ORIGINAL ARTICLE

# Enhanced Roll Powder Sintering Additive Manufacturing Technology

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**Abstract:** The article presents and evaluates three methods for upgrading Roll Powder Sintering (RPS) additive manufacturing technology (AMT). All innovative methods are designed so as to improve the properties of the objects shaped with RPS. Moreover, newly designed techniques produce the results of higher quality and are faster than previously used techniques. Method 1, the new ribbon perforation algorithm provides more space for the powder in the support stripe and lower laser beam frequency modulation. It not only reduces the amount of the support stripe used in a component roll, but also reduces its compression rate by about 2 times. The method 2 proposed technique improves the quality and increases the velocity of filling a support ribbon with powder by 1.6 times. The method 3 helps to increase the amount of powder in a component roll by increasing the consolidation and the fluidity of powder. The results indicate that the new methods can be integrated in a perforation and powder filling systems for enhanced RPS machines.

**Keywords:** High performance 3D printing; high precision 3D printing; inexpensive 3D printing

## Introduction

As the demand for AMT products has been steadily increasing for thirty years, today we see the rise of many innovative technologies, such as laser metal fusion, laser metal deposition, selective laser sintering, wire arc additive manufacturing, thermal spraying, electron beam melting, etc.

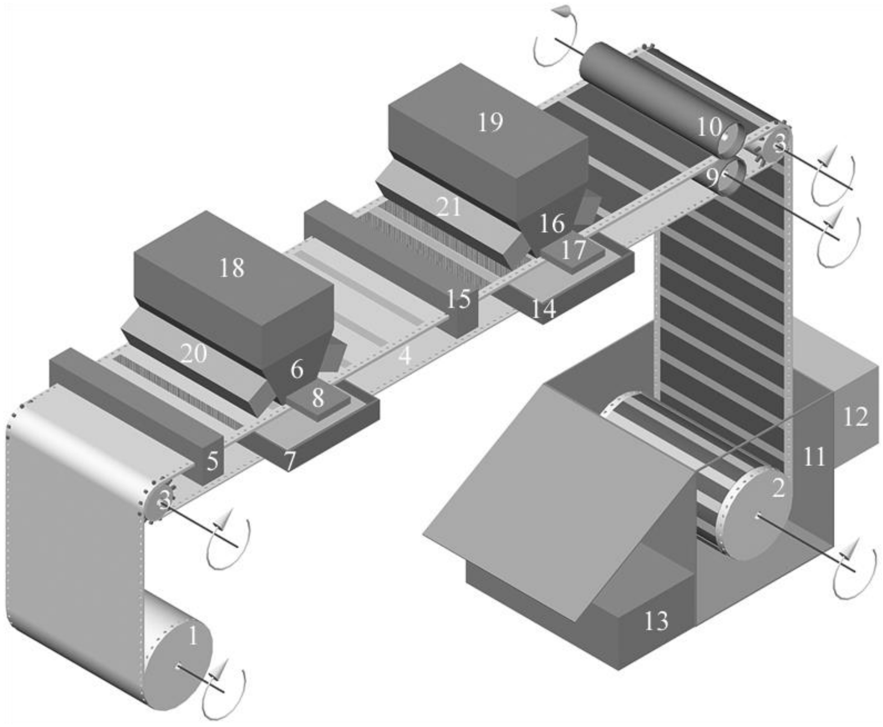
According to [1–3], RPS has significant advantages over the dominant AMT, currently available on the market, since it increases performance hundredfold, more predictable mechanical properties and smoother surfaces of made details, i.e. without “stair stepping effect” because of the sintering process, and so on.

At the same time, the continued progress of AMT [4–7] requires not only reducing costs and accelerating performances but improving the quality and the reliability [8, 9]. AMT, often referred to as 3D printing, is rapidly gaining popularity as it offers a number of strong benefits. These include material and productivity advantages as well as better design and production flexibility, what paves the way for mass customization. RPS [10, 11] is well positioned to support the use of additive manufacturing in making plastic, ceramic and metal objects.

