A Heuristic Approach to the Estimation of the Mass of the Waste Powder During Selective Laser Sintering of Polyamide PA2200

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Waste powder is part of the powder used during selective laser sintering that is not built into products and cannot be re-used. The amount of the waste powder influences the costs of the manufacturing. A part of the waste powder is the powder that remains attached to the products after their removal from the production chamber. The amount of the attached powder depends on many factors, and the estimation of the amount of the attached powder is a complex task.

This paper presents three methods for simple and fast, although not very accurate, estimation of the mass of the attached powder on the basis of calculation of mass of the products and the total mass of powder used during a production process. The results show that the methods may give a useful estimation of the mass of the waste powder in the long run if the products are not lightweight structures.

Keywords: Additive manufacturing, Selective laser sintering, Manufacturing costs

1. INTRODUCTION

The topic of costs of the additive manufacturing (AM) technologies became of interest in late 1990s, after the AM technologies left laboratories and started becoming commercial manufacturing technologies. However, a common and comprehensive model of the manufacturing costs is not developed after two decades of the efforts made by expert teams, which usually consist of experts in economy and AM engineers and technicians as consultants. One of the important reasons for lack of the common cost model of AM technologies is variety of the AM technologies. Various AM technologies have different costs, so that limited experience of the consultants often translated to limited applicability of the cost models developed by the economic experts. An extensive overview of the cost models of the AM is recently given in [1].

The progress in the development of cost models consisted in expansion of the considered number of factors that influence the AM costs. The initial cost models [2] were based on experiences of injection moulding, and it considered only variable AM costs, including machine costs per part, labour costs per part and material costs per part. Such models neglected important aspects of AM technologies, such as ability for recycling of the used material and requirements for extensive post-processing. An important breakthrough in the development of cost models was separation of the AM costs to direct and indirect costs, which led to proper consideration of high overhead costs of the AM technologies [3]. Further step in the development of the cost models was extensive study of the energy consumption [4], which exposed importance of the proper treatment of the utilization of the capacity of the used machine [5]. Due to the complexity of the AM technology, the refinement of the AM cost model was performed by advance modelling of the AM technology process by the Event-driven Process Chains methodology. The model was first that considered post-processing as an important aspect of the AM technology and it was further used for activity based calculation of AM costs [6]. Further improvement of the cost model was development of an algorithm for calculation of the production time fraction for each of the parts in a single AM job [7]. The described study of the AM costs led to the state-of-the-art model of the selective laser sintering (SLS) technology costs [8], which considers recycling of the used powder. However, this model does not consider structure of the waste material costs in the SLS process.

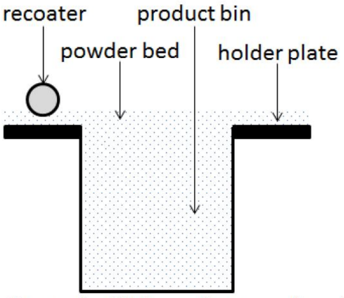

Figure 1: Part of a SLS production chamber where the powder resides

The waste powder represents a part of the powder that is not built into products, but still may not be used for recycling. There are two main sources of waste powder during SLS, the powder that remains in the production chamber after a production process, and the powder that remains attached to the products after they are taken out of the product bin.

The production process of AM technologies consists of sequence of processes of production of individual layers of the products. With the SLS technology, each of the layers is manufactured by melting of a thin layer of powder in the powder bed (Figure 1), which is closed inside the production chamber of a SLS machine. Before production of each of the layers, a small amount of the powder is brought to the production chamber, and the recoater of a SLS machine distributes uniformly the added powder over the top surface of the powder bed. After the production of a layer, a movable platform at the bottom of the product bin is lowered, and the manufactured layer is covered by the powder added for

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*Corresponding author: Address: Dositejeva 19, 36000 Kraljevo, Serbia: e-mail: soskic.z@mfkv.kg.ac.rs manufacturing of the next layer. However, since the product bin is supported by a holder plate, the powder is also distributed over the surface of the plate. When the product bin is removed from the production chamber, the powder on the holder plate remains in the production chamber, and has to be removed by vacuum cleaner before a new production process is started. The amount of the powder that remains in the production chamber after a SLS production process is roughly constant, and represents a part of the fixed production costs.

Figure 2: Removal of waste powder by machines (left) [9]and hand tools (right) [10]

When a product of the SLS manufacturing is taken out of the production bin, an amount of the powder remains attached to it. Some of the attached powder is connected to the product by adhesion, but a part of the attached powder is closed in internal cavities, holes and openings within the products. The attached powder is removed by dusting and blasting using machines, but sometimes is required time-consuming removing by hand tools (Figure 2).

