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Consumable additive FDM models in the production of aluminum alloy castings

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Abstract: This article describes the results of a study aimed at improving production technology of experimental castings from aluminum alloys by investment casting using models produced by 3D printing. The consumable models were produced using fused deposition modeling (FDM). Biodegradable polylactide (PLA) was used as a material for the models. In order to decrease the surface roughness of consumable PLA model. chemical post-treatment by dichloromethane needs to be performed. After immersion of the model into the solvent for 10s, its surface becomes smooth and glossy. Three-point static bending tests of PLA plates demonstrated a mechanical strength of average ~45.1 MPa. A thermomechanical analysis of polylactide demonstrated that in the course of heating of ceramic shell in excess of 150 °C, the polylactide model begins to expand intensively by exerting significant pressure on the ceramic shell. In order to decrease stress during the removal of polylactide model from ceramic mold, the heating time in the range of 150–300 °C needs to be heated to a maximum. The use of hollow consumable casting models with a cellular structure not higher than 30 % is also sensible. The stresses on the shell will not exceed its strength. Characteristic temperature properties of PLA plastic thermal destruction were detected using thermogravimetric analysis. Polylactide was established to completely burn out upon heating to 500 °C leaving no ash residue. Analysis of the results identified the burning modes of polylactide models from ceramic molds. Using a Picaso 3D Designer printer (Russia), the PLA models were printed used for production of experimental castings from aluminum alloys. It was revealed that the surface roughness (R_a) of a casting produced using a consumable model treated by dichloromethane decreases by 81.75 %: from 13.7 to 2.5 μm.

Keywords: investment casting, polylactide, 3D printing, fused deposition modeling (FDM), aluminum alloys, surface roughness.

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Особенности изготовления отливок из алюминиевых сплавов по выжигаемым аддитивным FDM-моделям

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Аннотация: Приведены результаты исследований, направленные на совершенствование литейной технологии получения опытно-экспериментальных отливок из алюминиевых сплавов методом литья по выжигаемым моделям, изготовленным с применением 3D-печати. Для создания выжигаемых моделей использовали метод осаждения расплавленной нити (FDM – fused deposition modeling), а в качестве материала моделей был выбран биоразлагаемый материал – полилактид (PLA – polylactide). Установлено, что для уменьшения шероховатости выжигаемой PLA-модели необходимо проводить химическую постобработку ее поверхности дихлорметаном. В результате окунания модели в растворитель на 10 с она приобретает гладкую и глянцевую поверхность. Испытания механической прочности PLA-пластин на трехточечный статический изгиб показали, что данный показатель составляет в среднем ~ 45,1 МПа. Термомеханический анализ полилактида выявил, что в процессе нагрева керамической оболочки выше 150 °С полилактидная модель начинает интенсивно расширяться, оказывая существенное давление на керамическую оболочку. Для уменьшения напряжений в процессе удаления полилактидной модели из керамической формы необходимо максимально увеличить время нагрева в интервале температур 150–300 °С, а также целесообразно использовать пустотелые выжигаемые модели отливки со степенью заполнения ячеистой структуры не более 30 %. При этом напряжения в оболочке не будут превышать ее прочность. С помощью термогравиметрического анализа выявлены характерные температурные характеристики термодеструкции PLA-пластика. Установлено, что материал из полилактида полностью выгорает при нагреве до температуры 500 °С, не оставляя после себя остатков золы. Анализ результатов позволил определить технологические режимы выжигания полилактидных моделей из керамических форм. На принтере Picaso 3D Designer (Россия) были напечатаны PLA-модели, которые использовали для получения опытно-экспериментальных отливок из алюминиевых сплавов. Выявлено, что шероховатость поверхности (R_a) отливки, полученной по выжигаемой модели, обработанной дихлорметаном, уменьшается на 81,75 % – с 13,7 до 2,5 мкм.

Ключевые слова: литье по выжигаемым моделям, полилактид, 3D-печать, метод осаждения расплавленной нити, алюминиевые сплавы, шероховатость поверхности.

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Introduction

Investment/lost-wax casting is a traditional technology for the production of high-precision products. This casting method enables the production of parts of the most complex shapes with thin walls and a high surface finish. The quality of investment/lost-wax castings is markedly superior to other casting methods, therefore this method is used in various fields.

The main problem in single and small batch production of products is the high cost of tooling. Traditional ceramic mold making requires the use of a melted/fired model produced in molds. This production process of making a mold is very complicated, and the cost of making such tooling is extremely high. This problem is resolved by integrating modern additive 3D printing methods into foundries [1; 2]. It is a relatively new production technology intensively developed and applied in various fields, including foundries [3—5]. The direct development of lost-wax models is not only cost-effective for small-scale and pilot production, but is also capable of creating very complex geometries that would be extremely difficult or too expensive to produce in the traditional way [6].

The process of making a lost-wax model using 3D printing allows the cost and time of casting production to be reduced. It also enabled the production of products of complex geometry in comparison to the conventional investment/lost-wax casting process [7—9]. These advantages are offset by the stepped surface of the model associated with the feature of 3D printing which can negatively affect the surface roughness and dimensional tolerances of castings.

Today, the most affordable and widespread 3D printing method is the technology of Fused Deposition Manufacturing (FDM) [10]. This method is comprised of layer-by-layer application of the molten polymer using an extruder. When compared to other additive manufacturing processes for lost-wax models, such as stereolithography (SLA), direct light processing (DLP), FDM 3D printing is one of the cheapest due to the low price of equipment and consumables, which makes it more widely available [11].

