3D Model Optimization for Hybrid Layer Printing

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Abstract—**In today modern manufacturing the use of virtual models in prototype development has been increased. Hybrid Layered Manufacturing (HLM) - is a new way to create prototypes of virtual objects. 3d modelling programs are not optimized enough for creating objects by layers. One of the problem is a flat surface printing, because during that process beads are printed which have a parabolic shape. That shape is unsuitable for creating a flat surface. The paper proposes a method that will allow to print layers with flat surface. For this purpose an analysis and calculations were made with the help of a written algorithm, which was used in virtual environment testing it on 3d models.**

Index Terms—**Printing, design optimization, shape, layered manufacturing.**

I. INTRODUCTION

In todays modern manufacturing the use of virtual models in prototype development has been increased. There is much software being used for creating 3d objects, such as: AutoCAD, 3ds Max, SolidWorks and others. Hybrid Layered Manufacturing (HLM) [1] is a Rapid Manufacturing (RM) process that builds metallic object prototypes from 3d virtual objects, through a combination of additive and subtractive processes. Hybrid manufacturing consists of rapid printing that uses Gas Metal Arc Welding (GMAW) technology [2] for layered deposition and computer numerical control (CNC) technology [3]. Rapid printing is called additive process because it works by adding layers on top of each other to create the whole object. Nowadays there are two main methods of rapid printing: direct metal laser sintering (DMLS) [4] and GMAW. The printing speed depends on how accurate we want to create objects surface. The accuracy in HML additive process is not essential compared to its speed. The desired accurately calculated surface is created with subtractive process by using CNC milling. There are two main modelling methods: SOLID and MESH. The most popular nowadays is SOLID modelling method [5]. The virtual models are usually created in SolidWorks, AutoCAD inventor and other CAD software. „SOLID" models are used for rapid printing because of their accurately calculated surfaces. MESH modelling method [6] uses coordinates system to represent a virtual object in space. To combine these two modelling methods we need to create a new software extension, written in Maxscript code. „SOLID" model is described by formulas to make its surface very accurate, however this method is used only for CNC. HLM system uses written algorithm to convert model from „SOLID" to „MESH" model for rapid printing. After rapid printing the algorithm converts it back to „SOLID" model which is used for CNC calculation and milling to ensure creation of accurate surface. Advantage of this system is the speed of printing which is faster compared to ordinary rapid printing system, because the accuracy is not required during printing. Another advantage is the usage of CNC milling. This process is used on a model that is already prepared for it, therefor CNC is using minimum power for milling a small amount of surface to make it accurately smooth. The system also has a slight disadvantage which is the complexity of the algorithm. Not only does it has to count all the accurate printing and milling but also controlling both processes at the same time. This makes it work a little bit slower but still being faster than a regular printing method. Not only does this system save printing time but also makes tools more durable.

II. PRINTING METHODS: DMLS AND GMAW

Printing systems that only use one additive process (layer printing) are mostly used for making plastic, rubber, other polymer or metal prototypes. There are two popular methods.

The most popular method is selective laser sintering method (SLS) or Direct metal laser sintering (DMLS) [4], which is widely used nowadays. It has many advantages. By using this method small accurate metal prototypes can be created. The printing speed is faster than other additive printing methods, and it is fully automatic. However the research has shown that printing laser is using a lot of energy and its efficiency is only 2–5 %.

The second method is GMAW – Gas Metal Arc Welding, which is an old method, but is being automated only recently. This method is much faster than SLS method because the created prototype has a rough, inaccurate

surface (Fig. 1). Compared to each other SLS printing speed is 2-10 g/min and GMAW printing is almost 800 g/min. This method is unsuitable for creating small objects, because the printing process takes place on a metal sheet. However this method is suitable for creating metal injection molds.

GMAW combined with CNC milling method forms a system called HLM [1]. By using computer calculations you can make this kind of metal welding into an automated process that can print accurate surfaces represented by virtual model.
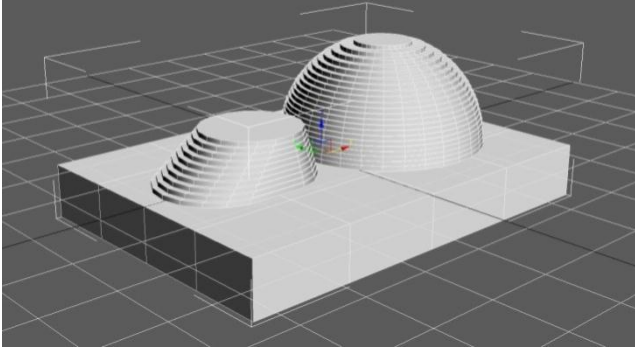

Fig. 1. Virtual prototype model prepared for GMAW printing.