The European space industry uses AMT to significantly reduce the weight and the production time of unique parts for “Ariane 5” [12, 13]. AMT can be applied to increase the strength-to-weight coefficient, which is of paramount importance in the aerospace industry, and to shorten the product development cycle, and, consequently, its cost [14]. The mechanical properties of a finished product are highly dependent upon the production process and the properties of the powder used in the process.

Successful industrial application of the RPS, as well as of the other AMTs, depends largely on fundamental engineering support together with appropriate means of verification [15].

For example, the purity of made parts requires decreasing the amount of the support ribbon. Another example is the density and the homogeneity of the powder inside the support ribbon. Therefore, it is necessary to improve the “flow ability” particles of the powder from a bunker to a perforated ribbon. Then, one




1) Ribbon roll
2) Component roll
3) Extending rollers
4) Supporting ribbon
5) First perforation system
6) Object powder upper bunker
7) Object powder lower bunker
8) Excess powder remover
9) Lower compression roller
10) Upper compression roller
11) Object sintering camera
12) Sintering control system
13) Object refinement system
14) Support powder lower bunker
15) Second perforation system
16) Support powder upper bunker
17) Excess support powder remover
18) Object powder atmosphere control system
19) Support powder atmosphere control system
20) Object powder ultrasound vibration system
21) Support powder ultrasound vibration system

Figure 1. Simplified general view of the modified RPS machine.

needs to increase powder packing density, i.e. to eliminate particle internal cavities and fractures. These properties are very significant not only for aerospace but for micro industry[16–20]. RPS is suitable for manufacturing micro components with submicron accuracy and a layer about 1 µm or less thick due to the perforation of an easily melting tape by a non-powerful laser system similar to “Blu-ray”. This technique allows to achieve submicron precision for micro electro mechanical systems [21–25], where precision is one of key requirements.

The aim of this work is to create enhanced RPS products based on new methods of support ribbon perforation and its filling with the powder of produced parts.

## Materials and Methods

### Conformal Transformation of 3D Coordinates to 2D

One of basic features of RPS is slicing the 3D object into a 2D stripe before printing it with the spiral coordinate system. It is evident that to define a point’s location in the volume three coordinates are overabundant and only two dimensions are enough because, when the plane is transformed into a roll like a carpet, the third dimension appears. The conversion of three-dimensional space to two-dimensional one is simple due to the equations of equivalence between 2D and 1D spaces. Theoretical analysis of the conformal coordinate transformation by the spiral of Archimedes is described in [26], algorithms and software are discussed in [27–29] and [30–32] accordingly. Research of algorithms for converting 3D objects into rolls, using the spiral coordinate system is presented in [33].

To make things clear, Figure1 shows a simplified general view of the modified RPS machine with the new techniques: perforation of a support ribbon and its filling in order to enhance the properties of shaped products.

The component ribbon perforation is similar to printing a sequence of pictures without a gap, Figure 2.

Figure 3 illustrates the transformation of a castle into a ribbon with spiral coordinate system.

### Perforation of the Support Ribbon

This paragraph demonstrates the method 1 of support ribbon perforation which provides a more homogenous and pure way of shaping objects with RPS. The cell size in a support ribbon determines its admixture, pores and hollows of the particles embedded in a component roll determine the density of the powder for sintering elements and its specifications. The higher density provides more predictable mechanical