The main materials used in FDM 3D printing are thermoplastics: acrylonitrile butadiene styrene (ABS) [12; 13]; polylactide (PLA) [13,14]; polyamide (PA) [15]; polyethylene terephthalate-glycol (PETG) [16]; polyether ether ketone (PEEK) [17]; polycarbonate (PC) [18] and others.

As an alternative to petroleum-based polymers (ABS, PA, PETG, PEEK, PC), polylactide, a biodegradable biopolymer, is widely applied in numerous industries. PLA is based on starch and polylactic acid, made from completely renewable natural materials.

Polylactide is a fully biodegradable thermoplastic polyester. It is a polymer of lactic acid derived from the processing of corn, starch, cellulose, and sugarcane. The non-toxicity of the material allows the printing process to be carried out even in poorly ventilated areas. The products of thermal degradation of polylactide are considered harmless, and it burns quite slowly. Due to its environmental friendliness, biocompatibility, biodegradability, renewability, high stiffness and tensile strength, and ease of processing, the use of PLA in the world is growing. In this regard, a number of authors are considering the possibility of using it for the manufacture of burnt models [19—22].

The main goal of the work was to study the technological possibilities of 3D printing for the rapid production of lost-wax models from polylactide with the subsequent production of experimental cast products from aluminum alloys.

Experimental

The lost-wax models were fabricated by the FDM method using polylactide (PLA) as the material of the models. A spool of PLA filament with a diameter of 1.75 mm was supplied by Bestfilament (Russia), a commercial manufacturer of filaments for 3D printing. Pilot lost-wax models of castings and models for mechanical testing were fabricated using a Picaso 3D Designer X printer (Russia) at a cellular structure filling rate of 30 %. A printer nozzle with a diameter of 0.5 mm was used. The thickness of the applied layer was 0.2 mm. The print and platform temperatures during the process were maintained at 200 °C and 75 °C, respectively. Print speed was 20 mm/s. Dichloromethane was used to polish the surface of the PLA models. The casting models were dipped for 5, 10, and 15 s directly into the solvent.

Three-point bending tests of PLA samples with sizes of 40×20×5 mm were performed using an Instron 5982 machine (USA). The traverse speed was 1 mm/min. The distance between supports was 30 mm, and the number of tested samples: 10 pieces.

Ceramic molds were made according to the traditional lost-wax casting technology using layer-by-layer application of a ceramic suspension consisting of an ETS-40 ethyl silicate binder and a filler (pulverized quartz) onto a model block. This was followed by sprinkling each layer with granular quartz with a particle size of 0.2 mm. A total of 5 layers were applied.

The calcination of ceramic experimental molds was carried out in a support filler in an electric resistance furnace at t = 900°C, in an air atmosphere (heating duration 5 h) and exposure for 2 h. The ceramic molds were filled with aluminum alloy AK7ch with the following chemical composition: wt.%: Al — the base; Si — 7.21; Mg — 0.36; Fe — 0.147; Cu — 0.011; Mn — 0.0026. This corresponds to State standard GOST 1583-93.

800 g of the AK7ch alloy was melted in a SNOL-1,6.2,5.1/11-I3 muffle electric furnace. Preliminary degassing of the melt was carried out by purging it with an inert gas (argon).

The melt was modified with a standard 25%NaF + + 62.5%NaCl + 12.5%KCl flux at 740—750 °C. On the surface of the melt, it was applied as an even layer in the amount of 1.5 wt % of the melt. After holding at this temperature for 10 min, the flux was thoroughly kneaded deep into the melt. After 15 min after the melt holding, it was poured at t = 710÷720 °C into calcined ceramic molds heated to 350 °C.

Experimental castings from AK7h alloy were subjected to thermal processing according to State standard GOST 1583-93 under T5 regime (quenching in water at 535±5 °C for 4 h, then aging for 3 h at 415±5 °C).

Thermogravimetric (TGA) and differential thermal (SDTA) analyses were performed using a TGA/SDTA 851 instrument (Mettler Toledo, Switzerland), at a heating rate of 10 °C/min to 1100 °C in an air atmosphere.

Thermomechanical analysis (TMA) of plastic was performed using TMA/SDTA 840 analyzer (Mettler Toledo) in the range t = 20÷350 °C.

The surface roughness (R_a) of the castings in the area of 50×50 μm was analyzed using a MicroXAM-100 optical profilometer (KLA-Tencor Corp., USA). In order to evaluate the surface roughness of the products, 2 castings were selected (with and without dichloromethane treatment), and 3 areas were examined on each sample: each with 4 measurements. Statistical analysis of the obtained results was performed using Statistica 10 software.

Results and discussion

The main areas of work were to study of the possibility of using PLA plastic as a material for the manufacture of experimental models in investment casting, as well as establishing the temperature characteristics of the model material.

Thermochemical transformations of polylactide up to 1100 °C were studied using TGA and SDTA methods. The results are presented in Fig. 1. The TGA curve at t = 30÷300 °C shows no recorded changes and the weight of the sample practically did not change (the loss was only 1.09 %).

Thermogravimetric studies demonstrated that the main weight loss of the substance occurs when the temperature rises to 390 °C and amounts to 96.98 %. An exothermic effect is observed on the SDTA curve. At t = 300÷390 °C, active thermal degradation of the polymer occurs (sample weight drops from 98.91 to 3.02 %). Complete burn-out of polylactide occurs at *t* ~ 500 °C, until it burns out completely, leaving no ash residue. Its further heating to 1100 °C practically does not cause any changes. The weight of the sample goes into minus. This is primarily due to the removal of residual moisture from the porous ceramic crucible as a result of heating to 1100 °C.