The amount of the attached powder is variable for each product and production process, and depends on many unpredictable factors. Some of the factors are of the objective nature, such as:

- shape, surface and volume of the product,
- quality and the composition of the powder,
- arrangement of products in the product bin,
- duration and regime of cooling of the product bin,
- quality of the manipulating equipment,

but some factors are of subjective nature, such as skill of the person who removes the powder and skill of the person who plans the spatial distribution of the products in the product bin. For that reason, even the processes that produce the same products, and with the same procedure, end up with different amounts of the waste powder.

The experience of research work (that will be presented later in the paper, see discussion of the results presented in the Figure 3) shows that the amount of the waste powder is in many cases even higher than the amount of the powder built in products and used for recycling, which inspired research presented in this paper.

2. MODELS

The total mass of the waste powder (W) may be expressed as the sum of the mass of the powder that remains in the production chamber (C) and the mass of the attached powder (A):

$$W = C + A \tag{1}$$

Since the area of the holder plate (S), the thickness of the powder bed (t) and the density of the powder (d) are known, the mass of the powder that remains in the production chamber may be calculated as:

$$C = S \cdot t \cdot d \tag{2}$$

On the other hand, as explained, the amount of the attached powder is almost impossible to calculate, and even very hard to estimate in general case. This conclusion calls for development of a methodology that may be “tuned” for specific cases, which may vary from SLS machine to SLS machine, from market to market, or even from company to company.

The nature of the problem calls for the *soft computing* techniques, which are applied to complex problems with many input variables that do not require high accuracy of solution. The soft computing techniques include fuzzy logic, evolutionary computation, machine learning and probabilistic reasoning. Since “tuning” of all of the aforementioned methodologies require substantial knowledge and understanding, in this paper we consider a simple heuristic approach that may be easily implemented in all cases.

Heuristic approach to problem, by Wikipedia, is “any approach to problem solving, learning, or discovery that employs a practical method not guaranteed to be optimal or perfect, but sufficient for the immediate goals. Where finding an optimal solution is impossible or impractical, heuristic methods can be used to speed up the process of finding a satisfactory solution. Heuristics can be mental shortcuts that ease the cognitive load of making a decision.” While the most obvious examples of heuristics include using a rule of thumb, educated guesses, intuitive judgment, stereotyping, profiling and common sense, in the recent decades were discovered and studied many heuristic techniques [11][12] that humans use unconsciously, which shows the evolutionary importance of the techniques.

One of simple, but often used, heuristics is *one-reason-decision-making*, where a complex estimation is made by looking for *only one “smart” predictor*, and the estimation is based on that predictor. With the aim to select the “smart” predictor that will be used to estimate the mass of the attached powder, in this paper are studied various possible descriptors of SLS processes, which are based on masses of products and product bin after production.

The masses are selected as the “smart” predictors for two reasons. The first reason is practical, since masses are quantitative parameters that may be subjected to numerical methods of theoretical and experimental research. Furthermore, the masses may be calculated before the start of the production processes, and measured after the process. Therefore, selection of the masses as the predictor of the SLS process enables development of quantitative models and their application for prediction of the amount of the attached powder. The other reason for selection of the masses as the “smart” predictor is that mass of the products and the powder are connected to some parameters that affect the amount of the attached powder, such as the size of the products and, to a certain measure, even their shape and arrangement in the product bin. Of course, the masses are not connected to many of the remaining relevant parameters, and one cannot expect accurate predictions using one-reason-decision-making heuristic approach to such a complex problem. Based on the same input data (the masses of products and whole powder in the production bin), several different one-reason-decision-making methods may be proposed.

2.1. Absolute mass method

The first approach is to use raw input data, the calculated or measured mass of products (P) and calculated or measured total mass of the product bin after production (T), as the predictor variables. The mass of the products is calculated using the data about the volume of the products (V), which may be taken from 3D modelling software, and the density of the products (w).

