NOVEL IMPLEMENTATIONS OF PLASMA SPRAYING FOR FABRICATING COMPONENTS MADE OF A MULTIHPASE PERFECT MATERIAL

Feng Wang(1), Ke-Zhang Chen(1), Xin-An Feng(2),

(1) Department of Mechanical Engineering, The University of Hong Kong, Hong Kong.
(2) School of Mechanical Engineering, Dalian University of Technology, Dalian, 116024, China
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Abstract

A component, which has a perfect combination of different materials (including homogeneous materials and different types of heterogeneous materials) in its different portions for a specific application, is considered as the component made of a multiphase perfect material. Based on the requirements for fabricating different types of heterogeneous materials, a hybrid manufacturing process with layered manufacturing, micro-fabrication, and mechanical machining has been developed under the guidance of Axiomatic Design. According to the hybrid process, this paper investigates the related technologies and selects plasma spraying technology to spread materials layer by layer; and further analyzes its key design parameters, improves plasma spraying technology, and presents a novel implementation of this technology.

1. Introduction

With recent development of high technology in various fields, some components and products have been required to possess a range of special functions, which may require component materials to possess some special properties (e.g. negative Poisson's ratio and zero thermal expansion coefficient). These special requirements cannot be satisfied by homogeneous materials but can be met by heterogeneous (as opposed to homogenous) materials, which may include composite materials, functionally graded materials (FGMs) and heterogeneous materials with a periodic microstructure. However, different portions of a mechanical component may have different special requirements and the components made of single material cannot meet all special requirements in its different portions, but only some. To meet all requirements, it would be necessary to use components made of different materials, including homogeneous materials and the three types of heterogeneous materials, thus satisfying all special requirements in different portions and also making the best use of different materials, just like nature's organisms (e.g. bamboo, tooth, bone etc.) which have perfect combinations between materials and functions after a long time of evolution. A component, which has a perfect combination of different materials (including homogeneous materials and different types of heterogeneous materials) in its different portions for a specific application, is considered as the component made of a multiphase perfect material.

To design and represent the components made of multiphase perfect materials according to the requirements from high-tech applications, a corresponding design method [1,2] (including both geometric and material design) and a corresponding CAD modeling method [3-5] (containing both geometric and material information) have been successfully developed and can be implemented by applying the functions of current CAD/CAE software. But, currently there exists no available method for fabricating the components made of a multiphase perfect material, although there are some existing methods that can manufacture the component made of a single composite material or FGM. In order to meet the need, a manufacturing technology, including its manufacturing process and the principle scheme of its corresponding manufacturing facilities has been developed [6] and applies spreading, engraving, and refinishing technologies. This paper further develops the spreading technology in more detail for this application.

2. Review of hybrid process for fabricating components made of multiphase perfect materials

Based on the analyses of the requirements for fabricating homogeneous materials and the three types of heterogeneous materials, a hybrid manufacturing process with layered manufacturing, micro-fabrication, and mechanical machining has been developed under the guidance of Axiomatic Design [7]. This process [6] has the following steps:

(1) If there is adjoining material regions which are higher than the layer to be spread, remove the superfluous material from the layer by an end mill to obtain precise boundary of the layer, since the spraying area of a jet is much larger than a pixel so that the practical area of the obtained layer is larger than the required area, and, at the mean time, suck out the formed chips by vacuum;

(2) Spread a material layer with the required thickness and constituent composition (for all material regions) and, at the mean time, spray the inclusions with the required distribution and quantity to stick in the layer (only for composite material region) for every pixel;

(3) Grind the top surface of added material layer by the annular end face of a cup grinding wheel to obtain a required thickness of material layer (layer thickness plus a grinding depth), since metal cladding is not flat enough and the thickness of the added layer is not accurate enough, and, at the mean time, suck out the formed chips or sludge by vacuum;

(4) Engrave or sculpt the layer to create the necessary voids for periodic microstructures with a required depth (layer thickness plus a grinding depth), and, at the mean time, suck out the formed chips or sludge by vacuum;

(5) Fill the voids with a material with both lower strength and high melting point to avoid the refilling of the material spread for next layer;

(6) Grind the top surface of the material layer again to remove superfluous lower strength material and the burrs formed in (3). This will ensure that the required thickness and flatness of the material layer is produced;

(7) Repeat Step (1) to spread material for next layer until the component is completely fabricated. The component so formed will have the required constituent composition, inclusions and their distribution, and/or periodic microstructures with lower-strength materials in the voids. The lower-strength metal in the voids will not affect the function of the component and can protect the component from erosion.

