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Methodsof Improvement in the Productivity of the Technological Process of Printing the Sand-Polymer Casting Mouldswith the Help of theAdditive Devices

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Abstract:*The goal of the present articleis toanalyseproblemsof improvement in the productivityof the additivetechnologiesin the course of their introductioninto industrial practiceDue toimprovementof the technologicalprocesses,theadditivetechnologieshave come into common use as concerns their industrial application, includingproductionof casting moulds.However, low productivity of these technologies (as compared with the traditional technology) imposes restrictions on the possibility of application of the equipment for manufacturing the sand-polymer casting moulds with the help of the method of the layered synthesis in the mass production. In the present article,we present results of our investigations(on the basis of review of topical publications/articles) in respect of possiblemethodsof improvement in the productivityof the technological processof printingthe sand-polymercasting mouldswith the help of the additive devicesdue topossiblestructuralalterations,changes in the layout,andtechnological changes.We have performedmathematical simulationandcorrectedpossibleparameters for the most attractive variants.We have come to conclusionthat methodof optimisationof the controlling system is the prospective method of improvement in the productivity.*

Keywords:*3D-printer; additivetechnologies;technologicalprocess;sand-polymer moulds;castingmoulds;productivity, print heads.*

INTRODUCTION

Methods, which are basedonthe layeredproduction technologies, ensure widening of areas of their application: beginning fromcreationof the aestheticalmouldsandfully functional prototypesand up to productionof special toolsandmouldsfor prototypesorup to production of the machine-tool attachmentsfor thepre-production prototypes.

We believe thatapplicationof the additive technologieswill be introduced into the wide industrial practice primarilythroughmanufactureof casting moulds. Therefore, we willconcentrate our attention on the articles, which are connected with this subject-matter namely.Lately,printing of the sand-polymer casting moulds finds wide applicationin the sphere of rapid prototyping. Therefore, this technologyexerts gradual influenceupon thetraditionalcastingindustrydue to the followingadvantages of this technology:possibilityof the gravity die castingin the course of designing and manufacturing,as well ashigh rate of assembly. Many researchersstate thatadditivetechnologiesare efficient onesin the course of manufactureof the technologicalprototypecastingswithin a short timeandwith low costs, whiledimensional tolerancesof such castings are fully consistent withthemetal casting processes(Bassoli et al., 2007).However,the discussion is under wayconcerningadvantagesof solutionsin accordance with the additive technologiesforfoundry specialists.In addition,there exists the problem that is connected withproductionof the equipment, which will ensureboth highaccuracyandeconomic efficiency(Chhabra and Singh, 2011).Authors of the article (Dimitrov et al., 2007)state (at the same time) thatthe already existing additive technologiesmake it possible to achievethe better dimensionaltolerancesas compared with thetraditional casting technologies, however productivityof the processandtolerance for qualityof the receivable surface (undulation) have yet to be optimised.

Content of the binding substancein the sandis the key factorin the course of manufactureof the sand mouldandit exerts a strong influence uponthe strengthof the casting mould, because namely this factor determinessuchcharacteristicsof the sand mouldasstrength, gas release, porosity,andmobility(Yang and Liu, 2011). In spite of the fact thatincreasedcontentof the binding substanceensures thestrength,which is required formaintainingthe structural integrityof the casting mouldin the course of mechanical processinganddecreaseof erosionfrom thesmeltmetal, big quantityof the binding substancecan causeexcessivevolumesof gasin the castingandcan cause defectsof the casting/mould,as well asit can cause an unfavourableinfluence uponqualityof the detail(Snelling et al., 2014).In addition, there existinvestigationsin respect of the contentof the binding substancein the systemof materialsof the 3D-printingof casting moulds.Results of these investigations are as follows:in the case of the 3D-printing,acastingmouldcontains(on average) the essentiallyhighercontentof the binding substance (up to 8%)as compared with thetraditionalmould sandwithout baking/sintering, Authors of these investigationshave made the following conclusions:mouldswithout bakinghad theessentiallyhighertensile strengthas compared with the moulds,which were manufacturedwith the help of the multistageprocessof the 3D-printingon the conditionof the subsequentthermal treatment.Thus, they have becomemore suitablefor the mechanical processingandit was possible to manufacture castingswith the lesserporosityandlesserdistancebetweenthe dendritic levers(Snelling et al., 2013; Coniglio et al., 2018). Therefore, the lessercontentof the binding substancemeansthe lesserreleaseof gas. At the same time, other authors (Snelling et al., 2013; 2014) have made the following conclusion: the required high percentage of the binding substance in the course of the 3D-printing on the sand moulds (> 8% in the cast form and > 3% after "drying and solidification") generates much more volumes of gas in the course of casting as compared with the traditional moulding without baking (< 1.5% of the binding substance). This factcausesdifficultiesin the course of creationof the casting without any defects. In other words,there existsthe contradictionbetweenthe strengthof the casting mouldandthe casting quality. In order todecreasegas defectsin the casting, which was manufacturedfrom the 3D-printingmoulds, it is necessary to take effortsin respectof optimisationof the solidification duration,as well asof the temperatureof solidificationof the residualbinding substancebefore the casting processwith the help of variationsof the usedmaterials,as well aswith the help of the cycleof thermalsolidificationof the mould, which is intendedfor the 3D-printing (Wen et al., 2015; Kang and Ma, 2017).