Based on the results of the thermogravimetric study, it can be concluded that when heated above 500 °C, PLA plastic samples have zero ash content. It should be noted that the ash content (solid residue) of the lost-wax model during the calcination of ceramic molds is a very important parameter which should be minimal or completely absent. Increased ash content leads to the formation of ash residues after calcination in the body of the shell, reducing the quality of the cast products obtained in them.

The study of the thermal destruction of the model material enabled the temperature and time parameters of the process of removing (burning out) polylactide from the ceramic mold to be defined. Burning temperature is more than 500 °C, the duration is at least 1 hour.

The main reason for the destruction of the ceramic mold during the burning of the polymer model is the difference in the expansion coefficients of ceramics and polylactide. The thermomechanical properties of the plastic were determined by TMA of polylactide in the temperature range of 20—350 °C (Fig. 2). As demonstrated by the data, in the range *t* = 20÷150 °C no significant changes were detected. Active expansion of polylactide begins at temperatures above 150 °C, indicating the beginning of the melting of the PLA plastic.

In the course of heating the ceramic shell above 150 °C, the polylactide model begins to expand rapidly, exerting significant pressure on the ceramic shell. Therefore, in order to reduce stresses in the process of removing the polylactide model from the ceramic mold, the heating time interval in the range *t* = = 150÷300 °C needs to be maximized. It is also advisable to use hollow lost-wax casting models with a cellular structure filling degree not more than 30 %. In this case, the stresses in the shell will not exceed its strength.

The use of polymer filament layer-by-layer deposition for the manufacture of accurate lost-wax models is limited due to the high surface roughness and inaccurate dimensions. This is due to the characteristics of their manufacturing technology. When 3D printing a product vertically, a corrugated structure is formed on its surface (the so-called staircase effect) [23; 24].

