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Multi-material part production by selective melting

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Research Article

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Multi -Material Parts Production by Selective Melting

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Abstract :

A method for 3D multi-material parts production has been elaborated. The selective melting machine concept and the concept of the build platform cleaning system are presented and discussed. A method involves the selection of powders of various materials according to diameter, the successive application of layers of powder of a given thickness during the vertical displacement of a piston of a build chamber, and the programmed selective sintering/melting of a given area in the plane of each layer. When the object-sintering process is finished, the unsintered powder is removed from the build chamber, and the powders are separated according to diameter by sieving with accuracy 99%, thus separating the powders of dissimilar materials. The separated powders are returned to feed containers and are reused. The combined flexible blade and suction systems for unsintered powder removal have been elaborated, which provides cross-contamination of not more than 1%.The influence of dissolution on the accuracy of the boundaries of various metals is estimated . Results of experimental investigations of material cross-contamination are presented. An experimental multi-100 SLM machine has been constructed . The proposed method is being partially applied quite successfully by some researchers. The presented technology for the manufacture of multi-material products is applicable in all powder bed fusion systems including a selective laser melting (SLM) and electron beam melting (EBM).

Keywords: multi-material ; powders; laser ; melting; dissolution

Introduction

The use of multi-materials may be viewed as a technically challenging and economically favorable manufacturing method [1]. Single material additive technology

systems cannot fulfil the requirements of some applications that require multiple material objects from one machine, such as compliant mechanisms, embedded components, 3D circuits, human tissues and medical-compatible implants. By utilizing multi-material components, economic and lightweight designs may be achieved via the reduction of required assembly processes and parts. Multi-material systems will enable the manufacturing of functional structures within products, such as conductive tracks or optical pathways, resulting in radically novel products with unprecedented degrees of functional density. The industry has already begun taking advantage of multi-material designs in numerous applications, including the coating of internal surfaces, the embedding of functional structures in electronics [2] and components with compliant hinges in automative industry [3].

A great deal of effort is going into the elaboration of the multi-material fabrication systems. Stereolithography has been adapted to support multiple materials [4]. This is accomplished by using multiple vats with UV-curable polymers. These systems can provide high resolution, but changing materials for each layer makes the printing process very complicated and slow. Also, efforts have been made to use selective laser sintering with multiple powders [5]. Multi-material inkjet-based systems have also been developed [6]. There are machines for selective laser cladding, which can produce a 3D multi-material product, but the production precision does not exceed 100-200 microns, and the product requires significant improvement, such as milling. The selective laser sintering/melting (SLS/SLM) process is well- suited to the incorporation of multiple powdered materials [7]. But all methods and machines presented on the market for producing 3D objects by selective laser sintering/melting are focused on the use of a single powder. Machines for the production of multi-material products by selective laser sintering/melting (SLS/SLM) process that makes it possible to obtain accuracy up to 10 microns, are absent.

Different approaches were made for multi-material parts production by selective laser melting/sintering. One-dimensional parts can be produced using standard SLM machine equipment. For fully three-dimensional multi- material parts production, new recoating methods and mechanisms have been elaborated, one of which is based on electrostatics [8], and the second one is a nozzle mechanism [9, 10] . The SLS/SLM process presently uses a roller or blade device to sweep thin layers of a single

powdered material across the build area. It was concluded that it is impossible to deliver multiple materials with a roller or blade without cross-contamination [11] . It has been proposed to replace this roller device with an array of hopper nozzles that can directly pattern regions of multiple powdered materials [12] . Also, the method that combines roller and nozzle delivery and vacuum removal has been proposed [13].