3. Spreading technology

3.1. Basic requirements for spreading technology

The second and the fifth steps of the hybrid process involve a spreading technique. The required spreading technology must be able to add the materials for building matrix layer and to spray the inclusions into the matrix layer according to their required distribution and quantity for composite materials, must be able to add different materials with certain volume fractions simultaneously for every pixel according to the specified composition function for functionally graded materials, and must be able to add materials with very thin thickness for heterogeneous materials with a periodic microstructure. A component containing all the three types of heterogeneous materials may have its constituent materials as metals, plastics or ceramics. Therefore, the basic requirements for this spreading technology can be summarized as:

(1) It can spread metals, plastics or ceramics.
(2) It can spread different materials with their required volume fractions simultaneously for every pixel;
(3) It can spray inclusions according to their required distributions and quantities;
(4) It can spread materials with very thin thickness.

3.2. Selection of the suitable spreading technology

The suitable spreading technology should satisfy all the above four basic requirements and may be selected from existing technologies, including layered manufacturing and micro-fabrications.

Layered manufacturing is a layer-by-layer fabrication of three-dimensional (3-D) physical models directly from a CAD model [8-10]. In principle, a 3-D CAD model of an object is created first using a suitable CAD software. The model is then 'sliced' into thin horizontal layers by the computer, based on which materials are spread, one at a time consecutively, and 'bonded' together to form a physical model (i.e. a prototype). Currently, layered manufacturing have had liquid-based, solid-based, and powder-based systems. Among them, Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), ProMetal 3D Printing (3DP), Selective Laser Cladding (SLC), Lasform, Laser Engineering Net Shaping (LENS), Precision Optical Manufacturing (POM), Laser Additive Manufacturing Process (LAMP), Wire-Arc Spray (WAS), and Multiphase Jet Solidification (MJS) can be used for fabricating components made of metals (i.e. satisfy Requirement (1)).

In SLS, SLM, EBM, or ProMetal 3DP, a layer of powders is deposited and leveled by a rolling device. The differences among them are that powder metals are bound by a liquid binder in ProMetal 3D Printing, electron beam in EBM, high power density laser in SLM without post-processing, and a thermoplastic binder using a low-powered laser in the SLS process with post-processing in a furnace where the binder is burned off and the particles are bonded by traditional sintering mechanics. With the rolling-spreading principle, they can neither spread different materials with required volume fractions for every pixel nor spray inclusion according to their required distributions and quantities. Even in Multiple Material Selective Laser Sintering (M^2SLS), multi materials can be deposited; but, after sintering, both the number and the volume of voids will be reduced and the sharp corner of the voids needed for certain periodic microstructures would disappear. Thus, they do not satisfy Requirement (2) and (3) and cannot be used for this application.

In SLC, Lasform, POM, LAMP, or LENS, the metal powder particles are blown directly into the laser-induced molten pool to form a cladding line. The differences among them are the number of tubes and the relative position between tubes and laser beam. The metal powders are injected from four feeder tubes into the focal point of a high-powered laser in LENS, POM, or LAMP, instead of using a tube in SLC or Lasform. Although only one type of materials is spread in these processes, it is possible in the future for LENS to inject up to three different material constituents with their required volume fractions from three of the four tubes, respectively, and spray inclusions from the last tube according to their required distributions and quantities simultaneously (i.e. satisfy Requirement (2) and (3)). However, the width of a cladding tract varies from 0.25mm to 2.54 mm determined mainly by the laser beam size and the thickness is about 5 mm determined by the laser power density, scan speed, and powder feed rate [8-10], which do not satisfy Requirement (4) sometimes. Furthermore, the microstructures in the previous layer will be damaged after cladding due to molten pool. Besides, inert atmosphere of argon is required to prevent oxidation of the powders, like all the full melting processes, and the object made by them has a rough surface finish and low-dimensional accuracy.

In WAS, the metal to be deposited comes in filament form. Two filaments are fed into the device, one is positively charged and the other negatively charged, until they meet and create an electrical arc. This arc melts the metal filaments, while simultaneously a high-velocity gas flows through the arc zone and propels the atomized metal particles onto the layer. Since it needs an electrical arc created via two metal filaments, this technology cannot be applied for plastics or ceramic (i.e. does not satisfy Requirement (1)). Furthermore, it can neither spread different materials with required volume fractions for every pixel nor spray inclusion according to their required distributions and quantities. Therefore, the WAS also does not satisfy Requirement (2) and (3) and cannot be used for this application.