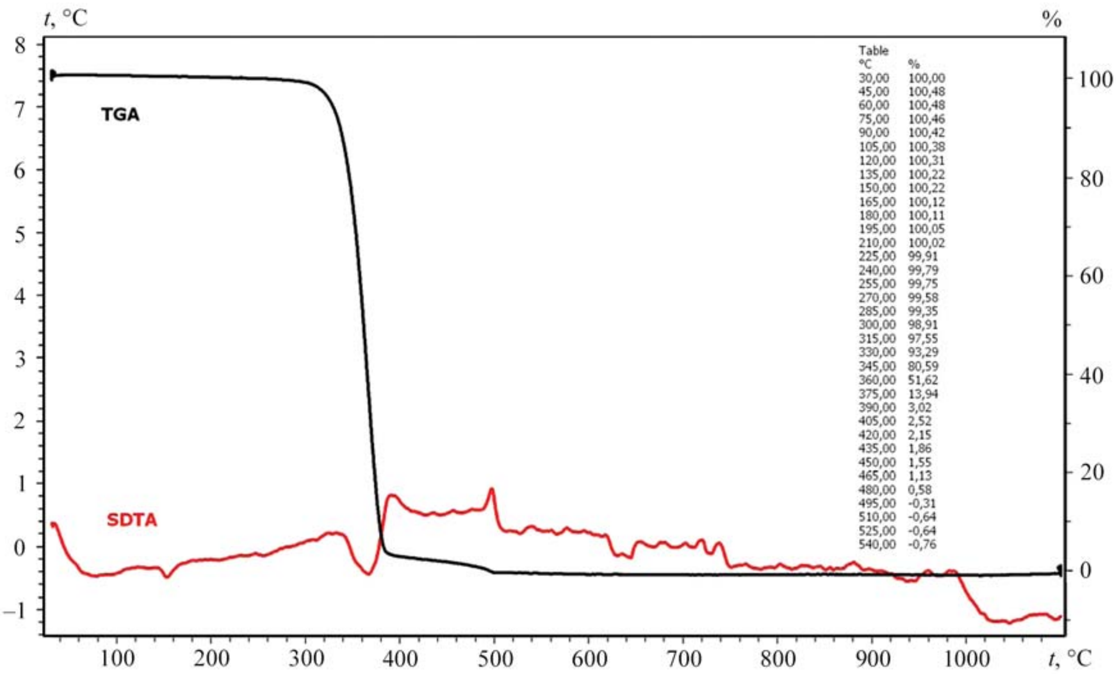

Fig. 1. TGA (black) and SDTA (red) curves of polylactide

Рис. 1. Кривые TGA (черная) и SDTA (красная) полилактида

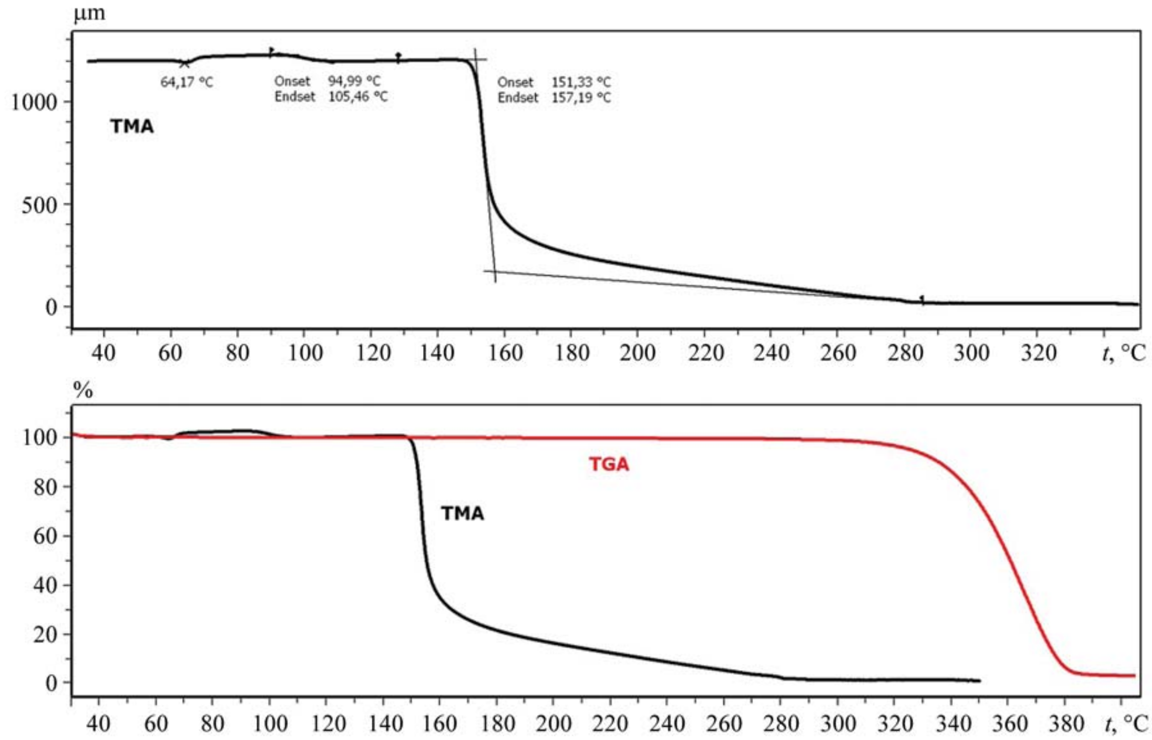

Fig. 2. TMA and TGA curves of polylactide

Рис. 2. Кривые TMA и TGA полилактида

Thus, certain subsequent post-processing procedures are required to improve surface quality [25—27]. At present, two main approaches are used to achieve a smooth surface of products: chemical or mechanical smoothing [28—30]. The latter method is inefficient in obtaining models with a complex geometric surface and a developed structure. The chemical method of smoothing the surface with volatile solvents is more effective.

In this work, dichloromethane (CH_2Cl_2) was used to reduce the surface roughness of the PLA lost-wax models (Fig. 3, *a*) [31]. According to the studies, holding the model in dichloromethane for 10s results in its surface being smoothed (Fig. 3, *c*). With a shorter exposure time in the solvent, the staircase effect is partially preserved (Fig. 3, *b*), and with a longer duration, the model surface swells (Fig. 3, *d*).

This simple, fast and cost-efficient chemical treatment gives the model a smooth and glossy finish, reducing labor and cutting tool costs.

Three-point static bending tests of PLA plates demonstrated a mechanical strength of an average ~45.1 MPa. This result is quite high for casting lost-wax models. Accordingly, during operation (for example, at the site of application of the suspension or during the transportation of model blocks), there is a low probability of their accidental breakage or the formation of dents.

Based on the results of the studies carried out on the Picaso 3D Designer X printer (Picaso 3D, Russia), experimental models were made from PLA polymer (Fig. 4, *a*). Quartz ceramics on a hydrolyzed ethyl silicate binder were used to form a ceramic shell (Fig. 4, *b*). A casting of the “bracket” type manufactured from AK7ch alloy demonstrates the possibility of obtaining suitable aluminum cast products (Fig. 4, *c*).

A comparative analysis of the surface of the experimental castings shows that the cast product acquires a smooth surface (Fig. 5) due to the chemical treatment of the lost-wax model with dichloromethane.

In order to assess the surface quality of castings, their roughness was measured using a laser optical profilometer and they were compared with each other. Figure 6 shows micrographs, as well as 2D and 3D relief of the surface of the castings. Images of castings are made in the same scale. The roughness (R_a) of the castings was measured in several places indicated in Fig. 5.

As illustrated in Fig. 6, the roughness of the samples was significantly reduced by the use of chemical post-processing of the lost-wax models with dichloromethane vapor. There are no surface lines between ad-