$$P = V \cdot w . \tag{3}$$

The mass of the product bin after production consists of the mass of the empty bin (B), the mass of products, and the mass of non-product powder (N):

$$N = T - B - P . \tag{4}$$

The non-product powder consists of the attached powder and the powder that may be used for recycling, so that mass of the powder for recycling (R) may be expressed as

$$R = N - A . \tag{5}$$

The simplest models based on the measured or calculated masses are based on the assumptions that the attached powder is proportional to the mass of products:

$$A = C_P \cdot P , \tag{6}$$

or to the mass of the mass of non-product powder

$$A = C_N \cdot N . \tag{7}$$

The heuristic approach here consists in translation of the common-sense statement CS1:“the more products you have, the more powder will be attached” to the sentence H1:“the higher mass of products, the higher mass of the attached powder is”. The last sentence may be modelled by the differential equation:

$$dA = C_P \cdot dP , \tag{8}$$

which has the solution $(A - A_0) = c_P(P - P_0)$. Since without products ($P_0 = 0$) there is no attached powder ($A_0 = 0$), the common-sense statement CS1 is modelled by the equation (6). The critical step here, which introduces the heuristic error, is actually heuristic translation of the sentence CS1 to the sentence H1. While it is the true that addition of another product to a production process always leads to increase of the amount of the attached powder, it is not always true that a production bin with higher mass of products will have higher amount of the attached powder in comparison with a production bin with smaller mass of products. In other words, various production bins with the same mass of products may have very different amounts of the attached powder. Hollow products, such as lightweight structures, contain substantially higher amounts of the attached powder than compact products.

A similar heuristics approach is applied to the derivation of the equation (7), where the common-sense statement CS2:“attached powder is a part of the non-product powder” is translated to the sentence H2:“the higher mass of the non-product powder, the higher mass of the attached powder is”. The logical connection between the sentences is less obvious, and it has to be assessed from the aspect of comparison of two product bins that have similar products mass, but different non-product powder masses: in such a case, the higher non-product powder mass indicates larger volume of space within and between the products, which leads to higher amounts of the waste powder.

The heuristic constants C_P and C_N should account for the influence of numerous remaining factors that affect the amount of the attached powder. The constants should be calculated using some exploitation data, and they may be applied for prediction of the attached powder if the other factors and exploitation conditions remain unchanged.

2.2. Relative mass method

The absolute mass method explicitly assumes proportionality between the masses of products and the attached powder, implying “scalability” of the model, which means that the model does not make differences in the prediction of the attached powder between small and large product volumes. In reality, the boundaries of the product bin and boundaries of the other products affect the amount of the powder that remains attached to a product. Therefore, it is possible to assume that the part of a product bin occupied by the products may be a valid predictor of the mass of the attached powder.

One way to estimate the part of a product bin occupied by the products is to calculate the ratio between the mass of the products and the total mass of the products and non-products, which is equal to the initial mass of powder (I)

$$I = P + N . \tag{9}$$

The ratio

$$p = P/I \tag{10}$$

represents the relative mass of the products (p), and the ratio

$$n = N/I \tag{11}$$

represents the relative mass of the products (n). Obviously, both p and n are positive and smaller than one, and it holds

$$p + n = 1 . \tag{12}$$

If, using the heuristic approach, the common-sense sentence CS3:”The more space occupied by products, the more attached powder will be” is translated to the sentence H3:”The higher relative mass of products, the higher relative mass of the attached powder”, then it may be modelled by the equation

$$a = c_p \cdot p , \tag{13}$$

where a stands for the relative mass of the attached powder,

$$a = A/I , \tag{14}$$

which serves as the estimator of the amount of the attached powder in this method.

By a similar heuristic approach the common-sense sentence CS4:”The more space occupied by non-product powder with the same space occupied by products, the more attached powder will be” is translated to the sentence H4:”The higher relative mass of products, the higher relative mass of the attached powder”, then it may be modelled by the equation

$$a = c_n \cdot n , \tag{15}$$

The heuristic constants c_p and c_n may be also determined from the exploitation data, and used for prediction in the similar exploitation conditions.

2.3. Product-to-non-product ratio method

The previous methods reveal that the common-sense cases may be made both for the assertion that the mass of products increases the mass of the attached powder and the assertion that mass of non-products increases the mass of the attached powder. On the other hand, considering one product bin, the increase of the mass of products means decrease of the mass of non-products and vice versa, so it is clear that one of the masses may hardly be the "smart" predictor that is looked for.

Another heuristic approach to the problem may be to characterize a production process (and a production bin) by the ratio between the mass of products and mass of non-product powder in the product bin (11):

$$\Pi = P / N = p / n . \tag{16}$$

The advantage of the approach is that it combines two input factors (masses of products and non-product powder) into a single predictor. The predictor is called *the product-to non-product ratio* (abbreviated as PNPr) in this paper. The PNPr predictor may be connected to the characteristic arrangements that arise in practice: hollow and lightweight structures are characterized by small values of PNPr, and compact packaging of products are characterized by high values of PNPr. The problem with PNPr is that in both of its extreme cases (low and high values of PNPr) the amount of the attached powder is high, so it is clear that a simple linear dependence between the attached powder and PNPr may not be established.