These methods don't yield a required spatial resolution or rate of powder delivery, as nozzle diameters smaller than 110- 200 microns are not possible to use [14], and moving speeds above 20 mm/s cannot create complete printed lines . Moreover, these methods are very sophisticated for industrial promotion**.** The method of selective sintering of multimaterial products using binders for binding powder particles with subsequent removal of the binder by sintering in a furnace is also being intensively developed [15] . But these methods are complex, and the materials for their implementation are quite expensive. And the resulting products cannot be used in extreme conditions of aerospace engineering. An interesting approach to the creation of multimaterial products by selective laser melting was proposed by Aerosint [16] . It is based on their patented powder deposition method. Using a matrix of gas locks, powder areas from two different materials are programmatically placed on the surface. But the accuracy of the method is not better than 0.5 mm; that is, the size of the powder pixel is not less than 0.5 mm. In addition, the system is extremely complex.

So far, at the present time, there are no technical solutions to be implemented in the framework of the industrial production process of manufacturing multi-material objects from metal, ceramics, and engineering plastics by SLS/SLM or EBM. A new method and machine for 3D multi-material parts production have been elaborated [17,18,19] , where standard recoating systems with roller or blade can be used. The main idea consists in using a narrow fraction of powders of various materials with different medium particle sizes and a special algorithm of powder layer recoating. This not only makes possible three-dimensional multi-material parts, but this method also enables the separation of the overflow powders of various materials for reuse. A similar multi-material SLM system is developed in the [20], but using a vacuum suction to remove the powder, which, as the results achieved show [21], sharply limits the accuracy of the product.

The proposed in this paper method is being partially applied quite successfully by researchers [22], opening prospects for its widespread implementation in industry. A comprehensive overview of the latest advances in multi-material technologies and their prospects is presented in [23,24].

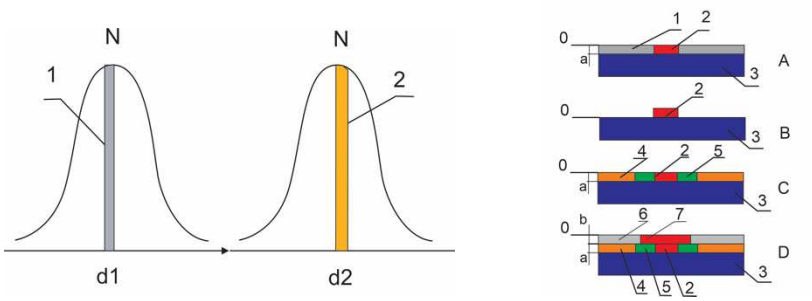
Multi-material processing

A method involves the selection of powders of various materials according to diameter, the successive application of layers of powder of a given thickness during the vertical displacement of a piston of a build chamber with an object to be sintered, and the programmed selective sintering/melting of a given area in the plane of each layer. After sintering , the piston is raised through a height of layer, and unsintered powder is removed from a layer. The piston is then returned, and a layer of powder having a different diameter and being of a different material is applied and selectively sintered. The process is repeated the requisite number of times depending on the number of materials applied in a layer, producing sintered areas from powders of dissimilar materials in a single layer. When the object-sintering process is finished, the unsintered powder is removed from the build chamber, and the powders are separated according to diameter, thus separating the powders of dissimilar materials. The separated powders are returned to feed containers and are reused. The technical result consists in the possibility of producing objects having prescribed properties using powders of dissimilar materials located in a single horizontal plane in a single layer. The principle of the method is illustrated in Fig. 1.

By sieving the powders of dissimilar material with different appointed diameters of the particles for each material, the material is selected (Fig. 1). As this takes place, particle diameters of the dissimilar powders are related as multiple .

On the build piston 3 of the build chamber (Fig. 1b, A), the layer **a** μm thick of powder 1 is applied . After sintering the area, the build piston is raised through a height **a** of the layer, and unsintered powder is removed (Fig.1b,B).