In accordance with theresultsof the review of literary sources,it is possible to draw the conclusionthatthere still existessential possibilitiesfor improvementandinnovationsof the solutionsof the rapid prototyping. In spite of theinventionof varioussolutionsfor the rapid prototyping, it is necessaryto investigatemanyfactorsfor introductionof the discussed technologiesintotraditionalcastingpractice. Thesefactorsare as follows: materialsof the additive technologies;systemsof the 3D-printing;accuracyof reproductionandqualityof surface;flexibility of geometry;duration of assembly;mechanicalandthermalproperties;costandsubsequentprocessingof models, moulds,anddetails. Cost is the maindetermining factorin the course ofmakingsolutionconcerningapplicationof varioustechnologiesof the rapid prototyping/for the 3D-printingbecausesystemsandmaterialsof the additive technologiesare still very expensiveas compared withthe traditionaltoolsof casting. At present time,the 3D-printingin the course of manufactureof the machine-tool attachmentsis the economical technology in the situations wherethe component, whichis to be casted, isat the initial stagesof the designing cycleandwhere it is necessary to haveonlysmallquantities of such components. In addition, the 3D-printingis the economical technology in the situations where it is necessaryto manufacturegeometrycallydifficultcastingsandwhere it is necessary tomake manychangesin the design of the products. It is also possible to draw the conclusionthatmany researchersandmanufacturersall over the worldtake part in developmentof the potentiallynewsystemsandmaterialson the basis of utilisationof the 3D-printingin order tomanufacturethe sand-polymercasting moulds.Therefore,introductionof the additivedevicesboth in thesingle/small-batch production, andin themedium-batchproductionhas become moretopicalthan ever. Thus, the taskof improvement in the productivityof devices has occurred in order to ensure high rate of the products manufacture.

MaterialsandMethods

In the course of our analysisof the processof manufacturingthe sand-polymer casting mould, we will considertypicaldevice. The additivedevicesfor manufacturingthe sand-polymercasting mouldsare designed as themechatronic complex that consists of themechanical sections, whichare synergeticallycombinedwith each other, such as: linearmodulesof movement, whichare developedon the basis ofthe ball-and-screw pair (BSP) orof the toothed beltand which are set in motionby the tracking servo-motors; devicefor applicationof the powder material; movable work platform; printingpiezoelectric head; controlling systemon the basis ofthe industrial controlleralong with the relevant installed software application.Within the frameworkof our investigations,we have developed speciallaboratory stand,which performsall operationsof the 3D-printingof the casting mouldin accordance with the followingcharacteristics: quantityof the controlled axes: 4 pieces; quantityof the working heads: 4 pieces; duration of manufacturingof one layer: no more than 1 minute; positioning accuracyof the print head: no worse than±80 micrometers;

It is possibleto separatethree technologicaloperationsin accordance with the principle of the device operation (see Fig. 1), which are repeatedcyclicallyup to the completionof the entire manufacturing cycle:

1. Applicationof the sand layer;
2. Loweringof the platform;
3. Introducingof the solidifying component (of the binding substance)into the sand layer.