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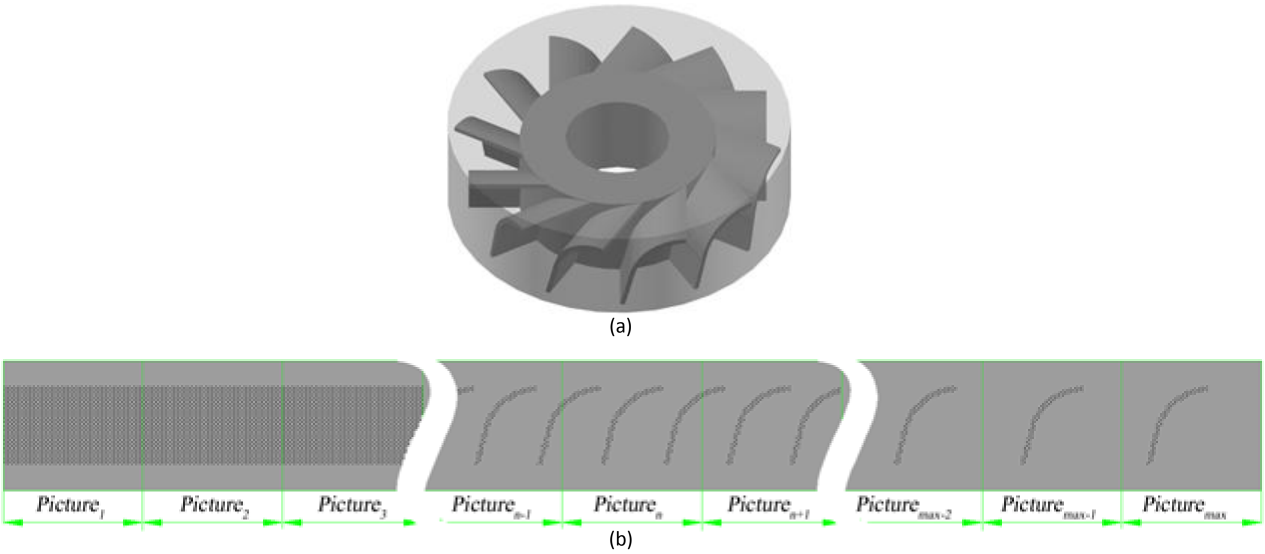


Figure 2. Impeller in a component roll (a) and it linear sequence of pictures of pictures in component ribbon without a gap(b).