Thereafter the piston returns to its previous position (Fig. 1b, C), and the layer **a** μm thick of powder, 4 other materials, and other particles diameter is applied. Selective laser melting is carried out at Area 5. The process is repeated the requisite number of times.



a b

Fig 1. (a) - Powders distributions; (b) - stages of multi-material sintering

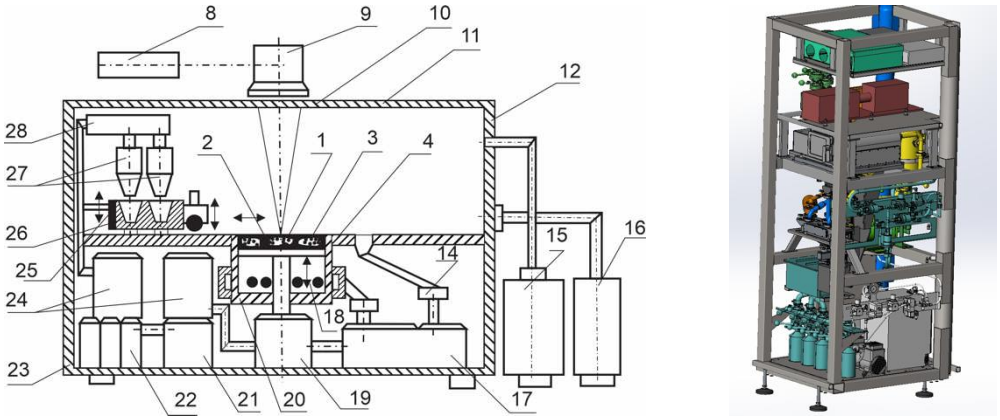
After the sintering of this layer, the build piston is lowered through a height **b** of the next layer (Fig. 1b, D) . The new powder layer 6 is applied, and the above-listed operations are carried out at the new layer; as an example, sintering the area 7.

After completion of the 3D object sintering , unsintered powder is removed from the build chamber, and separation of the powders according to their diameters by sieving is conducted, and in so doing , powders of dissimilar materials are separated.

From time to time, the ups and downs of the build piston at different heights and depths in accordance with the layer composition allow us to obtain sintered areas from powders of dissimilar materials in a single layer, to obtain spatial curve interfaces between the areas from dissimilar materials, and to produce fully three-dimensional multi-material objects. The harnessing of distinction in particle diameters of a powder from dissimilar materials for its separation makes it possible to achieve high efficiency of the powder reuse.

Concept of SLM multi-material machine

For the realization of the new method of multi-material processing, the concept of the SLM machine has been elaborated. The SLM machine is made up of a laser, a laser scanner with an F-theta lens, a processing chamber, a build chamber with a build piston that moves powder layers and 3D objects in a vertical direction, several feeding containers, a recoater powder feeding system that consists of several identical modules, a build platform, a cleaning system for removing unsintered powder, and a sieving station for unsintered powder gathering, separation, and vacuum transportation to powder feeding containers for reuse. The essence of the conception is illustrated in fig. 2:



a b

Fig. 2. (a) Selective laser melting machine scheme.(b)- design

8- laser, 9- laser scanner with lens, 0 – build platform, 1- powder layer, 2- 3D object, 12- processing chamber, 13- surface cleaning system, 14- shut off valve, 10- window, 20- build chamber, 15- gas system, 16- vacuum system, 17 – powder container, 18 – openings for removing the unsintered powder, 19 – motor of vertical transport, 21- system for powder separation by sieving, 22- containers of separated powders, 23-container of defect powder, 24- vacuum transport system , 25- roller , 26- re-coater powder feeding system, 27- powder feeding container, 28- distributer.

After finishing the sintering of the 3D object , the piston is lowered down and unsintered powder is removed through an opening in the build chamber. In the sieving station, the powder is separated into powders of dissimilar materials and reused.

This SLM machine offers essential dissimilarities and advantages over the known machines. There is the possibility to sinter several powders in the same layer sequentially instead of parallel. Owing to that, the technological regime of sintering of the dissimilar materials, with different melting temperatures and thermal conductivity, simplifies because within every step of sintering, powder is fed on the compact material. As well as the build platform cleaning system and system for material separation according to the size of a particle, it has no analogues. Now the project is under construction (fig. 2b).