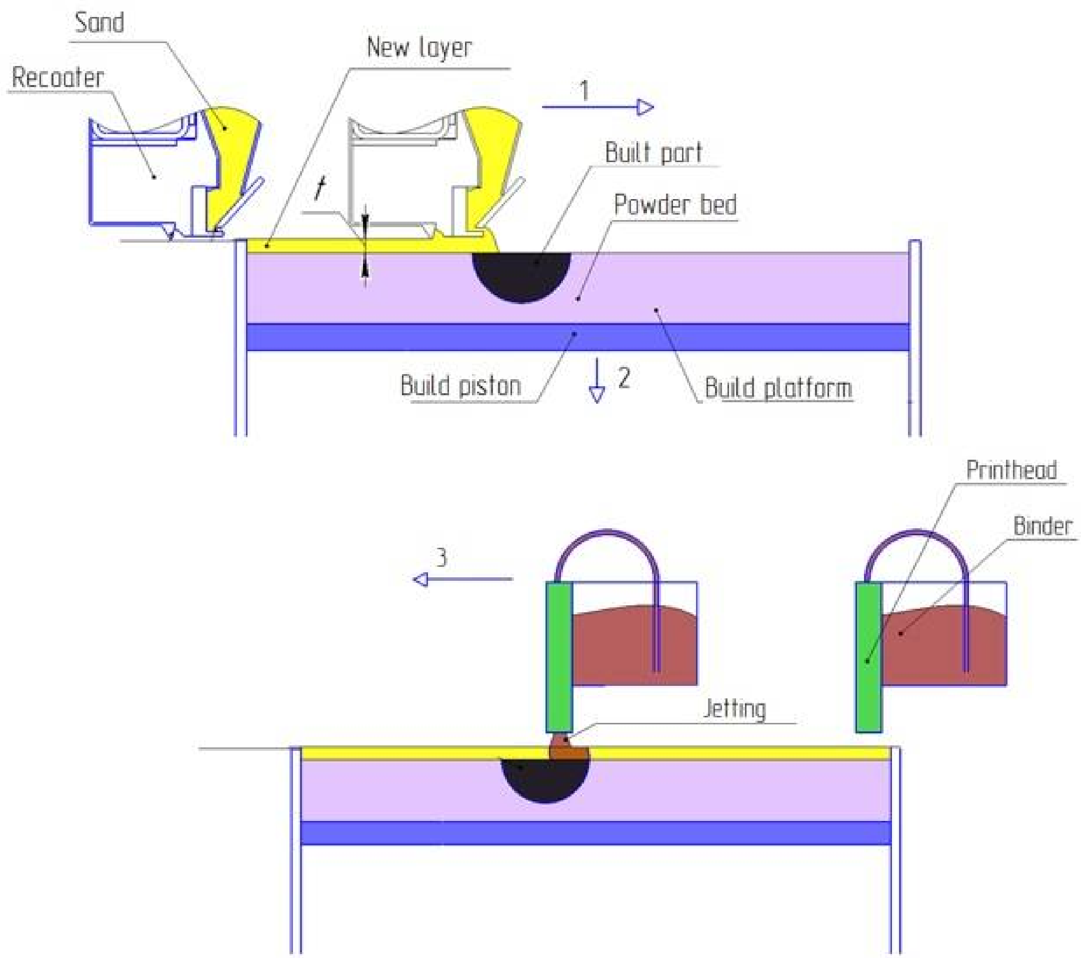

Fig 1: Algorithmof the device operation

Special devicefor applicationof the powdermaterial is used in order to ensure creation of the thin layer. There areseveralprincipallydifferentschemes of applicationof the powder material, however namelysuchmethod is considered as the most productive one.

Introducing of the binding substance is performed with the help of the print head.

It is possible to make conclusions in respect of productivity of the additive deviceon the basis ofthe period of time, which is required forcreationof the single layer. This period of time,in its turn,consists of the durationof applicationof the sand layer, as well asof the durationof introducing the binding substanceinto the sand layer. Loweringof the platformis initiatedin the beginningof movementof the device, which is intendedfor applicationof the powder material,andthis operation exerts no influenceuponthe totalperiod of time,which is required for creation of the single layer. Taking into account the above statements,it is possible to state thatin order to ensure improvement in the productivityof the entire additive device,it is necessaryto minimisethe period of time, which is required for creation of the single layer.

RESULTS AND DISCUSSION

This sectionis intended foranalysis ofall possiblecomponentsof the technological processof manufactureof the sand-polymermould.Later on,we will assessreservesof increaseof the rateof functioningof this technologyon the whole.

The mostobviousmethodof improvement in the productivityisaccelerationof movementsof allworkingcomponents. Thismethodhasa number of disadvantages;therefore,it cannot beused in practice. In order to increaserateof movementof the workingcomponents,it is necessaryto useotheractuators, which are more expensive. This factwill result inthe lossof potential consumers due to high competition in the market. In addition, maximumpermissiblespeedof movementof the device, which is intendedfor applicationof the powder material,is limitedby the specific featuresof the technologyfor manufacturingthe sand-polymercasting mouldswith the help of the layered synthesis method. If the predeterminedvaluesof the speed will be exceeded,then a negativeinfluenceof particlesof the layer, which is applied,upon the previous layerwill occur. This fact willworsensuchparameters,asaccuracyandstrengthof the relevant product.

Speedof movementof the print headis limitedby the technical possibilitiesof the working frequencyof the piezoelectric elements,which are usedas structural componentsof the print head. Therefore, in order toincreasespeedof movementof the print head,it is necessaryto useanothermodel, which is more expensive. This fact results in the increaseof the costof the entiredevice (this situation is similar to the situation with actuators).

It is proposedto analysethe followingmethodsof improvement in the productivityand these methods must be further investigated:

Constructive methods:

1. Amalgamation/combinationof the device for application of the powder materialandthe print head in the single mechanism;

2. Increaseof the working zone, which is coveredin the course of one working movement,due toincreaseof quantityof the print heads;

Technological methods:

3. Optimisationof trajectoryof movementof the print head;

4. Increaseof the working frequencyof the piezoelectric print head;

5. Changein dimensionsof the dropsof the binding substance,which is introducedby the print head;

Amalgamation/combination of the device for application of the powder material and the print head in the single mechanism

Combination of the device for application of the powder material and print heads is the first method of improvement in the productivity, which envisages structural changes of mechanisms of the additive device. A similarideawas proposedby other researchers(Symes et al., 2012).

Having analysedthe widelyusedvariantof the additive device structure, in accordance with whichboth workingcomponents (device for application of the powder materialandprint heads) are separated one from another, it is possible to understand thatperiod of timeof manufacturingof the single layerincludes durationof the working movement, as well asdurationof the idle movement, whichis requiredfor returnsof eachcomponentto thehome/initial position. In addition, there isthe delaybetween the moment of processingthe sensor signalon thesuccessful achievementof the home positionby oneoranothercomponentandthe moment of subsequentsendingthe signalon theactuationof the next component. In the case ofcombinationof these components,it is possibleto reducebothdurationof the idle movements, anddurationof the downtime, thusdecreasingthe totaldurationof manufacturingof the single layer (Fig.2).

In accordance with theexperimental data,which were obtainedat the laboratory stand, durationof variousoperationsis equal to (at the average):

- Working movementof the device for application of the powder material – 28%;
- Idlemovementof the device for application of the powder material – 8%;
- Working movementof the print headsin the course of introducingthe binding substance – 38%.
- Idlemovementof the print heads – 23%;
- Durationof the downtimein the course ofprocessingandsendingthe signal – 3%