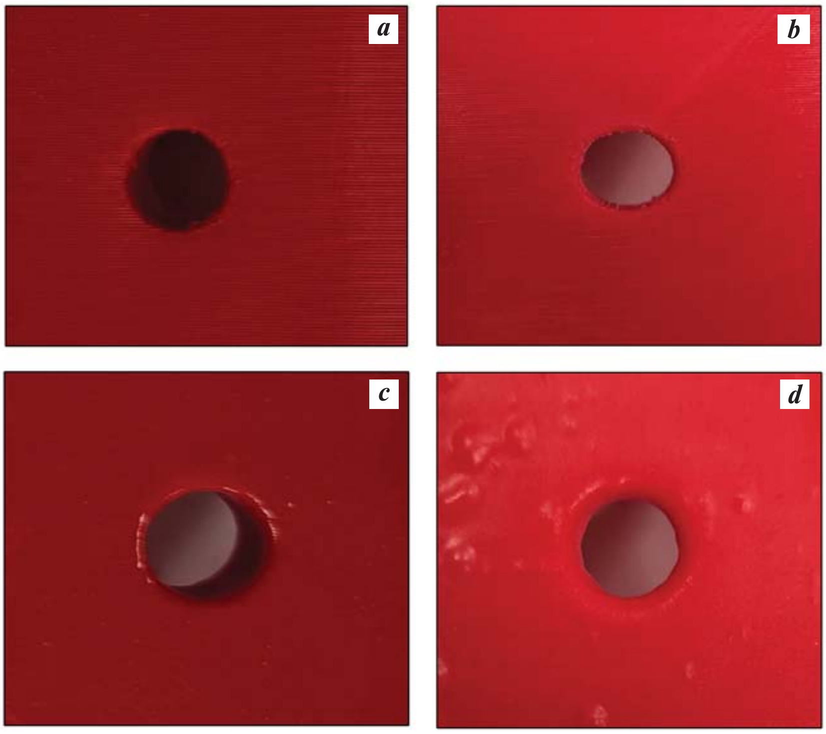

Fig. 3. External view of surface of consumable PLA model
a – after 3D printing; ***b***–***d*** – after processing by dichloromethane for 5 s (***b***), 10 s (***c***) and 15 s (***d***)

Рис. 3. Внешний вид поверхности выжигаемой PLA-модели
a – после 3D-печати; ***b***–***d*** – после обработки дихлорметаном в течение 5 с (***b***), 10 с (***c***) и 15 с (***d***)

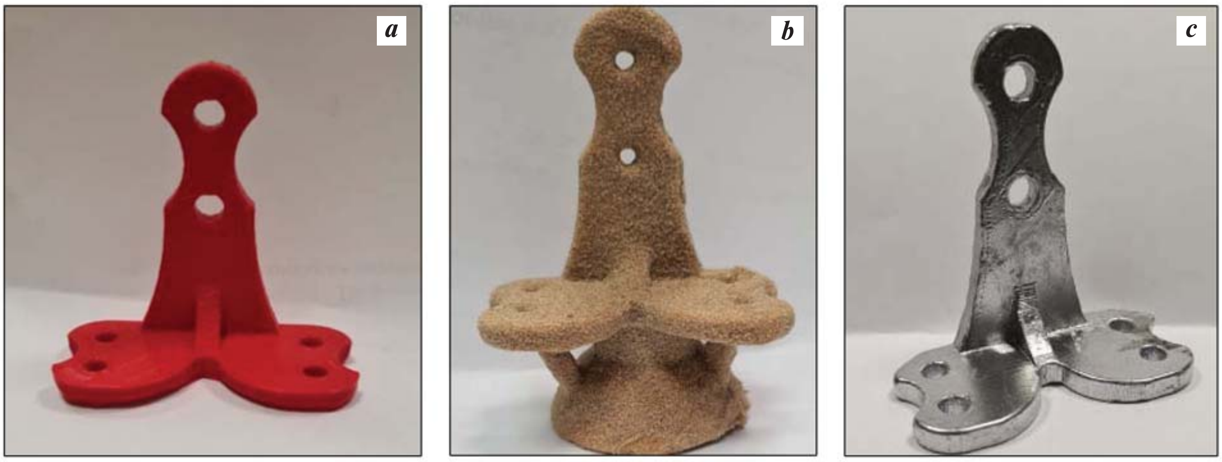

Fig. 4. Experimental PLA model (***a***), applied ceramic layer (***b***), and final aluminum casting (***c***)

Рис. 4. Опытная PLA-модель (***a***), она же с нанесенным слоем керамики (***b***) и готовая алюминиевая отливка (***c***)

jacent layers on the images of the surface of the castings, obtained by PLA lost-wax models and processed with dichloromethane (see Fig. 6, *b*). A noticeable reduction in roughness is observed and the effect of stairs is eliminated.

The surface roughness of castings produced using models before and after chemical processing is illustrated in Fig. 7. The distribution of Kolmogorov—Smirnov and Shapiro—Wilk quantitative indicators showed adequate results. Average values of R_a

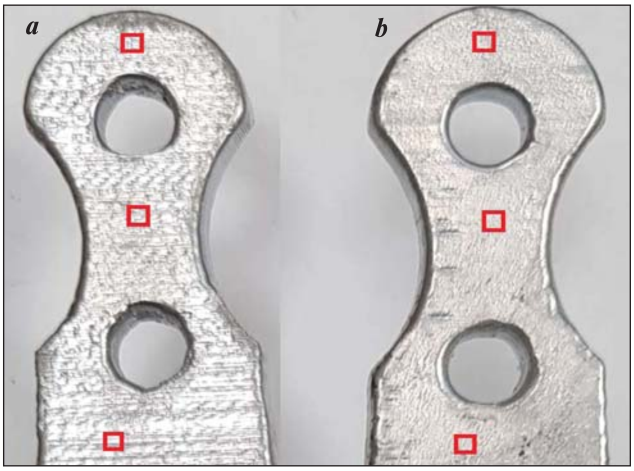

Fig. 5. External view of casting produced using non-processed model (***a***) and after its holding in dichloromethane (***b***)

Рис. 5. Внешний вид отливки, полученной по выжигаемой необработанной модели (***a***) и после ее выдержки в дихлорметане (***b***)

decrease from 13.7 to 2.5 µm. The roughness R_a of a casting produced using a consumable model processed by dichloromethane varies from 1.8 to 3.5 µm. Thus, the surface quality was improved significantly and the roughness decreased by 81.75 %.