Buid platform cleaning system design

Removal of the unsintered powder at the process of the multi-material 3D-object production has been the object of much attention in the realization of the method. The estimation shows that the height of the powder bead during the process of removing a powder layer with a thickness of 20-100 μm at a distance of 500 mm ranges up to 4-10 mm. High-quality cleaning is not possible exclusively mechanically. Because of this, an original combination of mechanical and suction cleaning has been

elaborated (Fig.3). From the powder bead, a suction cleaner draws off surplus powder. The brush cleaning is achieved by the gas supply through the axis of the roller and suction cleaner. This cleaning system allows you to remove layers 20-40 microns thick. Instead of a roller, the possibility of removing a layer using a flexible porous high-temperature silicone blade was investigated, which gave a positive result.

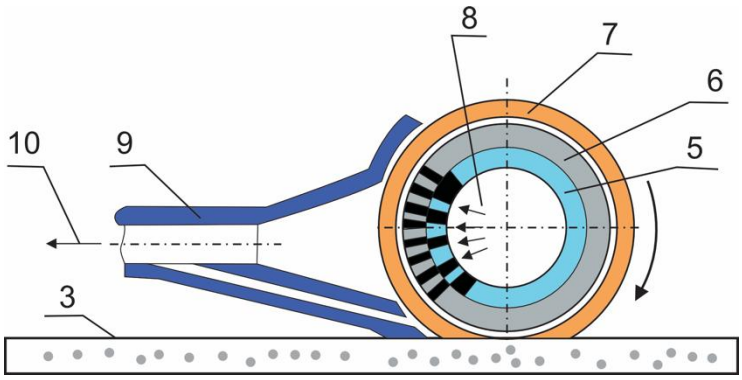


Fig. 3. Build platform cleaning system design

1- build platform, 2- powder beard,3- powder payer, 4- channel of suction removing of the beard, 5- axis of the cleaning roller, 6- shaft of the cleaning roller, 7- brush, 8- gas supply,9- brush cleaning device.

A purely suction method of powder removal is used in [20,26] . As shown in [26], purely suction removal cannot ensure the accuracy of removing thin layers of powder and can only accurately remove more than 3 layers. Poor powder removal results in cross-contamination. As noted in [27] cross-contamination reaches 14-40%, which leads, as shown in [25], to the appearance of wide transition zones in the contact area of different materials up to 300-600 microns wide [25]. Processes in the transition zone are key for SLM of multimaterial products.At the same time, the use at [22] of a mechanical powder removal system with the help of a flexible blades provides transition zones with a width of 100-150 micron, which makes it possible to create hierarchical interlocking interface [22] and minimize critical problems of interfacial bonding and ensure the connection of even non-fused materials.

A further development of the combined blade and suction system is shown in Figures 4,5 which shows the design of the system for applying several powders, in this case two powders, and removing unsintered powder.

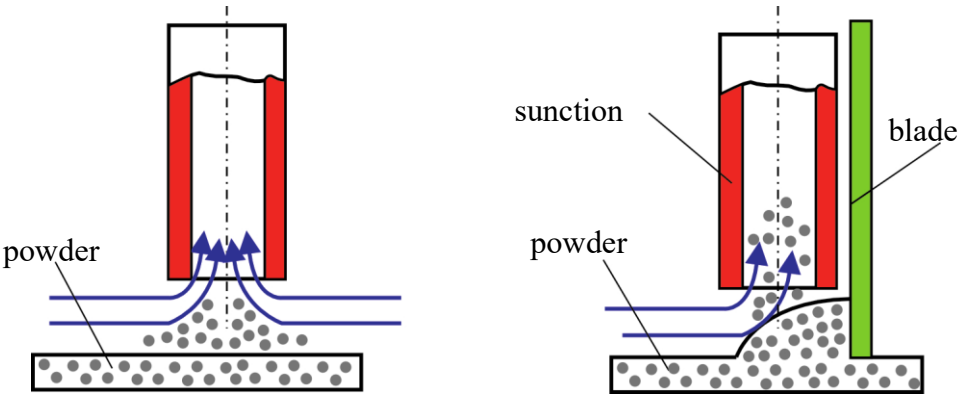


Fig. 4 Scheme of powder removal by suction (a); at by combination of a flexible blade and suction (b).