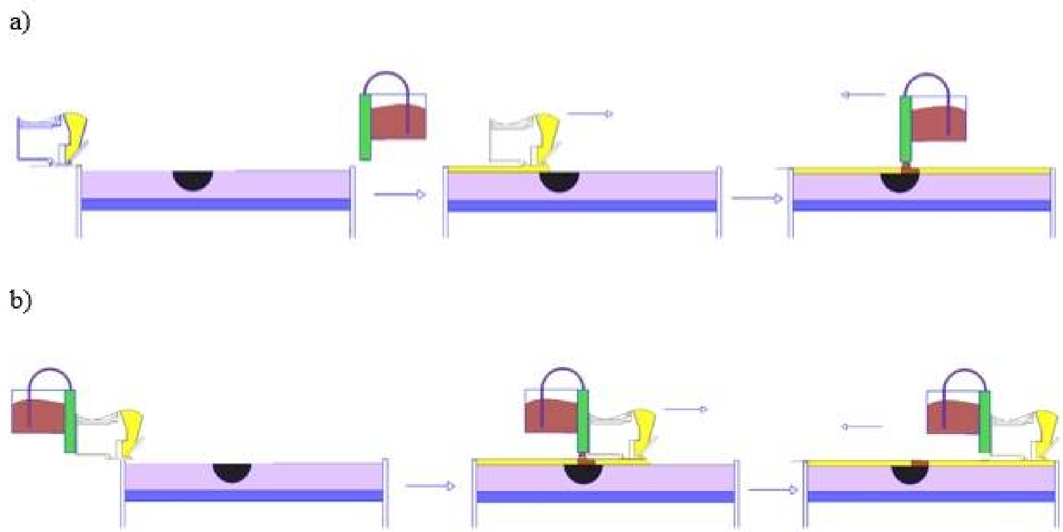

Fig2:a – separatedstructure of theentire device; b – combinationof the device for application of the sandandthe unitof print heads

In this case,it is possible to reducetotal quantityof operations, as well as to ensure coincidenceof the sand applicationandoperation of introducing the binding substance:

- Movement in the course of introducingthe binding substanceandthe sand application – 38%.
- Idlemovementof the unitof print heads – 25%;

Estimated differenceof the coincident variantis equal to 63% of the varianton the basis of separated structure.

It is interestingto ensurefurtheranalysis of this variant of improvement in the productivity,because ofotherstructuralmethodsof overlappingand coincidence of these components are possible, however it is necessaryto performinvestigationsanddetermine the conditionswhich will ensureincrease in the productivity.

It is possible, for example,that productivityin the great working zone will decreaseas compared withthe separated structure of the entire device. It is connected with the fact thatusually speedof movementof the print headis essentiallyhigher than the rateof movementof the device for application of the powder materialdue tothe lesser mass. Therefore, in the case ofbig dimensionsof the working zone,combinationof moduleswill decreasetotalproductivityof the device

Increase of the working zone, which is covered in the course of one working movement, due to increase in quantity of the print heads

The secondmethodofincrease in productivityis as follows:it is necessary to increasethe working zone, which is covered in the course of one working movement, due to increase in quantityof the print heads (Hansen et al., 2013). Decreaseof durationof manufacturingof the single layeris achieveddue todecrease in quantityof movementsof the print headsin order to ensure complete coverageof the working zone. Thisapproachmakes it possibleto increaseproductivityof the device in the shortest possible time;

however,it requiresto make changesofthe structureof the unitof print heads.In addition, it is necessary to ensureadditionalcash resources, because ofcostof the industrial print headsis high.

It is necessary to understand thatthismethodwill ensurean essential effectin the cases, whereadditionof 1 print heador 2print headswill letto reducequantityof movementsby1.5 – 2times.Such result is possiblein the case of smalloverall dimensionsof the working zone. It is possible that this methodwill be inexpedientfor the devices having great overall dimensions due toincreaseof the prime costof devices. In order to determineboundary conditionsof applicabilityof this method,it is necessaryto analysethe optimum ratiobetween quantityof headsanddimensionof the working zone.

Optimisationof trajectoryof movementof the print head

It is obvious that motion of the print headis connected with the mostunproductivespendingof timeof the technological process;therefore,optimisationof the movement geometryattracts attentionof many researchers (Wang et al., 2015; Gosselin et al., 2016).

If trajectoryof movementof the print headsis not optimized, then algorithmof movementof the additive deviceover the working zone is as follows(Fig.3).

The print headmovesfrom the home position to thestart point. As it can be seen from the Figure,the working zoneconsists of 4 sectors.Width of eachsectoris equal tothe width,which is coveredby the print head. In the case ofarrangementof detailsin allsectorsof printing,the headmovesfrom the start point over the trajectory,which is presentedin Figure 3(a). In this case,the print headperformsintroducing the binding substanceinto the sand layerin accordance with thepreviously programmedareas only.As concernsthe rest zones,the print head performsidlemovementover these zoneswith constant speed.In the case ofany otherarrangementof details,trajectoryof movementwill be changed (Fig.3b, 3c).

The most obvious operation with the purposeof improvement in the productivityisaccelerationof movementof the print headover the zones, where no printing is performed;therefore,durationof the idle movementwill be decreased. There are no limitationsin respect of thespeedof the idle movementfrom the partof frequencyof the print heads, because ofno printingis performed in this moment. In this case, we are only limitedby the technical possibilitiesof the servo-motor, which actuates movementof the print head(Fig. 4).