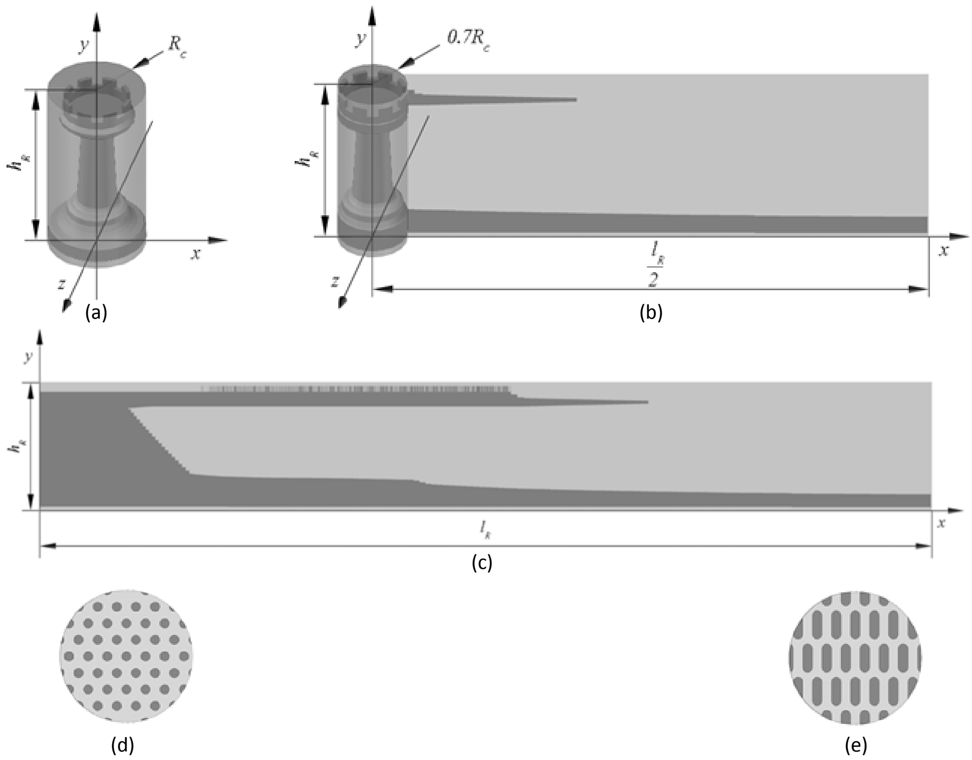


Figure 3. (a) A castle inside a roll, $R_C$ – radius of the castle, $h_R$ – height of the roll; (b) partial transformation the volume object into a ribbon, $l_R$ – length of the roll; (c) full conformal transformation 3D space to 2D one, length compressed scale; (d) and (e) dot and hatching perforation accordingly.

properties, thermal and chemical stability of the product.

The idea is to change the shape of holes and to decrease the cell wall thickness.

As stated in [1–3], while the component stripe is being rewound, the laser or droplets perforate it for the object powder disposal in a checkered fashion to lower the area between the neighboring holes. This solution leads to the amount of the support stripe being ~77%, Figure 3(d). The new method proposes to do the hatching perforation in the shape of dotted lines instead of the point one.

This technique helps to drop the admixture of a ribbon, for instance, by ~18%, i.e. to increase the amount of powder by about 2 times in comparison to the previous perforation technique, if to extend the duration of laser impulses by 3 times Figure 3(e). Consequently, since a support stripe is similar to "Styrofoam" (foam plastic) and composed of gas 98–99%, its mass share in a component roll decreases by about 0.6–1.2%. Such bubble/foam structure of a support material allows making holes easily with a non-powerful laser or tiny droplets with increasing purity of sintered components. When the filled ribbon is flattened evenly by the pressure rollers, merging neighboring filled holes will compress the component ribbon height by ~4 and ~2.5 times for dot and hatching perforation accordingly, Figure 4.

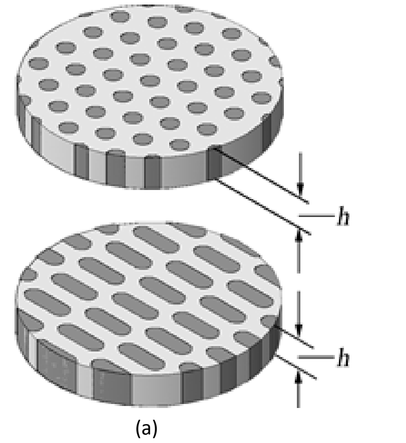


Figure 4. A piece of dot and hatching filled component ribbon before (a) and after compression (b).

Hatching which lengthens laser impulses by 3 times for more homogenous filling area of continuous powder is shown in Figure 5, where *l* is the distance between neighbor lines, *h* is the distance between centers of neighbor dots, *H* is the distance between centers of neighbor dotted lines.

In this way, area of meander for dot perforation can be expressed by the equation:

$$S_m = \frac{h}{2} l \tag{1}$$

area of powder point:

$$S_p = \frac{1}{4}\pi\left(\frac{d}{2}\right)^2 = \frac{\pi d^2}{16} \tag{2}$$

accordingly, area of component ribbon is equal:

$$S_r = S_m - S_p = \frac{h}{2} l - \frac{\pi d^2}{16} = \frac{8hl - \pi d^2}{16} \tag{3}$$

Therefore, area of meander for hatching perforation is:

$$S_{mh} = \frac{H}{2} l \tag{4}$$

area of extended powder point is:

$$S_{ph} = \frac{1}{4}\pi\left(\frac{d}{2}\right)^2 + 2\left(\frac{d}{2}\right)^2 = \frac{d^2(\pi+8)}{16} \tag{5}$$

and area of component ribbon is equal:

$$S_{rh} = S_{mh} - S_{ph} = \frac{8Hl - d^2(\pi+4)}{16} \tag{6}$$

The meander of a component ribbon perforation for both styles is shown in Figure 6.