Conclusions

This work focused on studying process variables of 3D printing for the rapid production of consumable models from PLA plastic, and subsequent fabrication of experimental cast items from aluminum alloys. The mechanical properties and ash content of burnt samples from polylactide were studied. Thermomechanical and thermogravimetric analyses of the polymer were conducted, resulting in the following main conclusions:

1. The static bending strength of 3D printed consumable PLA models was ~45.1 MPa.

2. The characteristic temperature properties of PLA plastic thermal destruction were detected using thermo-

a
b

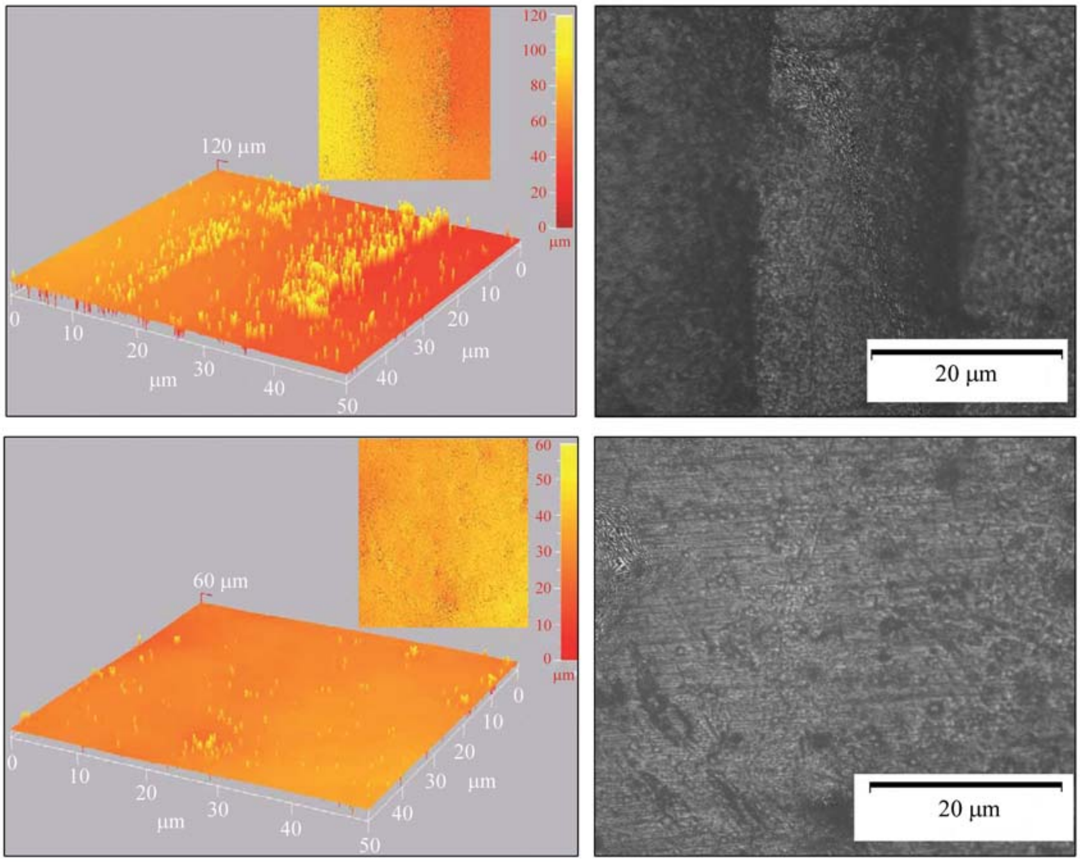

Fig. 6. Micro images 2D (on the right) and 3D (on the left), of surface of castings produced using consumable PLA models, without processing (***a***) and after holding in dichloromethane (***b***)

Рис. 6. Микрофотографии 2D- (справа) и 3D-изображения (слева) поверхности отливок, полученных по выжигаемым PLA-моделям, без обработки (***a***) и после выдержки в дихлорметане (***b***)

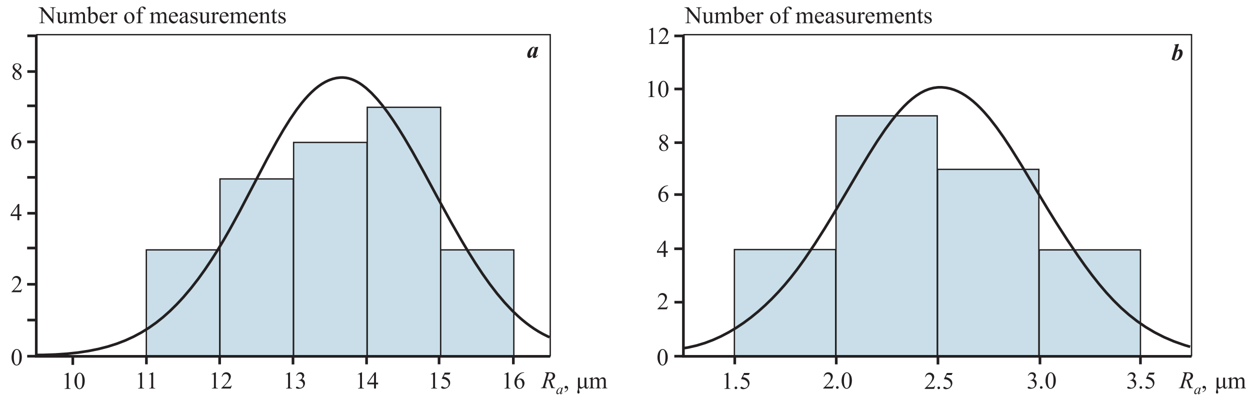

Fig. 7. Distribution histograms of surface roughness (R_a) of casting produced using non-processed model (***a***) and after its processing by dichloromethane (***b***)

Рис. 7. Гистограммы распределения значений шероховатости (R_a) поверхности отливки, полученной по необработанной модели (***a***) и после ее обработки дихлорметаном (***b***)

gravimetric analysis. It was established that polylactide completely burns out upon heating to 500 °C leaving no ash residue.