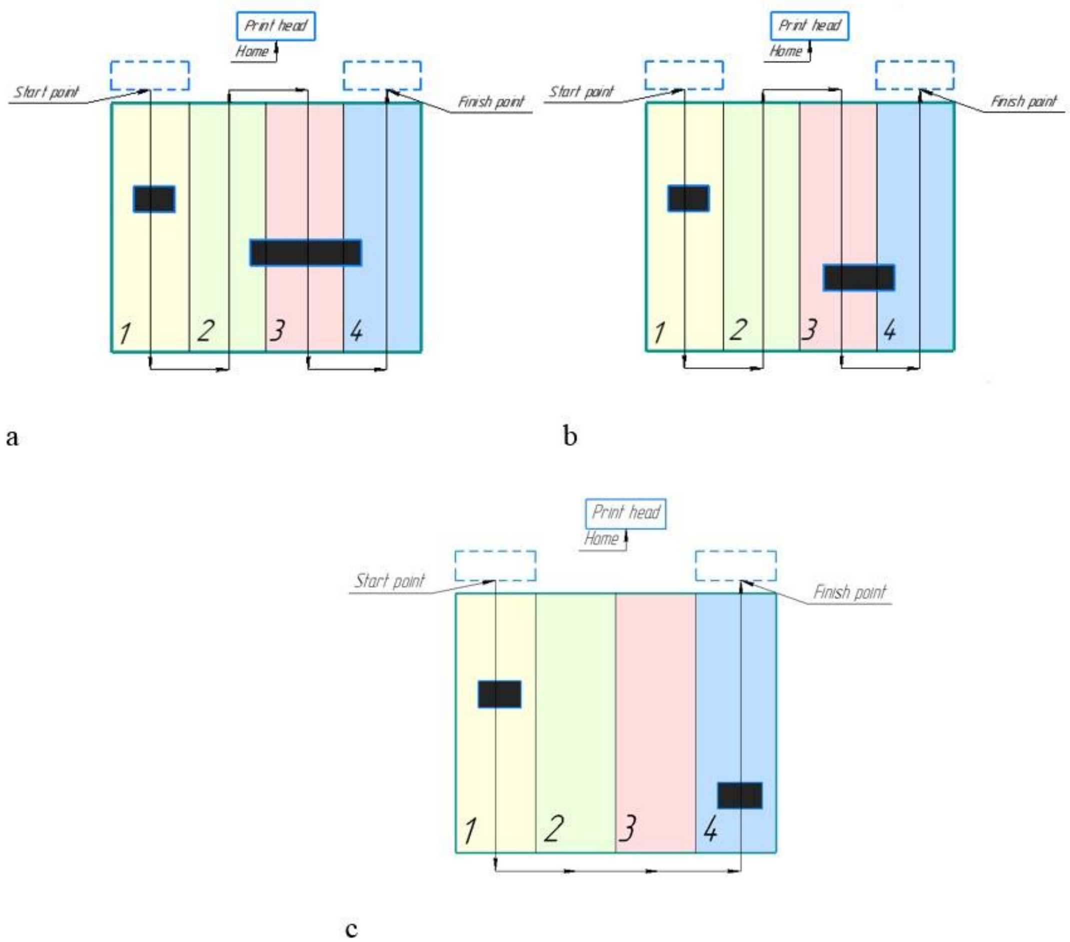

Fig 3: Movementof the print headwithout optimisation: a – details are situated in allsectors; b – details are situated in 1, 3,and 4 sectors; c – details are situated in 1 and 4 sectors.

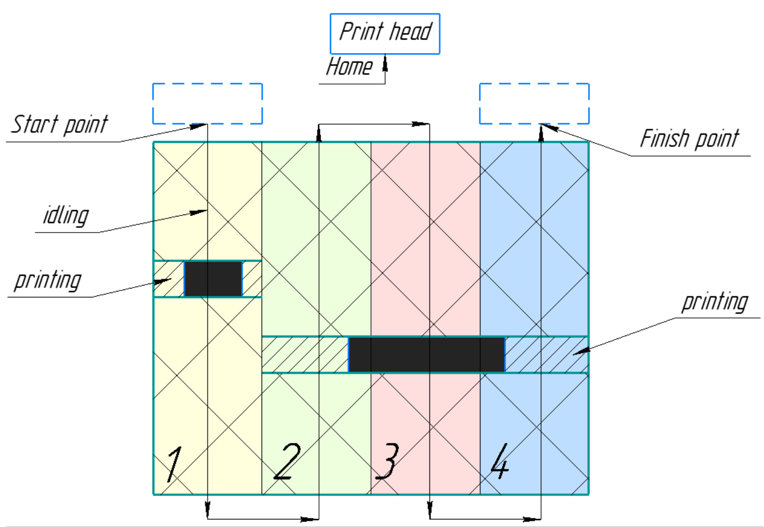

Fig4: The firstvariantof optimisation

The most developedvariantof improvement in the productivityisas follows: it is necessary to prevent movementsof the print headover thezones,whereno printing is performed (Fig. 5).In this case,the print headaftermovementover thezoneof printingmoves immediately tothe followingzoneof printing.

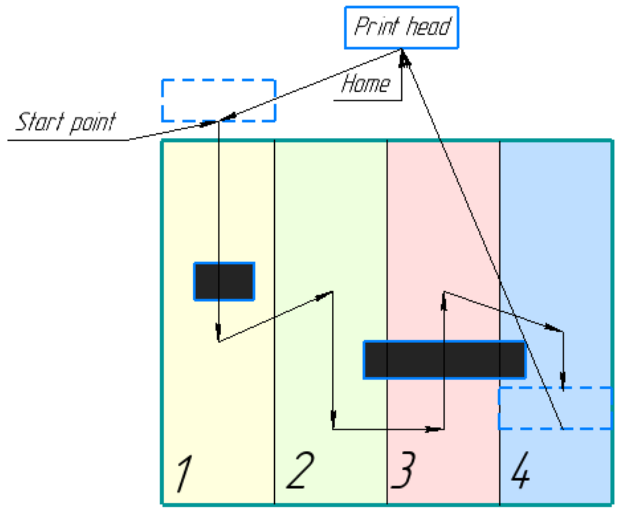

Fig 5: The secondvariantof optimisationof movementof the print head

We have analysedtwoabove-presentedvariants andcalculatedthatproductivityof the testing arrangement mould has increased by 12.1% in the case of the first variant of optimisation. As concerns the second case,we have achievedgrowth by52%.