When only the powder suction system is used for powder removal (Fig 4a) powder particles get into gas jet only due to gas static pressure difference in powder layer and gas jet, which is not effective.

When using a combination of a flexible blade and suction (Fig 4b) , the removed powder is fed into the gas jet with the blade and is carried away by the aerodynamic force of the stream, which ensures accurate thickness and effective removal of a thin 20-30 micron layer of powder. In addition, removing the powder relieves the burden on blade and an extremely flexible blade can be used.

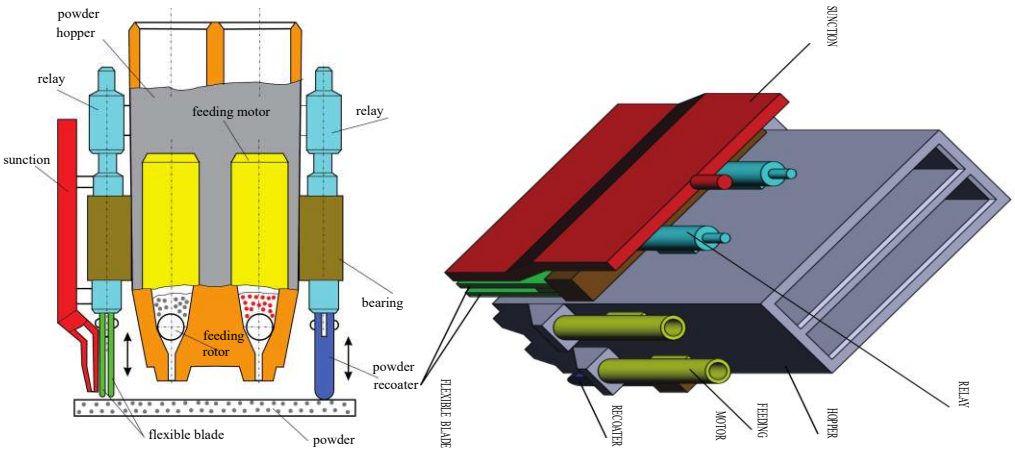
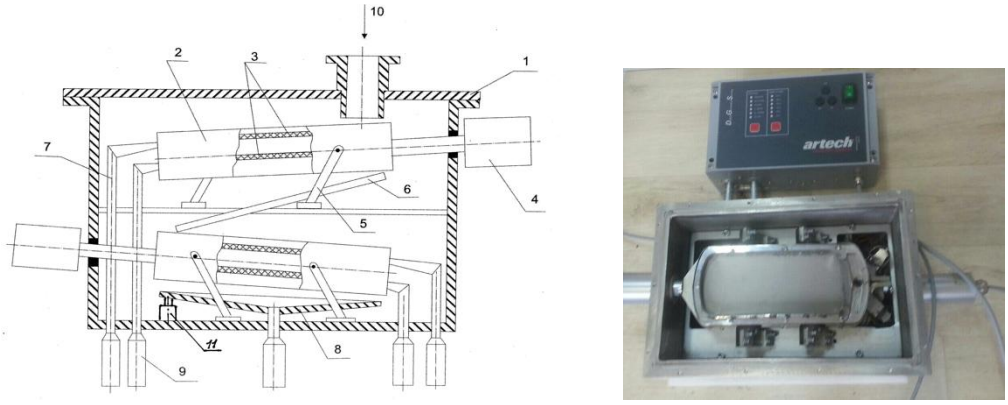


Fig. 5 Powder delivery and cleaning unit

System for separation powders of various materials

To separate powders of various materials both in the process of preparing for the sintering process of powders of various materials and at the end of the sintering process of a multi-material product for reuse, the system for powder separation was elaborated. It is recognized [26, 27] that the only viable methods for separating powders of various materials are sieving and magnetic separation. Obviously, sieving is preferred as it applies to any material. The results of experiments [27] showed that sieving provides 97.5 -99% efficiency in separating powders of various materials

The use of narrow fractions of materials proposed in [17, 18] is a decisive factor to ensure 100% separation by sieving in a special system. This system has been developed (fig. 6) and tested.



a b

Fig. 6. System for separating powders of various materials

1- housing, 2- sieves module, 3- sieves ,4 – ultrasonic converter,5- flexible holder,6- tray, 7- flexible tube, 8- pan, 9- powder cartridge, 10 – powder stream,11- vibrator.

