Magnetohydrodynamic pump application in complex form aluminum parts additive manufacturing

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Abstract. A review of Drop-on-Demand additive manufacturing methods was held. A method of complex forms aluminum parts production through the application of magnetohydrodynamic pump and 5 axis manufacturing process was proposed. 5 axis 3D printer assembly was shown. A few operation modes were proposed for such 3D printer and a method for fill lines paths calculating, needed for G-code automatic generation, was established. The algorithm for calculating printhead moving trajectory in the cylindrical parts manufacture mode was shown.

Currently, the main additive manufacturing (AM) technology, used for functional metal parts production is the selective laser melting (SLM). This process use high purity and spherical powder material, which sinter in a thin layer predetermined areas by laser beam. Although high speed of sintering, this solution has some drawbacks: complicated adjustment and preproduction, high requirements to powder material, low speed auxiliary operations (leveling powder layer). These peculiarities limit the AM technologies distribution for final parts production.

In this regard, the metal melt discrete feeding approach (Drop-on-demand method) for 3D printing parts (fig. 1, a) have begun to explore in the world. This approach doesn't require expensive printing process preparation (sifting, powder cleaning), doesn't impose special requirements to material, hasn't low-speed auxiliary operations and, hence, greatly simplifies final products manufacturing, thereby expanding application field of the method for mass production.

Drop-on-demand methods research caused interest of industry in 90 's, when this approach started to be used for microelectronic components manufacture [1]. Authors D.J. Hayes and D.B. Wallace used of bubble pair extrusion principle. Metallic ink drops extrude from the nozzle under it influence. Another molten metal droplets generation principle is described by the authors in sources [2, 3]. They suggest to use gas pulsating pressure, which is formed by high frequency solenoid valve. Investigation of Lead-Tin alloys drops carried out the scholars Tseng [4], Jiang [5] and Chao [6].

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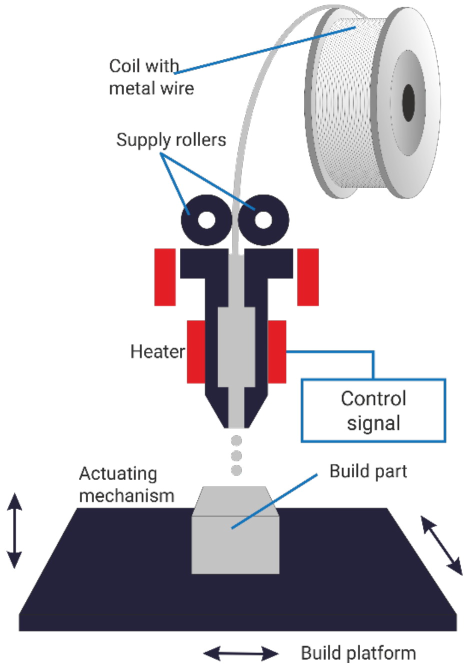
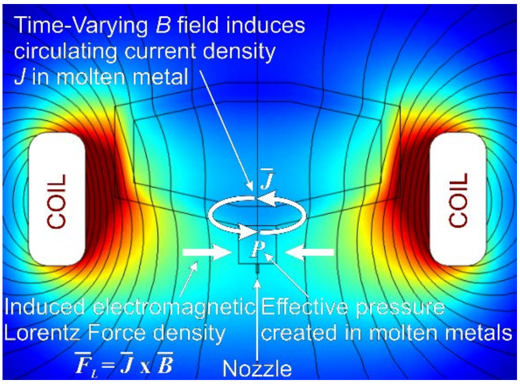


(a)



b)

Fig. 1. AM technologies for metallic alloys printing: a) selective laser melting b) metal melt discrete feeding.

Further Drop-on-demand printing development engaged the authors Q. Liu, M. Orme, R. Smith, who use the precision drip manufacturing (PDM) term [7]. The essence of the method lies in the ability to generate a stream of molten aluminum alloy droplets using piezoelectric actuator. In the present study, the aluminum alloys feeding by Magnetohydrodynamic (MHD) pump hold the authors S. Thirumangalath, S. Vader, Z. Vader [8].

The most prospective AM technology for aluminum parts producing is submitted on method with MHD pump (fig. 1, b). It is concluded on alternating magnetic field $\overline{B}$ impact to aluminum melt generated by the inductance coil. Coil current increase current density $\overline{J}$ in the melt, which in turn cause the Lorentz force $\overline{F_L}$, that increases pressure P and extrudes melt from the nozzle. Pulses leads to droplet formation in the nozzle output. Such approach has several advantages: contact less method of impact on metal melt, high speed drops generation and relatively high precision printing is provided.

Further study of discrete printing has opened up many new problems. One of them is related to printing complex form parts, because overhanging fragments printing of such details causes great difficulties. Due to printing features, easy remove supports using, such as water-soluble polyvinyl alcohol (PVA) support used in FDM technology is not possible, because of necessity to use support material with similar melting temperature to the basic material.

However, if use not standard 3-axis, but 5-axis printing, it can make possible to produce overhanging elements without support structures.