In order to obtainmoretopicalinformation,it is necessaryto performinvestigationsat variousarrangementsof details,as well as atmoreintense fillingof the working zone, however,it is already understood thatthismethodhasprospectsof development. It is necessaryto analyseinfluenceof the sectionsof accelerationanddeceleration, as well as todetermineboundary conditions.

Increaseof the working frequencyof the piezoelectric print head

Anothermethod, which is connected with print headsand which can improve productivityof the entire device, isincreaseof the maximum rateof printingof the print head (Wijshoff, 2010).Limitationsin respect offrequencyof operationof the piezoelectric elements, which areincluded to the structureof the print head, result in thepredeterminedrestrictionsin respectof the rateof movementof the print heads, because ofit is necessaryto observethe predeterminedratiobetween the working frequencyof the print headandits movement speedin order to ensure the required density of dots of the binding substance in the course of printing.

One of possiblevariantsfor solvingthisproblemisto replace the print headwith themodelwith higherfrequencyof operation;however,othermodelsalsohavethe restrictionin respect of themaximumfrequencyof operation, as well asin respect of theworkliquids,which are permissibleforoperationwith the print headas the binding substance.

There exists the following alternative, which ensures the higher frequency of operation: use of several print heads having the lesser frequency of operation of the piezoelectric elements, provided that these print heads are installed in the line one for another (Fig. 6).

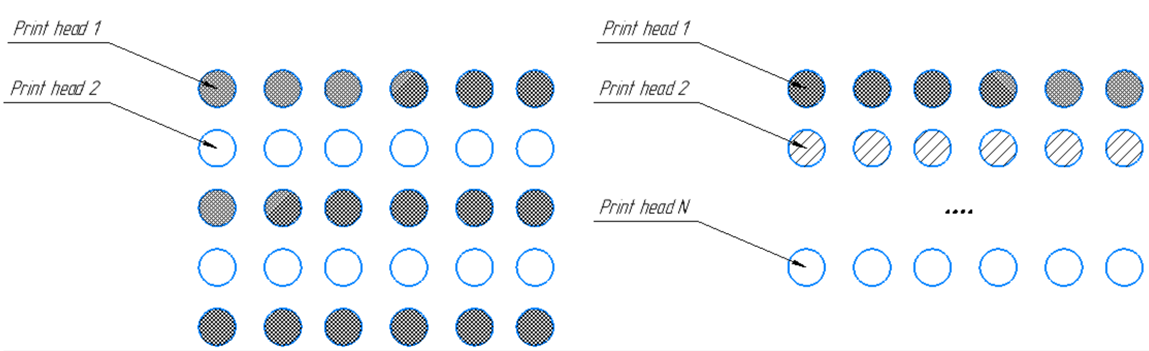

Fig 6: Useof severalprint heads

In this case,eachheadwillonly printits ownlinein the propermomentof time in the course of printing. The morequantityof headswillbe used, the lowerfrequencyof operationthese headsmust have. Totalfrequencyof operationof the entiresystemwillbe equal to:

$$H_{total} = N * H \quad (1)$$

where*H*isthe frequency of operationof the single print head, *N* isthe totalquantityof heads.

With the help of thisapproachit is possibleto achieveimprovementof the rateof printingup to anyrequiredlevel,however(as it was already statedabove)eachprint headhassufficientlyhighcost,therefore, use ofmany headswill result inthe totalincrease ofcostof the entire device.

Changein dimensionsof the dropsof the binding substance, which is introducedby the print head

In order to comply with thetechnologiesof printingthe sand-polymercasting mouldswith the help of the layered synthesis method,it is necessaryto ensure strict dosingof quantityof the binding substance, which is introducedby the print heads. However,it issmalldimensionof the drops(which are introducedby the print head)that ensuresflexibilityof the process, however thissmall dimension simultaneously increasesdurationof the processof productionof the relevant ready product. Therefore,the lesserdimension of the drop,the longer will be period ofoperationfor manufacturingthe ready casting mould. It is obvious that there exist the directly antithetical trends. So, it is necessary not only to find a balance of requirements in this situation, but also to prevent this direct connection of the drop dimensions with duration of manufacture of the relevant product (Wüst, 2014).

It is possible to adjust total quantityof the binding substance,which is appliedonto the surfaceof the sand, by changingsuchparametersof the print headasstepof ejectionof dropsof the binding substance (it is adjustedby the resolving powerof the printing process),anddimensionof drops (it is adjustedin the controlling systemof the print heads).

As it was already said above, it is necessaryto ensure highfrequency of operationof the print heads in order to maintain high rate of printing. By changingparametersof the resolving poweranddimensionsof drops, it is possible to achievethe required quantity of the binding substance,which is introduced,while maintainingfrequencyof operation of the print headsandincreasingproductivity of the entire device.

In order to improve productivity,it is necessaryto increasestepof ejectionof drops, thusdecreasingdensityof dots, however inthis case it is necessary toincreasedimensionof the drops,which are ejectedby the print head. Therefore, we will ensuretechnologicalrequirementsin respect of the requiredquantityof the binding substance, which is introduced,while we will not changefrequencyof operationof the print head (Fig.6).