Using an analogy (that is also a heuristic technique) to the methods of absolute and relative masses, an estimator of the amount of the attached powder may be introduced

$$\alpha = A / P = a / p , \tag{17}$$

which may be related to the PNPr. The indicator α will be called in this paper *the attached-to-product ratio* (abbreviated as APr).

A heuristic approach applied in this method is more complex because the selected predictor is more complex. If the extreme cases of the lightweight structures and highly compact packaging are omitted, than the higher values of PNPr generally indicate products with smaller amounts of cavities and channels, therefore smaller amount of the powder attached to products of the same mass, which, in turn, means that the APr will decrease. Therefore, the previous reasoning may be expressed by the common-sense sentence CS5:"The products with less holes, cavities and channels have less attached powder", which may be, using heuristics, translated into the sentence H5:"Increase of the PNPr leads to the decrease of the APr". The sentence may be mathematically modelled in different ways, and here will be modelled by the equation:

$$\frac{d\alpha}{\alpha} = -n \cdot \frac{d\Pi}{\Pi} , \tag{18}$$

which means that the relative reduction of the attached powder is proportional to the relative increase of the attached powder. This model is selected because it was noted in the practice that, from the aspect of the amount of the attached powder, "more empty" production bins are more sensitive to addition of new products in comparison to "more full" production bins. The explanation is that a part of the powder that will be attached to a new product is in "more full" production bins already attached to other products. The solution of the equation (18) is

$$\alpha = \frac{\alpha_{PN}}{\Pi^n} , \tag{19}$$

where α_{PN} represents the APr of the production processes with product mass equal to the non-product powder mass ($P = N$), when $\Pi = 1$. As it was the case with the previous methods, the heuristic constants α_{PN} and n should be determined using the existing exploitation data.

3. DATA

The proposed heuristic approaches are tested by the estimation of the waste powder in the "3D Impulse" SLS facility of the Faculty of Mechanical and Civil Engineering in Kraljevo of University of Kragujevac. The facility uses EOS Formiga P100 machine, and the dataset under study were the results of 186 production processes performed for various purposes, predominantly for the rapid prototyping applications. The selected processes were performed with the PA2200 polyamide powder, using the process parameters recommended by the manufacturer of the machine.

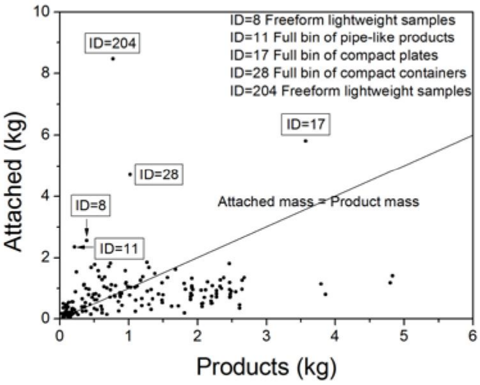

Figure 3: The masses of the products and the attached powder of the whole dataset

The mass of the powder that remains in the production chamber was calculated using the equation (2), and the obtained result was $C = 580$ g. The weight of the empty product bin was measured to be $B = (6450\pm5)$ g. The mass of the product bin after the production, the mass of the product bin after the removal of the parts with the attached powder, and the mass of the products were measured using an electronic stand with measurement error smaller than 5 g, and the obtained results were used for calculation of the non-product powder mass and the mass of the attached powder.

The mass of the attached powder was less than 2 kg in 181 of the production processes, and the relative mass of the attached powder was less than 30% in the 182 of the production processes. The masses of the products and the attached powder of the whole dataset are shown in the Figure 3, with the indicated data points that represent the production processes that had mass of the attached powder higher than 2 kg. In the inset are written explanations about the products manufactured in the five indicated processes. In two of the cases (production processes with ID numbers 8 and 204) the manufactured products were freeform lightweight structures that were manufactured for education and promotion purposes. In the three remaining indicated cases (production processes with ID numbers 11, 17 and 28), the manufactured products had the shapes that enabled compact arrangement of the products inside the product bin. An example of the compact arrangement of the manufactured products is given in the Figure 4, where the products were containers with dimensions suitable for stacking. Therefore, all of the indicated cases did not satisfy the assumptions of the heuristic models, and they were excluded from further consideration.