The separation process is carried out in an evacuated and inert gas-filled housing 1. The powder enters the system of four sieves 3, where, with the help of ultrasonic vibrators, it is divided into five fractions and dumped into five cartridges 9 for reuse. Separation of powders of different diameters and correspondingly different materials was efficiently produced and practically without cross -contamination.

Consider the stage of separation of powders of different materials in the process of producing a three-dimensional object from two powders of different diameters from two materials. The powder of material A with a particle diameter of 20 ± 5 μm and the powder of material B with a particle diameter of 60 ± 5 μm are separated. The powders

are filled up into two feeding containers 27 (fig. 2), separate for each material. We carry out the sintering process according to steps A-D (fig. 1b).

After stage D , all unsintered powder enters the powder sieving system, pos. 21 in fig. 2 and fig. 6.

This system contains a specially selected set of sieves 3 to screen a given set of powders. In a sealed case filled with an inert gas, two modules of sieves 2 are placed. Ultrasonic vibrators 4 are used for screening. The first module contains sieves with a cell of 60 microns and 45 microns. The second module contains sieves with a cell of 20 microns and 15 microns .

The unsintered powder enters a 60 μm sieve, and the defective powder with a size of more than 60 μm is screened out to a container, and the powder 60 μm or less passes to the second sieve, where the 60 μm powder is screened out and sent to a separate container 9 for material B.

The rest of the powder is sent along the tray 6 to the sieve with a cell of 20 microns. The 20 μm powder passes to the lower 15 μm mesh and is sent to a separate container 9 for material A. And the defective powder with a diameter of more than 20 μm is separated on the 20 μm mesh and sent to the defective powder container. The defective powder with a diameter of particles less than 20 μm is sent to the defective powder container. Thus, powders of various diameters of various materials are completely separated with 100% efficiency, and defective powder is separated regardless of its nature—metal or plastic.

This is not achieved in any other methods and devices.

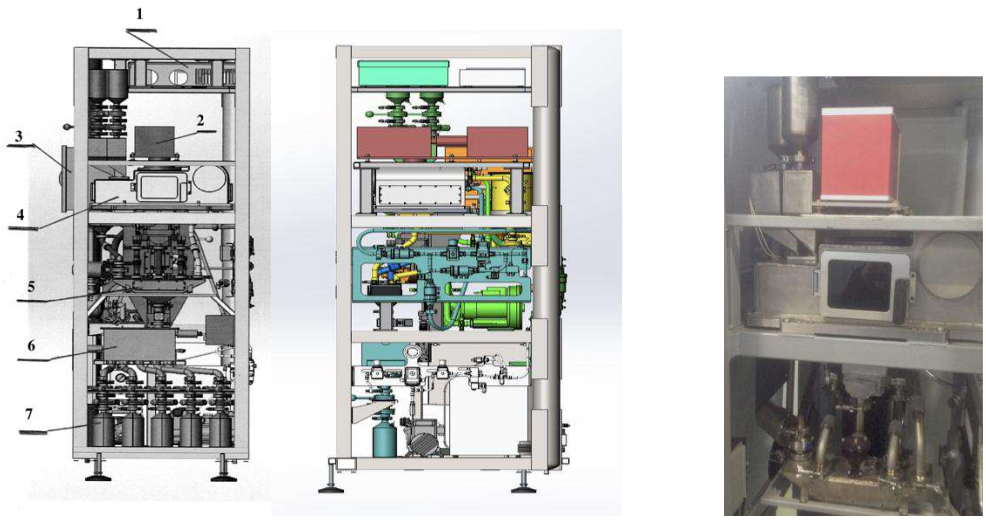
From individual containers 22 for each material (fig. 2), powders A and B are sent by means of a vacuum transport system 24 to feed containers 27, separate for powders A and B, for reuse.