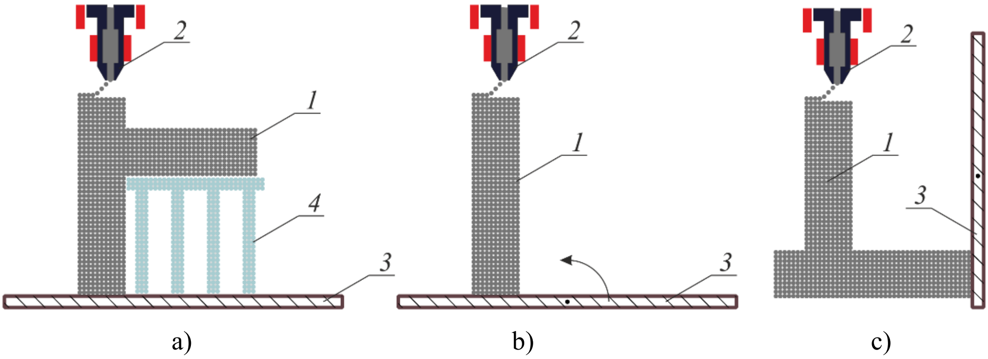


Fig. 2. Part manufacturing on 3D printer.
a - according to the traditional technology with support structures, on the proposed technology b - after vertical part printing, table turns; c - horizontal parts printing after the turn.

Figure 2 shows building process of overhang part *1* implemented by print head *2* on the platform *3* with ordinary 3-axis technology using support structures *4*. The same part building process with 5-axis technology using is shown in figure 2 b), c). Here vertical components (fig. 2 b) are printed at first, then the table *3* turns and prints overhang element *1* (fig. 2c) [9].

Therefore, seems promising use of multi axis 3D printing (fig. 3) with printing part turn and tilt ability. This design provides working surface *1* placement on the turntable *2*, which fixed on mobile platform *3*, with the possibility of longitudinal and transverse movements by sleds *7* and *8* and vertical travel by guides *6* and 90° tilt relative to the printhead *4* through shaft *5*.

The vast number of existing 3D printers and other CNC routers are managed using the instructions written in G-code. For conventional CNC machines, the operator manually, or automated, using special software, prepares the necessary file with the extension *.gcode. For 3D printers this file prepares exclusively automatically because of large number of statements in it. Further, file *.gcode is transferred to device, where the printing occurs[10].

Capable software to automatically prepare file for 5 axis 3D printer are not currently developed [11]. And due to size of file (usually, consisting of thousands and sometimes millions of code lines), manual G-Code files preparation is not possible.

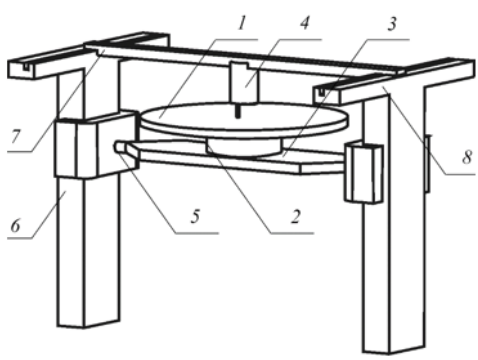


Fig. 3. 5 axis 3D printer layout.

Thus, for 5 axis 3D printer G-Code file automatically generation requires its own editor, which will provide to design 3D model and then generate 3D printer control program taking into account features of multi-axis special modes printing. Such modes include:

1. smoothing layers print on inclined surfaces to improve quality (reduction surface roughness) of final part.
2. detail tilt with subsequent additional elements printing on sides (fig. 4);
3. rotation parts printing;

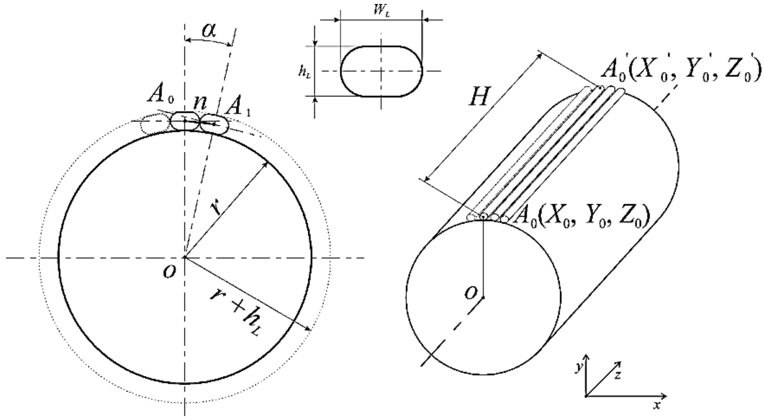


Fig. 4. Rotation parts printing scheme

To implement above described 3D printer operation modes is necessary to calculate start and final printhead path coordinates in each layer. Build mode with multidirectional layers printing on cylindrical part we consider by cylinder with radius *r*. Figure 4 shows fill lines with length *(H)* beginning at A_0 point with coordinates $\left(X_0, Y_0, Z_0\right)$ and terminating at A_0' point with coordinates $\left(X_0', Y_0', Z_0'\right)$. A series of droplets generated by 3D printer print head while moving can be visualized in a form of thread. Thread form is a circle in section, but after touching with a part it becomes close in shape to a rectangle with rounded corners with width W_L and height h_L, equal layer print height. Starting point is a cylinder base circle center at point *O*.