3. In the course of heating of ceramic shell in excess of 150 °C, the polylactide model begins to expand intensively. In order to decrease stresses during the removal of polylactide model from ceramic mold, the heating time must be increased to the range of 150—300 °C. In addition, the use of hollow consumable casting models with the filling extent of cellular structure not higher than 30 % would be sensible. The stress on the shell will not exceed its strength.

4. In order to decrease the surface roughness of consumable PLA model, chemical post-treatment by dichloromethane must be performed. The best solvent for smoothing model surface layers is dichloromethane. After immersion of the model into the solvent for 10 s, its surface becomes smooth and glossy.

5. The experimental results of the process variables were used. They were then verified under laboratory conditions allowing a good experimental casting of bracket type from aluminum alloys to be obtained. Castings produced on the basis of consumable models processed by dichloromethane show a decrease in the roughness R_a from 13.7 to 2.5 μm. Thus, the ladder effect is eliminated.

References

1. Rosochowski A., Matuszak A. Rapid tooling: The state of the art. *Journal of Materials Processing Technology.* 2000;106(1-3):191—198. https://doi.org/10.1016/S0924-0136(00)00613-0
2. Harun W. S. W., Safian S., Idris M. H. Evaluation of ABS patterns produced from FDM for investment casting process. *WIT Transactions on Engineering Sciences.* 2009;64(3):319—328. https://doi.org/10.2495/MC090301
3. Bassoli E., Gatto A., Iuliano L., Violante M. 3D Printing technique applied to rapid casting. *Rapid Prototyping Journal.* 2007;13(3):148—155. https://doi.org/10.1108/13552540710750898
4. Choe C.M., Yang W.C., Kim U.H., Ri B.G., Om M.S. Manufacture of centrifugal compressor impeller using FDM and investment casting. *The International Journal of Advanced Manufacturing Technology.* 2022;118:173—181. https://doi.org/10.1007/s00170-021-07894-7
5. Gao M., Li L., Wang Q., Ma Z., Li X., Liu Z. Integration of additive manufacturing in casting: Advances, challenges, and prospects. *International Journal of Precision Engineering and Manufacturing-Green Technology.* 2022;9:305—322. https://doi.org/10.1007/s40684-021-00323-w
6. Kumar P., Ahuja I.P.S., Singh R. Application of fusion deposition modelling for rapid investment casting. A review. *International Journal of Materials Engineering Innovation.* 2012;3(3—4):204—227. https://doi.org/10.1504/IJMATEI.2012.049254
7. Kumar P., Singh R., Ahuja I.P.S. Investigations for mechanical properties of hybrid investment casting: A case study. *Materials Science Forum.* 2015;808:89—95. https://doi.org/10.4028/www.scientific.net/MSF.808.89
8. Kumar P, Singh R, Ahuja I.P.S. A framework for developing a hybrid investment casting process. *Asian Review of Mechanical Engineering.* 2013;2(2):49—55. https://doi.org/10.51983/arme-2013.2.2.2346