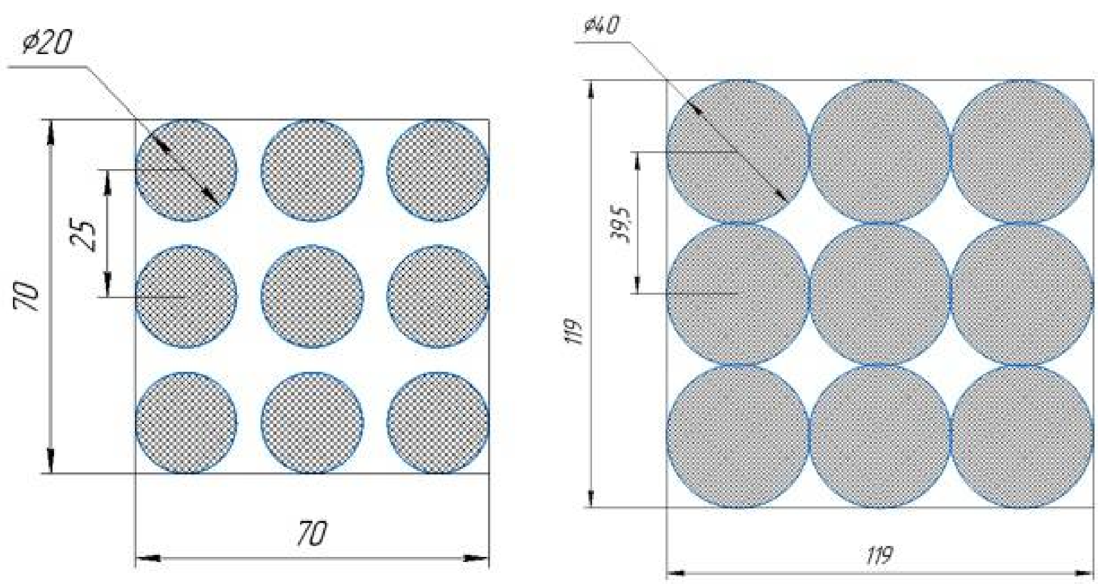

Fig 6: Changingstepof ejectionof the dropsin the case ofincreasein dimensionsof the drops

As concernsthe firstvariant,dimensionof the dropsis equal to 20micrometers;the dropsare arrangedwith thestep 25micrometers, percentage of the area filling is equal to 57.7 %.In the case of the samearea of filling (which is equal to 57.7 %)andincreasein dimensionsof the dropsby2timesin diameter(up to 40micrometers) andby4timesin area,distancebetween axes of dropswill be increasedup to39.5micrometers. Such increasein dimensionsof the dropsby two times will letincreasespeedof printingby1.58timesat the samefrequencyof operationof the print head.

Majorityof modelsof the print headshavepossibilitiesfor changing dimensionsof the drops. Therefore,thisvariantofincreaseof the rateof printingcanbe implementedwithout replacementof the print heads.

In view of thehighcostof the print heads, we see that the most preferablevariantisas follows: applicationof headswith the lesserfrequencyof operation, however,on the conditionof bigdimensionsof the drops, because ofsuchmodels(as a rule)havethelowercost. However,from thetechnological point of view,bigdropcanresult inworseningof qualityof the receivablemould (Fig. 7).