This method is already being used in many different product manufacturing companies. This method is used to create metal injection molds, however these companies experience some disadvantages of this method. One of the main disadvantages is creating an accurately flat layer surface, to make it suitable for other layers. Nowadays HML cannot create a flat surface. This problem is solved by milling a surface to make it flat. This kind of process takes a lot of time and needs to be improved. In our paper we present a method for printing flat surface. During the printing a bead (Fig. 2) is created with a parabolic shape, therefore it's difficult to make a flat surface from these kind of beads. Printing bead can be written by formulas which make it possible to improve printing.
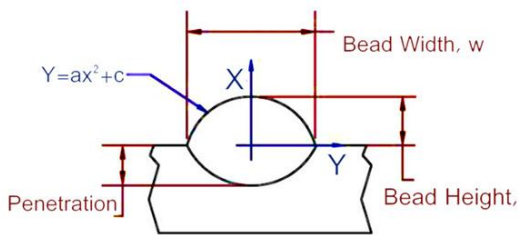

Fig. 2. Bead cross-section model [1].

This shape can be written by this formula [1]

$$y = ax^2 + c. \tag{1}$$

It is assumed to be symmetrical parabola. This algebraic form in terms of (a, c) can be written in geometric form in terms of (h, w), as follows

$$a = -\frac{4h}{w^2}; c = h, \tag{2}$$

where h – height of a bead, and w-width of a bead. Therefore the geometric form of the parabola is

$$y = h \left[1 - \left(\frac{2}{w} x \right)^2 \right]. \tag{3}$$

Also, the track cross-sectional area (Fig. 2) is given by

$$A = \frac{2}{3} wh. \tag{4}$$

For area calculation we are using process parameters such as the amount of metal material per time unit, and also speed during printing [1]

$$A = \frac{2}{3} wh = \frac{\pi v_w r_w^2}{4 v_t}, \tag{5}$$

where v_w- bead printing speed, r- wire cross-section radius, that is used for calculating wire cross-section area, and v_t- wire pushing speed, determining the amount of wire used for printing. v_w and v_t parameters depend on each other because when the wire pushing speed is stable the printing speed also has to be stable, otherwise size of the bead will change. To ensure a stable process additional code is used.
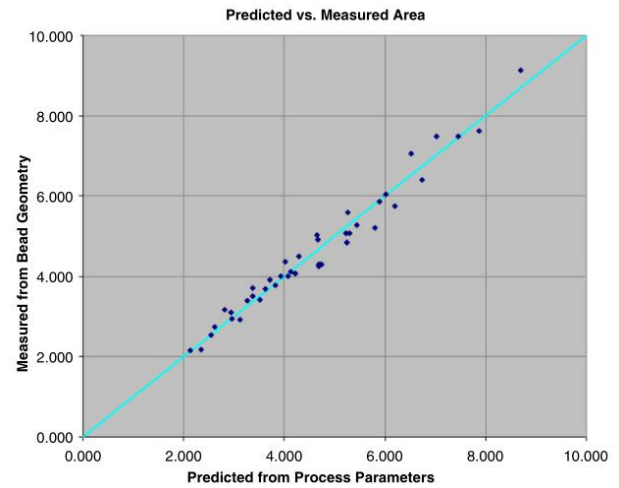

Fig. 3. The correlation between the calculated and experimentally derived parameters [1].

The form of a bead depends on various forces such as gravitational pull, surface tension, electromagnetic force. Because of these forces the shape of a bead cannot be the same as calculated. Experiments have shown (Fig. 3) that predicted and measured parameters correlation is close to one [1] which means that they are similar enough to use calculated results for experiments. One of the problems is printing a second layer. The first layer needs to be flat in order to print a second layer. It is difficult to create a flat surface because of the parabolic bead shape. Nowadays this problem is fixed by milling the layer until it is flat, however this method takes a lot of time and energy

III. ALGORITHM FOR OPTIMIZING GMAW METHOD

We are proposing a method for printing layers with flat surfaces. An algorithm was written for this reason in Maxscript language. It regulates the printing process and virtual objects of different types for different processes. The objects are being printed by using a MESH type virtual object (Fig. 1). In order to get a flat surface we need to

calculate a distance between bead trajectories. The distance needs to be small enough to make beads collide with each other to create a small amount of extra material for filling the gap between beads (Fig. 4).