Results and discussions

Multi 100 SLM machine

A machine for selective laser melting has been developed and created to produce 3D multi-material products from two powder materials with a working volume of 100×100×150 mm (fig. 5). The design of the machine is based on the patented method [17, 18, 19] described above, and all the presented innovative solutions are implemented in it. The machine is completely autonomous in the sense that to carry out the manufacturing process of the product, it only needs to be connected to a 220-

240V network and filled with powders. The filling of powders is carried out through a special unpacking chamber 3, where a can with a powder is opened in an inert atmosphere and poured into a powder collector 5. Next, the powder in the powder separation module 6 is dispersed into fractions poured into cartridges 7. Cartridges with powders of various materials are moved to storage hoppers on top of the technological chamber 4, and, during sintering by laser 1 with scanner 2 are dosed into carriages, from which powders are applied to the piston of the build chamber. The powder that is not sintered in the process is poured into a collector 5 and separated in module 6 according to size, and therefore the powders of different materials are separated and dumped in cartridges 7.

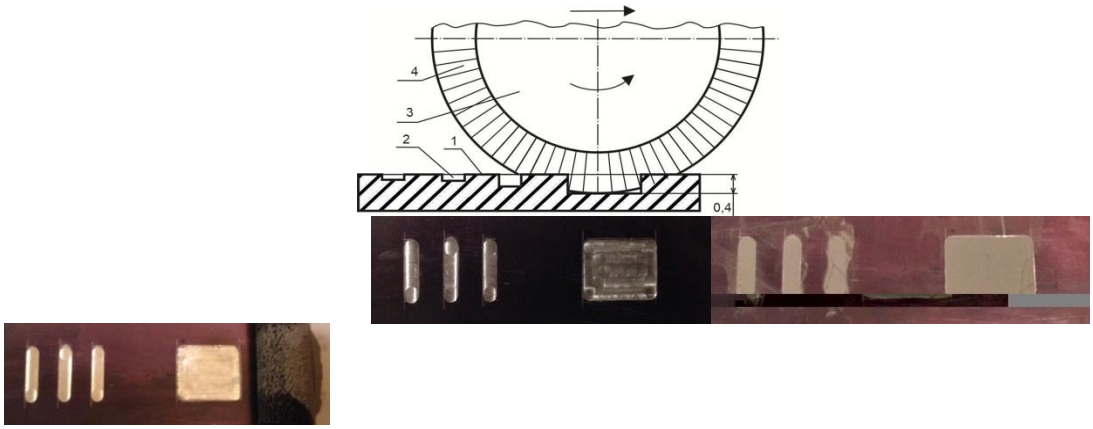


a **b** **c**

Fig. 7. Multi 100 SLM machine construction

Investigation of material cross - contamination

One of the main problems in multi-material processing is material cross-contamination [26,28]. The cross-contamination effect in our designed system has been studied experimentally. A special experimental procedure has been conducted (fig. 8).



a b c

Fig. 8. Scheme of experimental procedure. 1- plate, 2- grooves,3- roller,4- pile coating. Stages of the experimental procedure a-b-c.

Grooves 2 in a steel plate of depth 50, 100, 200, and 400 microns were filled with steel powder 30 μm in diameter . Cleaning roller 3 with the special high-temperature (T > 1500 K) silica pile coating 4 was moved with rotation and removed the powder from the grooves (fig. 6). Experiments showed that the pile coating absorbs and removes the powder perfectly, leaving less than 0.1% (experimental limit) of the powder (fig. 8c). During operation of the cleaning system, the roller is cleaned by a vacuum cleaner.