Calculate number of fill lines in layer is made in equation (1):

$$n' = \frac{2 \cdot \pi \cdot (r + h_L)}{W_L}. \tag{1}$$

Then, estimated number of lines n' is rounded to an integer n in smaller side $n = \lfloor n' \rfloor$, and computes the resulting width of each line by (2). After fill lines angular step A_p calculated (3):

$$W = W_L \cdot \frac{n'}{n}. \tag{2}$$

$$A_p = \frac{2 \cdot \pi}{n}. \tag{3}$$

Start points coordinates A_i calculation of each fill line i, where $i \in [1..n]$ compute by (4):

$$\begin{aligned} X_i &= r \cdot \cos(A_p \cdot i), \\ Y_i &= r \cdot \sin(A_p \cdot i), \\ Z_i &= 0. \end{aligned} \tag{4}$$

Final points A_i' coordinates (X_i', Y_i', Z_i') calculation of each line i is carried out by the same equations (4), but $Z_i' = H$. Points A_i and A_i' added in array when calculating. At the end close path formed by adding the first point to the end of the array.

For ability to print non straight lines (spiral lines by cylinder generatrix), lines start points (A_i) are defined in the same way as in previous case, and final point (A_i') - by the following equations (5):

$$X_i' = r \cdot \cos\left(A_p + \frac{180 \cdot H \cdot \tan(\beta)}{\pi \cdot r}\right),$$
$$Y_i' = r \cdot \sin\left(A_p + \frac{180 \cdot H \cdot \tan(\beta)}{\pi \cdot r}\right), \quad (5)$$
$$Z_i' = H,$$

where β is a tilt angle to cylinder generatrix of the line A_iA_i', which passes through a point A_i in plane drawn through generatrix and tangent to cylinder side surface.

Definition of part layers number L compute by dividing required cylinder radius R on layer height h_L:

$$L = \frac{R}{h_L}. \quad (6)$$

Algorithm for calculating start A_i and final A_i' filling lines points coordinates is shown in figure 5. Input data required for the calculations, is entered in block *1*. Blocks *2* and *5* calculate fill line parameters by expressions (1), (2), (3) and (6). Cycle which starts with block *4*, creates filling layers. Lines with coordinates computed by expressions (4) and (5) are created in the cycle shown in blocks *7-10*. Block *14* creates a control program (G-code).

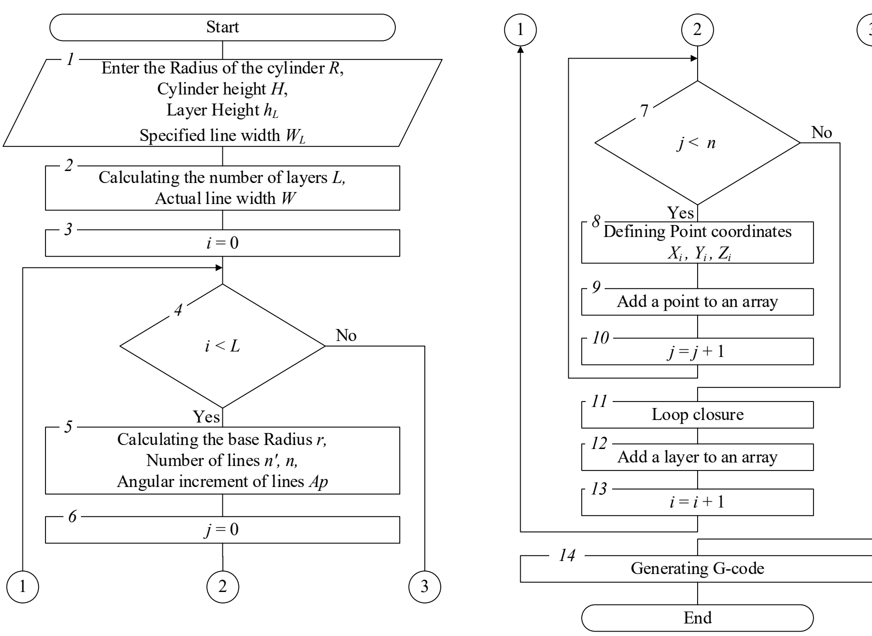


Fig. 5. Algorithm for calculating start and end line points coordinates

The most prospective direction was defined at overview of Drop-on-Demand printing methods. It based on MHD pump use for droplet generation in aluminum parts additive manufacturing. Method improvement for production complex form parts without support structures is suggested. It is concluded in use of 5 axis printing with part tilt and rotation ability during the printing process. 5 axis 3D printer assembly was shown. The proposed decision is intended to print the leveling layers on inclined surfaces, for printing additional elements on the lateral surfaces and printing rotation parts. Fill lines paths for programming G-code generation was calculated for implementation proposed operation modes. Algorithm of start and end filling lines points coordinates calculation was determined.

Further work aimed at improving fill algorithm for new printing modes, study aluminum alloys print parameters using MHD pump.

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