Modern three-dimensional printing equipment requires additional software packages, apart from those used in modelling. Such programs have their own structure, and some even in their own language. CNC milling equipment has its own language, whose structure is similar to the simulation code for SolidWorks software. While it is used for CNC calculations, it can as well be used for using those calculations to print beads by applying some changes in the code.
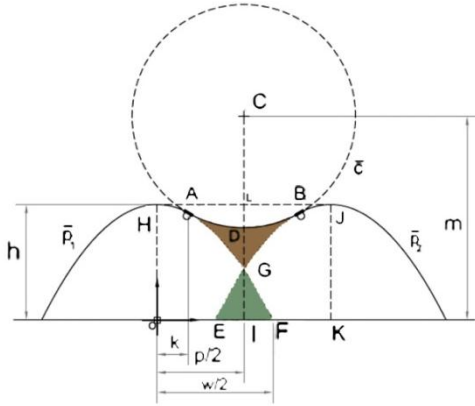

Fig. 4. Collision of two metal beads.

The changes made in the algorithm are relatively small, dividing the whole program into two parts. In the first part of algorithm we must establish main parameters, from which the height of a bead depends on. After that the whole MESH model is divided into layer of that calculated height. Furthermore the algorithm is capable to divide the layer into trajectories (spiral) (Fig. 5).
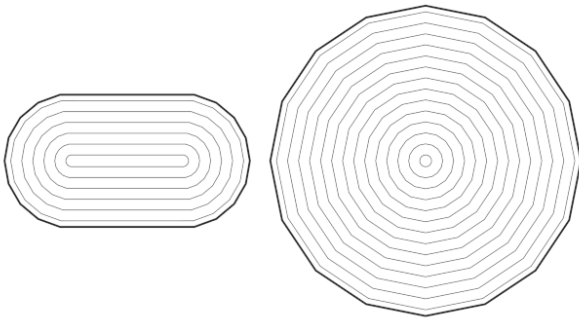

Fig. 5. Calculated bead trajectories.

This way printed layers are almost perfectly flat. If we look at a picture (Fig. 5) we can see that a layer has corners, that shows it being model in coordinate system or in other words MESH time modelling. The algorithm changed the topology of the model from SOLID to MESH to accelerate the speed of printing.

Also those trajectories are calculated very accurately for printing a flat surface. This is the most important part in the algorithm, because the whole printing process depends on layer surface. We can calculate the distance between bead trajectories by:

$$\overline{p_1} : y = h\left[1 - \left(\frac{2}{w}x\right)^2\right], \qquad (6)$$

$$\overline{p_2} : y = h\left[1 - \left(\frac{2}{w}(x - p)\right)^2\right], \qquad (7)$$

$$\overline{c} : \left(x - \frac{p}{2}\right)^2 + (y - m)^2 = R^2, \qquad (8)$$

where $\overline{p_1}$ and $\overline{p_2}$ are expresions of the consecutive parabolas, $\overline{c}$ –is a fillet, p–the distance between trajectories, R – radius of a circle which represent $\overline{c}$ fillet and m – the height between a ground and a centre of given circle.

As the overlapping volume fillets the two parabolas, circle $\overline{c}$ are tangent to the parabolas $\overline{p_1}$ and $\overline{p_2}$ at points A and B respectively. Thus, the slopes of $\overline{p_1}$ and $\overline{c}$ at A are equal. Let k be the x–coordinate of the point A. The slopes of $\overline{p_1}$ at A is given by

$$\left(\frac{dy}{dx}\right)_A = -\frac{8h}{w^2}x\bigg|_A = -\frac{8hk}{w^2}, \qquad (9)$$

where k –x - coordinate projection of a parabolas slope, h - height of a bead, w − width of a bead.