## Compaction before compression

Compaction can be defined as the consolidation of particles with the reduction in bulk volume, as a result of minimized gaseous phase. A closer packing of the powder particles is the major mechanism for greater mechanical strength of sintered objects, because it involves the magnification in the particle-particle interactions. During the air removal process the particles move closer to each other and establishing bonds between the particles depends upon their shape and molecular structure.

Furthermore, in view of the improvement of the powder particles fluidity, these particles should be in controlled atmosphere too. As described in [38],

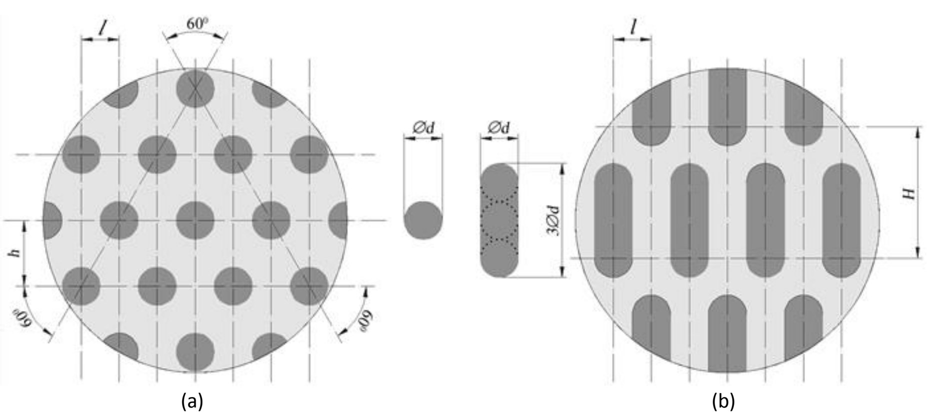


Figure 5. Dot (a) and hatching (b) perforation with lengthens laser impulses by 3 times.

removing air holes between powder particles decreases it viscosity. For instance, rolling in hydrogen medium increases the ribbon thickness by70% in comparison to the airy medium, and rolling in vacuum increases the ribbon thickness by9.5%. With increasing the velocity of rolling, the difference increases by about 1.6 times.

For these reasons, RPS system of filling ribbon with powder requires modification by the method 2, i.e. upgrade with atmosphere control device for boosting its performance and the quality of manufactured items.

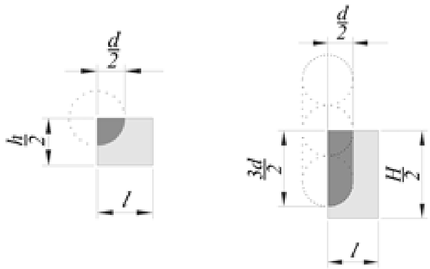


Figure 6. Meander of dot (a) and dotted line (b) perforation.

## Ribbon filling with object powder

This paragraph describes an additional method 3 for even greater homogeneity and purity of RPS products based on the enhancement of support ribbon filling. Obviously, higher precision in controlling the portion and the density of the powder in a sintering roll provides higher quality of manufactured items.

Ultrasonic micro feeding of powders is a tested method for solid free forming and pharmaceutical dosing [34]. A wide range of stable rates of flow for uniform powder doses is achieved by the acoustic vibration system. Ultrasonic allows using a nozzle diameter, transmission fluid depth, waveform, voltage amplitude, frequency and oscillation duration for the powder flow control.

When a wave pulse is sent, the powder stream “switches on”, and the fine particles drop. When the wave ceases, the flow effectively closes, and the powder flow stops. The features of physical modeling based on the arching mechanics are analyzed in [35, 36] and [37].

