mould (a), external surface of the mould (b)

The cross-section of the mould fragment is presented in Fig. 17a. The diversification in the ceramic fraction value, its irregularity and location can be noticed.

Fig. 18 presents the mould cross-section, which allows measuring the wall thickness. In addition, it shows discontinuities in successive ceramic layers.

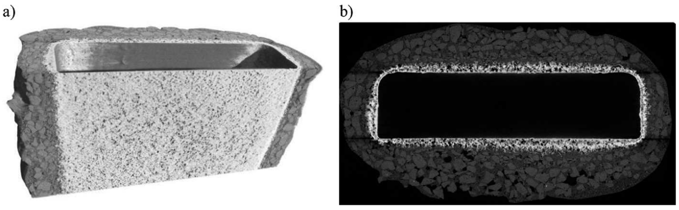

Fig. 17. Cross-section of the tested fragment of the mould (a), cross-section of the tested mould fragment – another shot (b)

The results of observation of the mould fragment with marked cross-sections, in which the thickness of the mould walls were measured, are presented in Fig. 18, while the results of the mould thickness measurements in the x-y cross-section are presented in Fig. 19a, in the x-z cross-section in Fig. 19b and in the y-z cross-section in Fig. 19c.

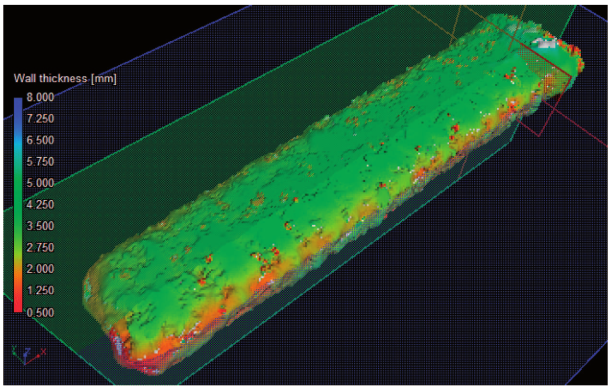

Fig. 18. Observation of the mould fragment with marked cross-sections, in which the wall thickness was measured

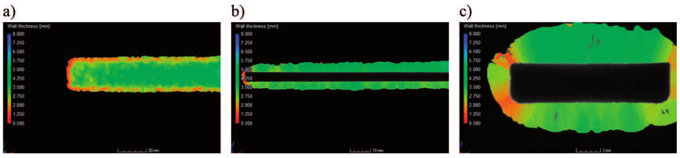

Fig. 19. Thickness of the mould wall: a) in the x-y cross-section, b) in the x-z cross-section, c) in the y-z cross-section

Tomographic observations indicate large diversification of the thickness of the mould walls, being within range: 1-8 mm.

5. Conclusions

1. It was found, on the bases of the performed investigations, that there is a diversification of shapes, dimensions and structure of the set of patterns as well as of the mould.
2. The presented investigation results of the quality assessment of sets of patterns and ceramic moulds carried out with using photogrammetry, thermovision and tomography hold a significant promise for the possible application of these methods in production of critical parts of aircraft engines.
3. The main expectation in relation to photogrammetric methods is the possibility of the scanned object reproduction in a form of a three-dimensional image, at maintaining the accuracy of the order of hundredth part of millimeter. Photogrammetry, apart from the thickness identification of the mould walls, allows for controlling the set of patterns by the superposition of the image obtained in the scanning process on the standard model.
4. An accurate correlation between the thermovision image and the mould state, especially its inner defects in a form of porosity, discontinuity, diversification of individual ceramic coatings thickness, etc. allow measurements with the application of computer tomography, which enables creation of fault standard catalogue of moulds and corresponding thermograms.
5. A successive stage of investigations will constitute the production of blades of nickel super alloys. After pouring moulds with liquid metal, crystallisation, mould breaking and cutting casting set, the identification number will be assigned to each individual blade. During a multistage quality control, by marking - on specially prepared sheets - the place and kind of fault, the so-called fault maps will be prepared. Such activity will be aimed at correlating casting faults (with taking into account the kind and place of their occurrence), revealed during the accurate acceptance inspection, with deviations of the set of patterns in relation to the *.CAD model, distribution of the mould walls thickness, mould structure at the cross-section and the quality of the inner mould surface.