The slope of the circle, $\overline{c}$ is given by

$$\left(x - \frac{p}{2}\right) + \frac{(y-m)dy}{dx} = 0. \qquad (10)$$

By combining (9) and (10) formulas we get

$$\left(x - \frac{p}{2}\right) + (y - m)\left(-\frac{8hk}{w^2}\right) = 0. \qquad (11)$$

As the point A lies on $\overline{p_1}$, its coordinates are given by

$$A = \left(k, h - \frac{4hk^2}{w^2}\right). \qquad (12)$$

Substituting this value of A in Eq. (11)

$$\left(k - \frac{p}{2}\right) + \left(h - \frac{4hk^2}{w^2} - m\right)\left(-\frac{8hk}{w^2}\right) = 0. \qquad (13)$$

As the point A also lies on the circle $\overline{c}$, substituting the coordinates of A in the Eq. (8) and rearranging the terms, one can obtain m as

$$m = h - \frac{4hk^2}{w^2} \mp \sqrt{R^2 - \left(k - \frac{p}{2}\right)^2}. \qquad (14)$$

Now we can see a dependency between m and p. By getting a flat surface layer we need a fillet $\overline{c}$ to be as straight as possible. This fillet shoul be represented by a circle with a very large radius R. To make these kind of calculations we need to insert process parameters such as v_w - bead printing speed, r - wire cross-section radius and v_t − wire pushing speed. Correlation (Fig. 3)., suggests that the theoretical and practical values match, so the theoretical track dimensions (h and w) can be used (14) formula. By inserting R value into this equation, which is approaching infinity, can be used for finding p, which will show us the required distance between bead trajectories, where the smooth surface is formed.

However, as mentioned above, due to gravity, surface tension, electromagnetic force, the track will never be in the form of the theoretical. Surface layer can be created close to the theoretical.

The algorithm (Fig. 6) converts 3d models created in the SolidWorks environment to MESH type models, which can be opened by other software such as 3ds Max. The algorithm automatically prepares a model for printing (Fig. 1)and also defines the trajectory of the print tracks (Fig. 5). Prepared models are then transferred to the printing machine.

```
convertTo $ PolyMeshObject
$.name = "voxell"
modPanel.addModToSelection (Vol__Select ())
ui:on
$.modifiers[#Vol__Select].level = 2
$.modifiers[#Vol__Select].type = 1
$.modifiers[#Vol__Select].invert = on
$.modifiers[#Vol__Select].Volume = 3
$.modifiers[#Vol__Select].node = $model2voxel
modPanel.addModToSelection (DeleteMesh ())
ui:on
modPanel.addModToSelection (Shell ()) ui:on
$.modifiers[#Shell].outerAmount = 0.95
```
Fig. 6. Part of the software code which is used for printing layers.

Experimental studies were conducted in a virtual environment. For this reason 3ds Max software was used. According to the process parameters v_w - bead printing speed, r - wire cross-section radius and v_t – wire pushing speed, vizualisation of the colided beads was calculated. Different parameters were used for this experiment in virtual environment (Table I) and in all cases the surface of the layer is smooth but is never absolutely flat (Fig. 7).

TABLE I. PRINTING PROCESS PARAMETERS.

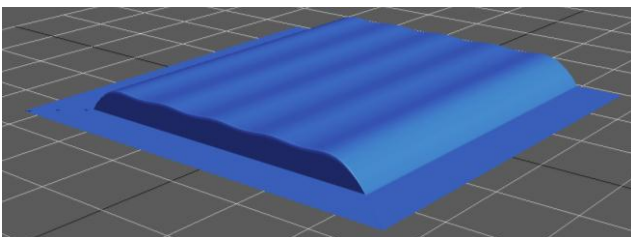| No.	v_t (mm/s)	v_w (mm/s)	p (mm)
1	6	1	1,8
2	5,5	0,9	1,71
3	5,2	0,8	1,65
4	5	0,8	1,572
5	4,8	0,7	1,52
6	4,5	0,7	1,5

Fig. 7. 3D visualization of a layer calculated by the algorithm.

IV. CONCLUSIONS

After analysis and calculation to get a flat surface layer an algorithm was written. A 3d prototype model was created, which was used for experimental testing. Experiments have shown that it is possible to get a close to flat surface layers by using these process parameters: $v_t = 5,5; v_w = 0,9$. By using them we could calculate a distance between trajectories $p = 1,71$. This distance is the most optimal in order to obtain a smooth surface. The algorithm can accurately calculate the trajectories and helps to form a flat surface. Due to gravity, surface tension force and electromagnetic force, the surface is not completely smooth, but close to being flat. To obtain a completely smooth surface, the CNC milling can be used to remove a small portion of the layer. Written algorithm speeds up the printing time and prolongs equipment life.

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