Dissolution effect on sintering accuracy

When sintering the multi-material object with high accuracy, particular attention has been given to shrinkage and dissolution. When the solid phase and melt are in contact, a process of dissolution of a solid phase in melt occurs, which leads to border blur. At a unidimensional approximation , the position of a solid surface is defined as [29] :

$$\Delta X=2b(\alpha t)^{0.5}; \quad (1)$$

where α – diffusivity, b – factor dependent on material, for steel b = 0.75.

Nominal diffusivity of solid elements in molten steel, for example, is assumed to be $\alpha = 1 \times 10^{-9}$ m^2/s for all the elements[30]. The calculations also considered the effect of enhanced diffusion of solid elements due to melt flow by increasing the diffusivity arbitrarily to a value of $\alpha = 1 \times 10^{-6}$ m^2/s. The results of calculations are presented in Fig.9.

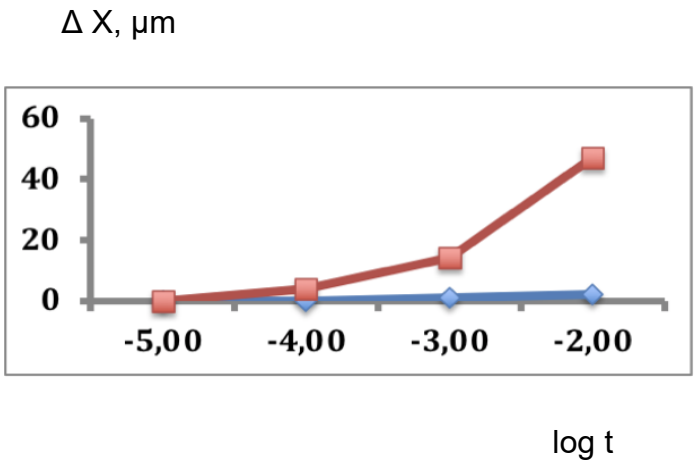


Fig. 9. Dissolution of solid in melt versus time : ■ - α = 1 ×10^{-6} m^2/ s , ◆ - α = 1 × 10^{-9} m^2/

It is obvious that it is necessary to minimize the time of contact of melts of various metals at their boundary.When using point-by-point ultrasonic powder dispensing to deliver multiple materials at designed locations in the process of fusion [31], there is a process of fusion of various powders with different thermophysical characteristics and different melting points. This causes difficulties in controlling the fusion mode and leads to defects in the transition zone [31]. In the developed method, this is ensured because the powder of one of the metals is melted and sintered to another metal, which is in a solid state.

Conclusions

A new method and selective melting machine for 3D multi-material parts production have been elaborated , where standard recoating systems with roller or blade can be used. The main idea consists in using a narrow fraction of powders of various materials with different medium particle sizes and a special algorithm of powder layer recoating. This not only makes possible the creation of three-dimensional multi-material parts, but this method also enables the separation of the overflow powders and unsintered powders of various materials for reuse with high efficiency up to 99%.

When sintering the multi-material object with high accuracy, particular attention has been given to shrinkage and dissolution .

The cross-contamination effect has been studied experimentally. Not more than 0.1% cross-contamination is fixed. A special sieving and cleaning system has been elaborated that

provides 99% separation of narrow fractions of spherical powders of two various materials. The experimental Multi 100 SLM machine has been manufactured and is currently being tested.

Multi-material technology has the potential to become an important manufacturing resource for the next generation of AM technology. This is because single-material AM systems cannot fulfill the requirements of some applications that require multiple material objects from one machine, such as compliant mechanisms, embedded components, 3D circuits, human tissues, medical-compatible implants, etc.

The developed technology for the manufacture of multi-material products is applicable in all powder bed fusion systems including a laser beam melting and electron beam melting.

The presented method and devices for its implementation have already found application in research laboratories and can be implemented on an industrial scale, unlike many other options for building machines for producing multi-material products.

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Author contributions: **Yuri Chivel**: Conceptualization, methodology, data analysis, experiment, writing-review & editing.

Author contributed to the study conception and design. Material preparation, data collection and analysis were performed by Yuri Chivel. The first draft of the manuscript was written by author. Yuri Chivel read and approved the final manuscript

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