REFERENCES

[1] ASM Metals Handbook: Casting, ASM International, Handbook Committee **15**, (2002).
[2] Information materials of GOM mbH.
[3] Information materials of Steinbichler Optotechnik GmbH.
[4] Al.-Hanbali and others, Assessement of laser scaning system for deformation measurements, IAPRS **33**, part B5/2, Amsterdam (2000).
[5] C.S. Fraser, Stiliker, Deformation monitoring of a landslide area by high-precision photogrammetry, FIG XVII International Congress, Sofia (1989).
[6] G.W. Johnson, Practical Integration of Vision Metrology and CAD in Shipbuilding, International Archives of Photogrammetry and Remote Sensing, Vienna (1996).
[7] W. Lorensen, H. Cline, Marching Cube, A High Resolution 3D Surface Construction Algorithm, Computer – Graphics **21**(1), 4, 163-170 (1987).
[8] Postrzeganie barw – podstawy [access 29.03.2013 r.] available in Internet: http://www.atm.edu.pl/ 28638.xml/.
[9] J.C. Murphy, G.C. Watsel, Photothermal Methods of Optical Characterization of Materials, Mater. Eval. **44**, 1224-1230 (1986).
[10] B.I. Sandor, D.T. Lohr, K.C. Schmid, Nondestructive Testing Using Differential Infrared Thermography, Mater. Eval. **45**, 72-395 (1987).
[11] D.R. Green, J.A. Hassberger, Infrared Electro-Thermal Examination of Stainless Steel, Mater. Eval. **35**, 39-43 (1977).
[12] P. Cielo, Thermographic Nondestructive Evaluation of Industrial Materials and Structures, Mater. Eval. **45**, 452-460 (1987).

[13] W. Minkina, Pomiary termowizyjne: przyrządy i metody, Częstochowa (2004).

[14] Information materials of FLIR Systems, Inc.

[15] Information materials of ITA spółka z ograniczoną odpowiedzialnością S.K.A.

[16] A.R. Lowrey, K.D. Friddell, D.W. Cruikshank, Nondestructive Evaluation of Aerospace Composites Using Medical Computed Tomography (CT) Scanners, Paper presented at the ASNT Spring Conference, Washington, D.C., American Society for Nondestructive Testing (1985).

[17] T.J. Vogl, W. Clauss, G.Z. Li, K.M. Yeon, Computed Tomography: State of the Art and Future Applications, Springer-Verlag Telos (1996).

[18] J. Banhart, Advanced Tomographic Methods in Materials Research and Engineering, Oxford University Press, (2008).

[19] G.T. Herman, Fundamentals of Computerized Tomography: Image Reconstruction from Projections, Springer (2009).

[20] A. Kadauw, J. Bast, D. Fiedler, I. Betchvaia, H.C. Saewert, Computer simulation of squeeze moulding and validation of results using industrial computer Tomography (ICT), Archive of Metallurgy and Materials **52**, 3 (2007).

[21] GE Measurement & Control Solutions.

[22] A. Kadauw, Characterization of the parameters of sand moulds in compaction process by use of the industrial computer tomography (ICT), Archives of Metallurgy and Materials **59**, 3 (2014).

[23] S. Kluska-Nawarecka, D. Wilk-Kołodziejczyk, J. Dajda, M. Macura, K. Regulski, Computer-assisted integration of knowledge in the context of identification of the causes of defects in castings, Archives of Metallurgy and Materials **59**, 2 (2014).

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