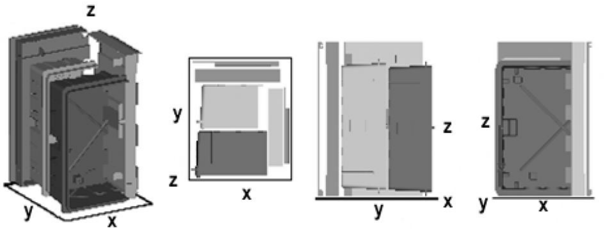

Figure 4: The arrangement of products in the product bin in a case of high mass of the attached powder due to the compact arrangement of products

The distribution of the mass of the attached powder versus the products and non-product powder masses for the remaining 181 production processes is shown in the contour diagram shown in the Figure 5.

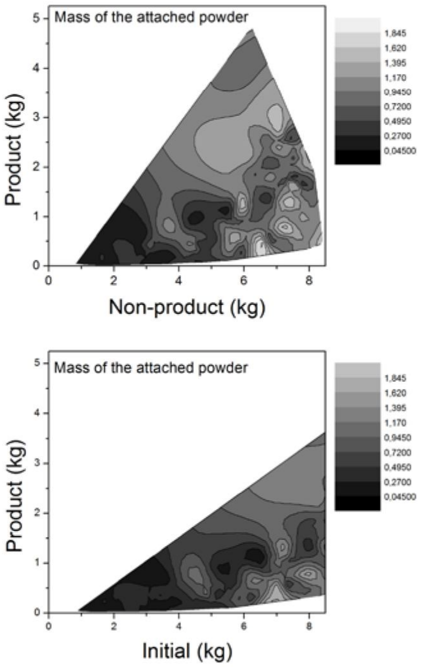

Figure 5: Contour plot of the masses of the attached powder vs. products and non-product powder masses (top diagram) and vs. products and initial powder masses (bottom diagram) of the dataset

Since the light colours in the used grey-scale scheme indicate higher amounts of the attached powder, the Figure 5 indicates that the lowest values of the attached powder mass occurs with small masses of products in small production volumes, while the largest masses of the attached powder are found in production processes with small masses of products and large masses of non-product powder.

4. RESULTS

The presented data were tested against the models presented in the section “Models” of the paper.

4.1. Absolute mass method

Figure 6 shows the exploitation data (points) presented according to the absolute mass methods, using the products mass, in the top diagram, and non-product powder mass, in the bottom diagram.

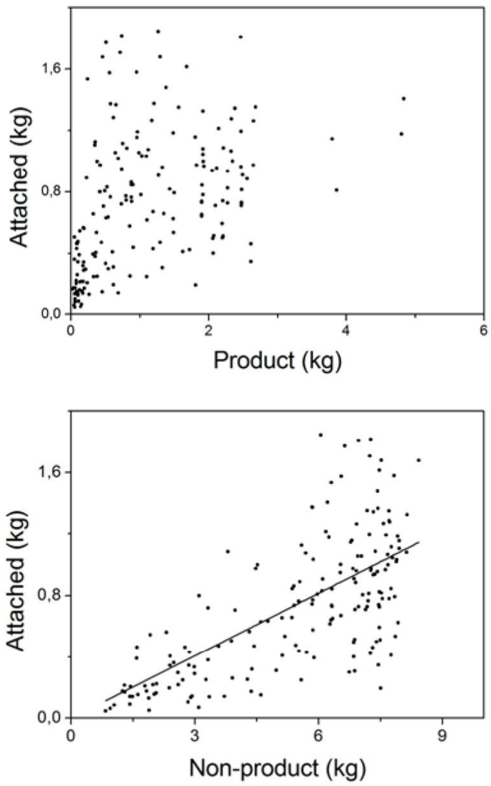

Figure 6: The results of the analysis of the exploitation data according to the absolute mass methods using the equation (6), at top, and (7), at bottom

Even the visual inspection of the diagrams in the Figure 6 suggests that products mass cannot be a predictor of the attached powder mass. The conclusion is confirmed by the calculation of the correlation coefficients between the considered quantities: the correlation coefficient between the products mass and the attached powder mass (r_{AP}) is not strong, $r_{AP} \approx +0.41$, indicating positive weak correlation between the products mass and the attached powder mass. That means that, while in many cases higher products mass appears along higher mass of the attached powder, there are still many cases when higher products mass appears along lower mass of the attached powder. Therefore, the translation of the CS1 to H1 is often incorrect, and calculation of the attached powder mass using the equation (6) is not justified.