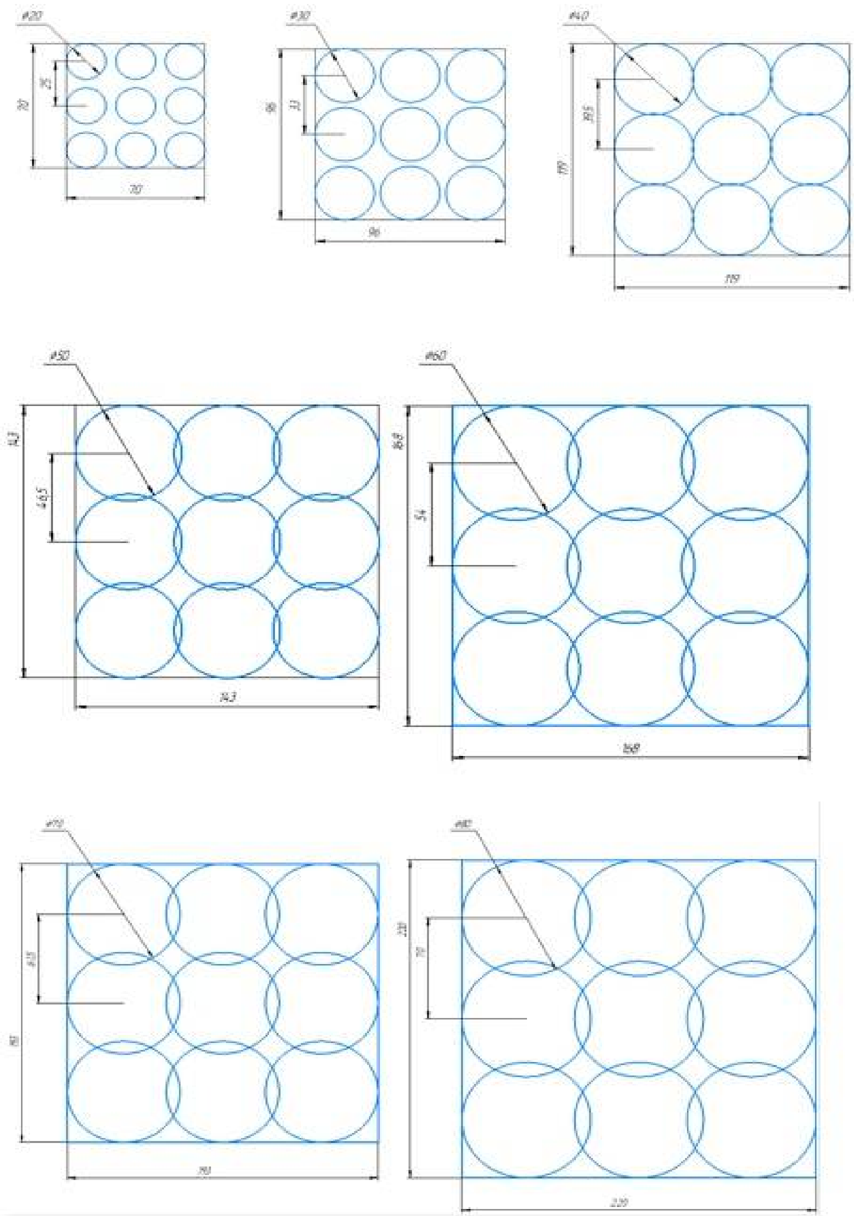

Fig 7: Distributionof dropsdepending on their dimensions

As it can be seen from the above figure, in the case ofincreasein dimensionsof the drops,there isoverlapping/superimpositionof drops, and this fact causesworseningof detailsof the mould, as well asit causes changesindimensionsandqualityof drops.

Havinginvestigateddependenciesof the coefficientof increaseof the rate$K_v$from the coefficientof increaseof dimensionsof the drops$K$, we have foundthe followingdependence (Fig.8).In this case, we have assumed that nominaldimensionof dropsis equal to 20micrometers.

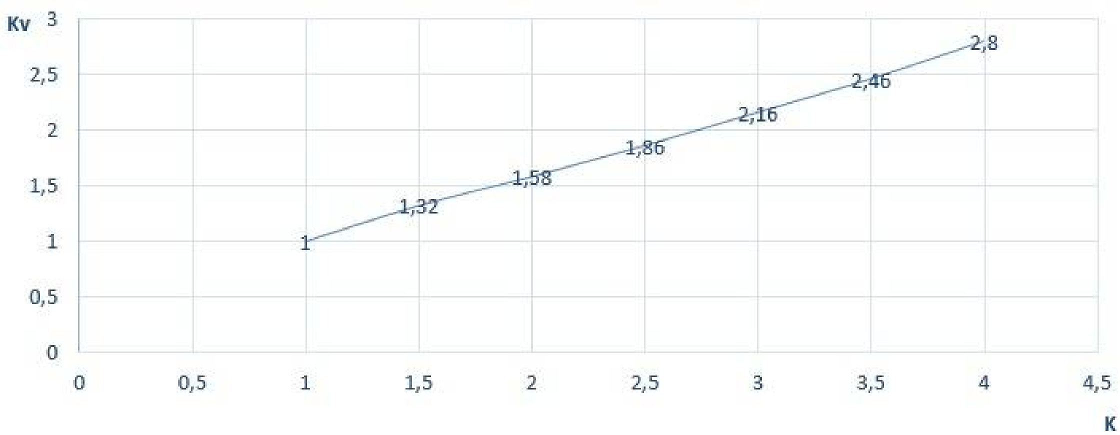

Fig. 8: Chart ofdependenciesof the coefficientof improvementof the rateof printing$K_v$from the coefficientof increasein dimensionsof the drops$K$

Increasein dimensionsof the dropsmakes it possibleto increasespeeddue toincreaseof the stepof ejectionof dropsof the binding substanceby the print heads. As it can be seen fromthe chart above, dependenciesof bothcoefficientsarelinear ones. In the case ofincreasein dimensionsof dropsby 4 times,it is possible to increasespeedof printingby 2.8 times. In the situation, where it is not necessary to ensure high quality of the sand mould, as well as in the case of technical possibility of the print head to ensure such range of changing dimensions, this method can essentially increase productivity of devices. In addition,it is very interestingto analyse variantof differentiationofdimensionsof the drops(which are introduced to the sand) in thesedependenciesfromthe requiredtoleranceon thesurface quality, It is obvious thatin the course offormingvarious sectionsof the relevant product, itcanbe necessary to ensuredifferentaccuraciesof reproductionof the prescribed surface.Therefore,having decreasedtolerancesfor theareas of minor importance,it is possible to hope for theadvantagewithout lossof quality.

CONCLUSION

Allmethodsof improvement in the productivity, which we have analysed,havebothpositiveandnegativeaspects. It is not possibleto state unambiguously thatany oneof the presentedmethodsisa universal oneandthat it canbeusedat anyadditiveequipment as the method, which ensuresoperation in accordance with the principleof the stream printing.

In orderto ensure achievementof the bestresult,it is necessaryto combinevariousmethodswith each other, thusincreasingefficiencyof eachmethodanddecreasingnegativeaspects.

It is necessaryto perform furtherinvestigationsinthissphere in orderto find optimummethodsof improvement in the productivity. However,it is already possible to state thatthe prospective wayisthe methodof optimisationof the controlling system. Inthiscase,it is possible to achievean essentialgrowthof productivitythroughimprovementofthe controlling componentswithout increaseof the costof these devices.

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