9. Badanova N., Perveen A., Talamona D. Concise review on pattern making process in rapid investment casting: Technology, materials & numerical modelling aspect. *Advances in Materials and Processing Technologies*. 2022;8:966—978. https://doi.org/ 10.1080/2374068X.2021.1959113
10. Vyavahare S., Teraiya S., Panghal D., Kumar S. Fused deposition modelling: a review. *Rapid Prototyping Journal*. 2020; 26(1):176—201. https://doi.org/10.1108/RPJ-04-2019-0106
11. Bakar N.S.A., Alkahari M.R., Boejang H. Analysis on fused deposition modelling performance. *Journal of Zhejiang University: Science A*. 2010;11(12):972—977. https://doi.org/10.1631/jzus.A1001365
12. Raney K., Lani E., Kalla D.K. Experimental characterization of the tensile strength of ABS parts manufactured by fused deposition modeling process. *Materials Today: Proceedings*. 2017;4:7956—7961. https://doi.org/10.1016/j.matpr.2017.07.132
13. Milde J., Hrušecký R., Zaujec R., Morovic L., Görög A. Research of ABS and PLA materials in the process of fused deposition modeling method. In: *28th DAAAM International Symposium on Intelligent Manufacturing and Automation*. Vienna, Austria, 2017. Vol. 28. P. 812—820. https://doi.org/10.2507/28th.daaam.proceedings.114
14. Hanon M.M., Marczis R., Zsidai L. Influence of the 3D printing process settings on tensile strength of PLA and HT-PLA. *Periodica Polytechnica Mechanical Engineering*. 2020; 65(1): 38—46. https://doi.org/10.3311/PPme.13683
15. Knoop F., Schoeppner V. Mechanical and thermal properties of FDM parts manufactured with Polyamide 12. In: *26th Annual International Solid Freeform Fabrication Symposium*. University of Texas at Austin, 2015. P. 935—948.
16. Szykiedans K., Credo W., Osiński D. Selected mechanical properties of PETG 3-D prints. Procedia Engineering. 2017;177:455—461. https://doi.org/10.1016/j.proeng.2017.02.245
17. Xiaoyong S., Liangcheng C., Honglin M., Peng G., Zhanwei B., Cheng L. Experimental analysis of high temperature PEEK materials on 3D printing test. In: *9th International Conference on Measuring Technology and Mechatronics Automation (ICMTMA)* (14—15 Jan. 2017). Changsha, China, 2017. P. 13—16. https://doi.org/10.1109/ICMTMA.2017.0012
18. Domingo-Espin M., Puigoriol-Forcada J.M., Garcia-Granada A.A., Llumà J., Borros S., Reyes G. Mechanical property characterization and simulation of fused deposition modeling polycarbonate parts. *Materials & Design*. 2015;83:670—677. https://doi.org/10.1016/j.matdes.2015.06.074
19. Nguyen T.T., Tran V.T., Pham T.H.N., Nguyen V.-T., Thanh N.C., Thi H.M.N., Duy N.V.A., Thanh D.N., Nguyen V.T.T. Influences of material selection, infill ratio, and layer height in the 3D printing cavity process on the surface roughness of printed patterns and casted products in investment casting. *Micromachines*. 2023;14:395. https://doi.org/10.3390/mi14020395
20. Gallien F., Gass V., Mortensen A. Investment casting of periodic aluminum cellular structures using slurry-cast table salt moulds. *Materials & Design*. 2022;215:110488. https://doi.org/10.1016/j.matdes.2022.110488
21. Ukey K., Hiremath S., Majumder H. Investigation of investment casting pattern using fused deposition modeling. *Engineering Science & Technology*. 2021;2:201—207. https://doi.org/10.37256/est.222021904
22. Nikitin K.V., Tukabayov B.N., D'yachkov V.N., Nikitin V.I., Deev V.B., Barinov A.Y. Improving the casting process in ceramic forms using additive technologies in manufacturing model kits. *Russian Journal of Non-Ferrous Metals*. 2021;62(6):675—681. https://doi.org/10.3103/S106782122106016X
Никитин К.В., Тукабайов Б.Н., Дьячков В.Н., Никитин В.И., Деев В.Б., Баринов А.Ю. Совершенствование процесса литья в керамические формы за счет применения аддитивных технологий при изготовлении модельных комплектов. *Известия вузов. Цветная металлургия*. 2021;27(5):58—66. https://doi.org/10.17073/0021-3438-2021-5-58-66
23. Alsoufi M.S., Abdulrhman E.E. How surface roughness performance of printed parts manufactured by desktop FDM 3D printer with PLA+ Is influenced by measuring direction. *American Journal of Mechanical Engineering*. 2017;5(5):211—23. https://doi.org/10.12691/ajme-5-5-4
24. Caputo M., Rashwan O., Waryoba D., McDade K. Surface texture and thermo-mechanical properties of material extruded and ironed polylactic acid. *Additive Manufacturing*. 2022;59:103084. https://doi.org/10.1016/j.addma.2022.103084
25. Kumar P., Ahuja I.S., Singh, R. Effect of process parameters on surface roughness of hybrid investment casting. *Progress in Additive Manufacturing*. 2016;1:45—53. https://doi.org/10.1007/s40964-016-0004-9
26. Taşcıoğlu E., Kıtay Ö., Keskin A.Ö., Kaynak Y. Effect of printing parameters and post-process on surface roughness and dimensional deviation of PLA parts fabricated by extrusion-based 3D printing. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*. 2022;44(139). https://doi.org/10.1007/s40430-022-03429-7
27. Garg P.K., Singh R., Ahuja I., Multi-objective optimization of dimensional accuracy, surface roughness and hardness of hybrid investment cast components. *Rapid Prototyping Journal*. 2017;23(5):845—857. https://doi.org/10.1108/RPJ-10-2015-0149

28. Panda S.S., Chabra R., Kapil S., Patel V. Chemical vapour treatment for enhancing the surface finish of PLA object produced by fused deposition method using the Taguchi optimization method. *SN Applied Sciences*. 2020; 2(916):1—13. https://doi.org/10.1007/s42452-020-2740-1
29. Tiwary V.K., Arunkumar P., Deshpande A.S., Rangaswamy N. Surface enhancement of FDM patterns to be used in rapid investment casting for making medical implants. *Rapid Prototyping Journal*. 2019;25(5):904—914. https://doi.org/10.1108/RPJ-07-2018-0176
30. Hashmi A.W., Mali H.S., Meena A. A comprehensive review on surface quality improvement methods for additively manufactured parts. *Rapid Prototyping Journal*. 2022;29(3):504—557. https://doi.org/10.1108/RPJ-06-2021-0133
31. Jin Y., Wan Y., Liu Z. Surface polish of PLA parts in FDM using dichloromethane vapour. In: *The 3rd International Conference on Mechatronics and Mechanical Engineering (ICMME 2016)* (MATEC Web of Conferences). 2016. Vol. 95. P. 05001. https://doi.org/10.1051/matecconf/20179505001

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M.S. Varfolomeev – determined the research objectives, conducted experiments, wrote the manuscript.

I.A. Petrov – tested the samples for strength, measured the surface roughness, participated in the discussion of the results.

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