On the other hand, the correlation coefficient between the non-product powder mass and the attached powder mass (r_{AN}) is substantially higher, $r_{AN} \approx +0.69$, indicating a stronger positive correlation between the products mass and the attached powder mass. That means that in a substantial number of cases higher non-product powder mass appears along higher mass of the attached powder, so there is evidential support for the CS2, and even, to some extent, to the translation of the CS2 to H2. By linear regression of the exploitation data to equation (7), the value $C_N = 0.135 \pm 0.005$ is obtained, and the coefficient of determination (COD) of the regression is 0.86.

4.2. Relative mass method

Figure 7 shows the exploitation data (points) presented according to the relative mass methods, using the relative products mass, in the top diagram, and the relative non-product powder mass, in the bottom diagram.

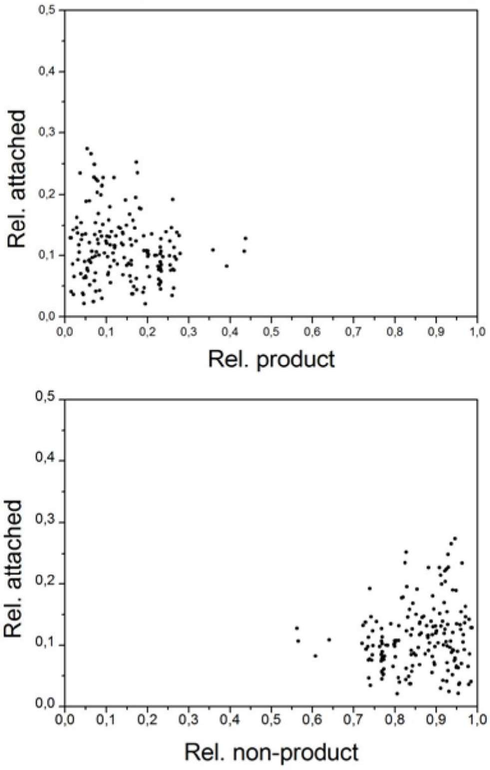

Figure 7: The results of the analysis of the exploitation data according to the absolute mass methods using the relative product mass (top), and relative non-product mass, (bottom)

The visual inspection of the diagrams in the Figure 7 clearly suggests that relative product mass, nor relative non-product mass, may be predictors of the relative attached powder mass. The conclusion is confirmed by the calculation of the correlation coefficients between the considered quantities.

The correlation coefficient between the relative product mass and the relative attached powder mass (r_{ap}) is negative and small, $r_{ap} \approx -0.18$, indicating a very weak negative correlation between the relative products mass and the relative attached powder mass. That means that higher relative product mass appears a bit more often with lower than with higher relative masses of the attached powder.

Similar holds also for the correlation between the relative non-product mass and the relative attached powder mass, since the correlation coefficient (r_{an}) is positive and small, $r_{an} \approx +0.18$, indicating a very weak positive correlation between the relative non-product mass and the relative attached powder mass. That means that higher relative non-product mass appears a bit more often with higher than with lower relative masses of the attached powder.

Therefore, the heuristic translations of both CS3 to H3 and CS4 to H4 are incorrect, so models proposed by the equations (13) and (14) are not valid.

4.3. Product-to-non-product ratio method

As it was explained in the section „Models", the connection between the PNPr and the amount of the attached powder is complex, and it is illustrated in the Figure 8, which shows exploitation data in the attached-to-the-non-product ratio vs. PNPr diagram (at top) and the relative product mass vs. PNPr diagram (at bottom).

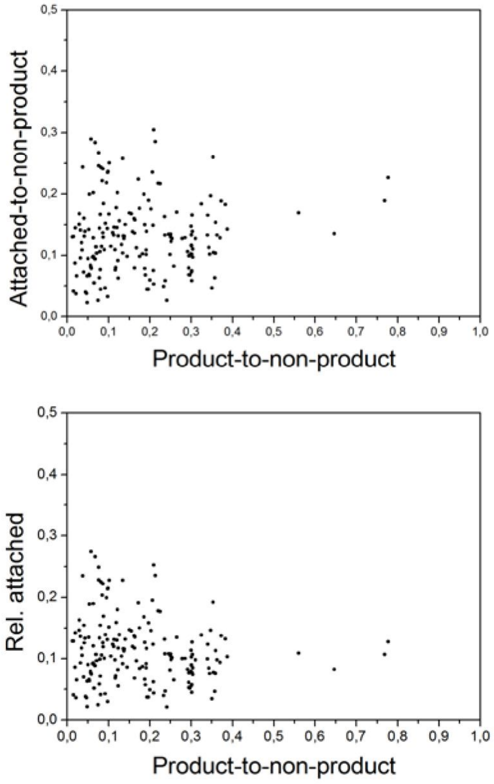

Figure 8: The exploitation data presented in the attached-to-the-non-product ratio vs. PNPr diagram (at top) and the relative product mass vs. PNPr diagram (at bottom)