The powder flow through a different diameter nozzle in a bunker is initiated by the ultrasound and stopped by silence. Special electrical signal waveforms and voltage amplitude lead to different vibration modes, i.e. square wave excitation easily provides stable micro feeding and stronger amplitude makes the dose larger.

For many powders, the dose mass is growing with increased oscillation duration almost linearly.

Figure7 demonstrates the simplified scheme of even number ultrasound emitters for object powder compact placing.

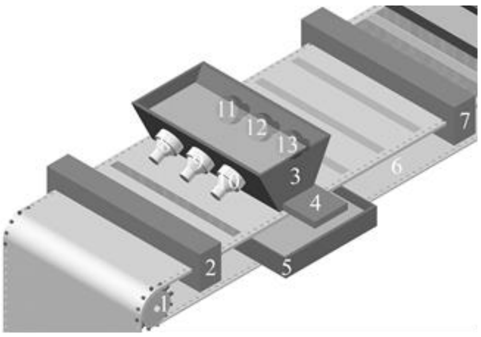

Figure 7. The scheme of ultrasound emitters for object powder compaction: 1)Extending rollers, 2)First perforation system, 3) Object powder upper bunker, 4) Excess powder remover, 5)Object powder lower bunker, 6) Supporting ribbon, 7) Second perforation system, 8–13)Object powder ultrasound vibration emitters.

## Results and discussion

Based on the described dotted linear perforation of the support ribbon, powder compaction and component ribbon filling with ultrasound vibration the improved RPS 3D printer is proposed.

Consequently, for the standard laser printer resolution of 1200 dpi, the dimension of a lengthened cell is about 21×63μm. If the area is perforated with the rounded parallelepiped size of about 15×58μm, then a part of support ribbon is about60% or less.

In comparison to the previous perforation method, the new one not only reduces an amount of a support stripe in a component roll by ~1.3times, but also its compression rate by~2times. The difference of the amount of the component powder in a sintered object between the previous perforation style and the new one is about180%.

Using vibration and atmosphere control device facilitates the process of powder filling. These are effective solutions to improve the quality and the performance of a shaping process.

Table1 demonstrates comparison of enhanced RPS properties with previous version.

## Conclusion

Using the proposed methods make better the quality of produced parts and the performance of RPS 3D printer.

The effect of the ribbon hatching perforation in the shape of dotted lines instead of a point one with reduced pulse repetition rates for lasers is explained. The new method shows how to decreased area of support ribbon.

Changing the shape of holes from the cylindrical to the rounded parallelepiped one lowers the amount of a

Table 1. Several specifications of dot and hatching perforation for a component ribbon.

| Specification | Previous RSP | Enhanced RPS |
|---|---|---|
| Laser perforation fashion | Dot | Hatching |
| | Ribbon area, % | |
| | ~77 | ~60 |
| | Powder area, % | |
| | ~23 | ~40 |
| | Ribbon admixture amount, % | |
| | ~0.8–1.6 | ~0.6–1.3 |
| Powder compaction system | absent | Increasing the velocity of rolling by ~1.6 times |
| Ultrasonic vibration system | absent | Greater density, homogeneity, purity and predictable mechanical properties of manufacturing products |
| Roller compression rate | ~4 | ~2.5 |

stripe in a component roll for sintering and increases the amount of powder in comparison to the previous checkered fashion perforation. As a result, the ribbon admixture amount is changed from ~0.8–1.6% to ~0.6–1.3%. It was shown that the new methods provide to lower the amount of the support ribbon by 18% and to boost the velocity of the powder filling and its density about twice as much.

Powder compaction is an important integration step for the objects manufacturing. Increased mass of the powder in the component roll with ultrasound technique improves the mechanical properties of sintered objects.

Optimization of methods such as perforation of the support ribbon, powder compaction and filling of the component ribbon enhanced properties of RPS products.

The new described techniques confirm the unique potential of the RPS upgrade and acceleration transmission to the fourth technical revolution with enhanced technological tools.

## Disclosure statement

No potential conflict of interest was reported by the author.

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