The correlation between the attached-to-the-non-product ratio and PNPr is very weak and negative, with the coefficient of correlation being $r_{81} \approx -0.17$, and the correlation between the relative product mass and PNPr practically does not exist, with the coefficient of correlation being only $r_{82} \approx +0.06$.

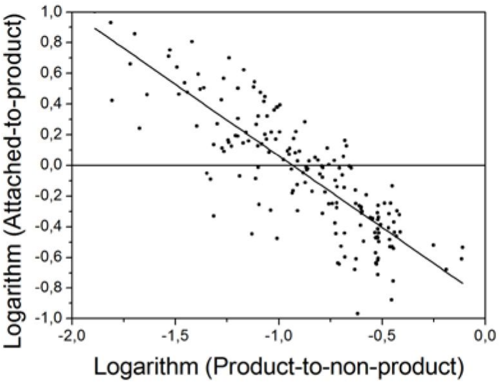

Figure 9: The exploitation data presented in the log-log diagram of APr vs. PNPr ratio

For the analysis of the product-to-non-product ratio method, the exploitation data are presented in the form of log-log diagram of APr vs. PNPr ratio in the Figure 9. The equation (19) may be re-written in the form

$$\log\alpha = \log\alpha_{PN} - n\log\Pi\,, \qquad (20)$$

which shows that the heuristic model based on the PNPr predicts a linear form of the APr versus PNPr log-log diagram.

The coefficient of correlation between the quantities shown in the Figure 9 is $r_9 = -0.86$, which shows strong negative correlation between the two quantities, further supporting the heuristic translation of the CS5 to H5 and model represented by the equation (19). If the data in the APr versus PNPr log-log diagram are fitted to the equation (20), the values $\log\alpha_{PN} = (-0.87 \pm 0.05)$ and $n = (0.93 \pm 0.05)$ are obtained, with the coefficient of determination (COD) close to 0.70. Therefore, the fitting procedure predicts that the $\alpha_{PN} \approx 0.135$.

5. ANALYSIS

The results presented in the section "Results" of the paper, and summarized in the Table 1, show that two of the proposed models may explain correlation between the mass of the attached powder and the masses of products and non-products. The first model is the absolute mass model that predicts the attached mass on the basis of the mass of non-product powder using the equation (7) with value $C_N = 0.135$. The second model is the PNPr model that predicts the APr on the basis of the PNPr using the equation (19) with values $\alpha_{PN} = 0.135$ and $n = 0.93$.

Table 1: Correlation between the predictors and estimators

Heuristic predictor	Attached powder estimator	Correlation coefficient
Product mass	Attached mass	+0.41
Non-product mass	Attached mass	+0.69
Rel. product mass	Rel. attached	-0.18
Rel. non-product	Rel. attached	+0.18
Product-to-non-product ratio	Rel. attached	-0.17
Product-to-non-product ratio	Attached-to-non-product	+0.06
Logarithm of product-to-non-product ratio	Logarithm of attached-to-non-product ratio	-0.84

It may be shown that the PNPr model reduces to the absolute mass model if it is assumed that $n \approx 1$. Actually, the identity $\alpha_{PN} = C_N$ holds because of the definitions of the two quantities

$$\alpha_{PN} = \left(\frac{A}{P}\right)_{(P=N)} = \frac{A(P=N)}{P(P=N)} = \frac{A(P=N)}{N(P=N)} = C_N\,, \qquad (21)$$

and if it is assumed the $n \approx 1$, then

$$\alpha = \frac{\alpha_{PN}}{\Pi^n} = \frac{\alpha_{PN}}{\Pi} \Rightarrow \frac{A}{P} = \frac{C_N}{\frac{P}{N}} \Rightarrow A = C_N \cdot N\,. \qquad (22)$$

With the aim to estimate the difference between the two methods, the amounts of the attached powder predicted by the two methods are calculated using the equation (7) and the equation

$$A = C_N P\left(\frac{N}{P}\right)^n\,, \qquad (23)$$

which may be derived from the equations (19) and (21). The obtained results are used to calculate two measures of the quality of prediction:

- the prediction of the amount of the attached powder in subsets of the initial dataset; the total amount of the attached powder is essentially the business relevant quantity, because it measures the overall quality of predictions;
- the average relative error of the prediction over the whole dataset, which measures the quality of individual predictions;

The results of the calculations are shown in the Table 2, and they show that the absolute mass method has better prediction of the overall waste.

Table 2: Relative error of prediction of the attached powder in the subsets of the dataset

Subset boundaries	Absolute mass method	PNPr method
1-30	18%	32%
31-60	19%	6%
61-90	2%	7%
91-120	6%	15%
121-150	4%	16%
151-181	10%	6%
Average	10%	14%

The average relative error of the individual predictions is 53% for of the absolute mass method, and 46% for the PNPr method.

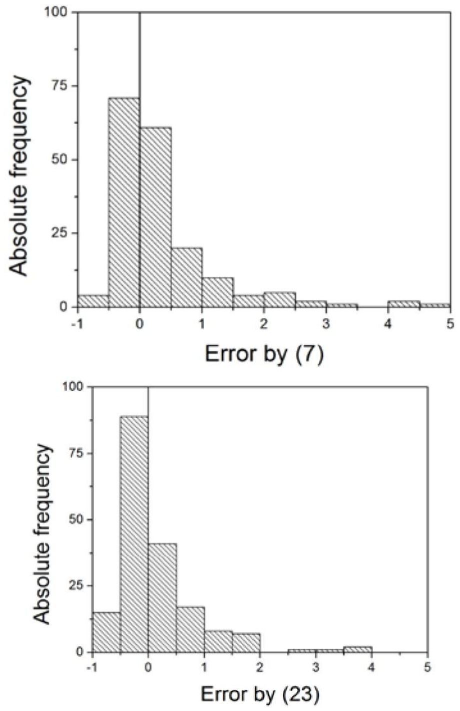

Figure 10: The distribution of errors of the absolute mass method (top) and the PNPr method (bottom)

The explanation for the apparent discrepancy in the estimation of the quality of the methods (although the PNPr method has better predictions for individual production processes, the absolute mass method has better overall prediction) is that the PNPr method mainly underestimates the amount of the attached powder, while the absolute mass method has better balance between the overestimation and underestimation of the estimated quantity. The distribution of errors of the absolute mass method and the PNPr method are presented in the Figure 10, which illustrates the much larger asymmetry of the predictions of the PNPr method in the relative error range (-0.5, 0.5), where the majority of the errors belong.

6. CONCLUSION

The paper presented a study of possibilities to develop simple methods for estimation of the amount of powder that remains attached to products after manufacturing by SLS technology. The study analysed the data about 181 manufacturing process obtained during exploitation of the EOS Formiga P100 machine using the PA2200 powder in “3D Impulse” laboratory of the Faculty of Mechanical and Civil Engineering in Kraljevo.

Three groups of methods for prediction of the mass of the attached powder were developed. Using a heuristic approach “one characteristic of the production process may be sufficient to roughly estimate the mass of the attached powder”, each of the methods uses just one predictor quantity that is calculated on the basis of masses of products and the non-product powder in a production process. On the basis of a heuristic reasoning, which used come common-sense statements about the selected predictors, for each of the methods were developed mathematical models for prediction of the mass of the attached powder.

The models were tested against the exploitation data, and the results show that only two methods:

- an absolute mass method model, based on the proportionality of the non-product powder mass, as predictor, and the mass of the attached powder, as estimator, expressed by equation (7), and
- a PNPr method model, based on ratio between the masses of the products and non-product powder, as predictor, and the ratio between the attached powder and the product mass, as the estimator, expressed by the equation (19),

show significant correlation between respective predictor and estimator. The absolute mass method is simpler and has better prediction of the overall mass of the attached powder, but the PNPr has slightly better predictions of the mass of the attached powder of the individual production processes.

Due to the large errors of estimations of both methods, the conclusion of the research is that the heuristic approach to the calculation of the waste powder in SLS processes may be used in commercial purposes for long-term estimations of the waste powder, using the method described by the equations (1), (2) and (7). In the case of the PA2200 powder and EOS Formiga P100 machine, the long-term estimation of the waste powder of a production process is obtained by summing the fixed part of the waste powder, with mass 580 g, with the variable part of the waste powder, which is, with long-term accuracy of the order of 10%, estimated as 13.5% of the mass of the non-product powder of a production process.

Further research will be oriented toward extension of the analysis to wider set of input quantities, such as the surface of the products and the volumes occupied by products and non-product powder.

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