In MJS process, the material used is a powder-binder-mixture that is heated to beyond solidification point in a heated chamber and then squeezed out through a computer-controlled nozzle by a pumping system to build the part layer by layer. Since only one metal constituent is used and does not satisfy Requirement (2) and (3), this technology cannot be used for this application.

According to the above analyses, there is no available layered manufacturing technology that can be applied directly for the second and the fifth steps of the hybrid process. Thus, the attention was focused on micro-fabrication technologies [11-13], which refer to the fabrication of devices with at least some of their dimensions in the micrometer range. These technologies were developed for producing integrated circuits (IC) and have now been adopted to create the complex 3D shapes of many MEMS and Microsystems. In the area of micro-fabrications, there are two categories of technologies other than the special LIGA micromanufacturing technology, i.e., surface micromachining by adding material and bulk micromanufacturing by removing material. The former can be used for the second and the fifth steps of the hybrid process. In the surface micromachining methods, two major categories can be distinguished: direct line-of-sight impingerment deposition technologies called physical vapor deposition (PVD) and diffusive-convective mass transfer technologies called chemical vapor deposition (CVD). PVD uses some methods to vaporize the desired material at lower pressures and make it move to and deposit on the surface of the substrate by condensation. Evaporation, Sputtering, Molecular Beam Epitaxy (MBE), Laser Ablation Deposition, Ion Plating, and Cluster Deposition represent the PVD techniques. In CVD process, the constituents of a vapor phase, often diluted with an inert carrier gas, react at a hot surface (typically higher than $300^{o}C$) to deposit a solid film by chemical reaction. There also are many different types of CVD methods, such as Plasma-enhanced CVD (PECVD), Atmospheric Pressure CVD (APCVD), Low Pressure CVD (LPCVD), Very Low Pressure (VLPCVD), Metallorganic Chemical Vapor Deposition (MOCVD), and Spray Pyrolysis. They differ each other mainly from the way of reactant gases generated, the chemical reactions, and the operation conditions. But, the PVD and CVD techniques rely mostly on atomistic deposition, i.e., atoms or molecules were individually depositing onto a surface to form a coating. Even if some of them may meet all the four requirements mentioned previously, the thickness of the layer is too thin and the spreading time for this application will be very long.

Fortunately, there is a technique called Plasma Spraying, in which particles, a few microns to 100 μm in diameter, can be transported from source to substrate. In atmospheric spraying, a high intensity arc is operated between a stick-type cathode and a nozzle-shaped, water-cooled anode as illustrated in Figure 1.

Plasma gas, pneumatically fed along the cathode, is heated by the arc to plasma temperatures, leaving the anode nozzle as a plasma jet or plasma flame. Fine powder suspended in a carrier gas is injected into the plasma jet where the particles are accelerated and heated. The temperature of the particle surface is lower than the plasma temperature, and the dwelling time in the plasma gas is very short. The lower surface temperature and short duration prevent the spray particles from being vaporized in the gas plasma. As the molten particles splatter with high velocities onto a substrate, they spread, freeze, and form a more or less dense coating, typically forming a good bond with the substrate. The resulting coating is a layered structure with a minimum thickness of 0.025 to millimeters so that this technique satisfies Requirement (4). Since almost any material can be coated or layered on substrate under atmospheric condition [11], this technique also satisfies Requirement (1). If another channel is added in anode nozzle for a different material powder as shown in Figure 1, it can also satisfy Requirements (2), that is, it can spread different materials with their required volume fractions simultaneously for every pixel. If another pipe is added beside the nozzle, the inclusions can be sprayed for composite material regions, which can meet Requirement (3). Therefore, it can be concluded that Plasma Spraying technique can be used for the second and the fifth steps of the hybrid process.

4. Design analyses of plasma spraying

In recent years, plasma spraying has diversified as a manufacturing tool for near net shape free-standing components with numerous industrial applications [14], which include corrosion- and temperature-protective coatings, superconductive materials, and abrasion resistance coatings. However, such conventional plasma spraying cannot be applied directly to manufacture the components made of a multiphase perfect material, and must be improved to satisfy the basic requirements for spreading technology used in the second and the fifth steps of the hybrid process.

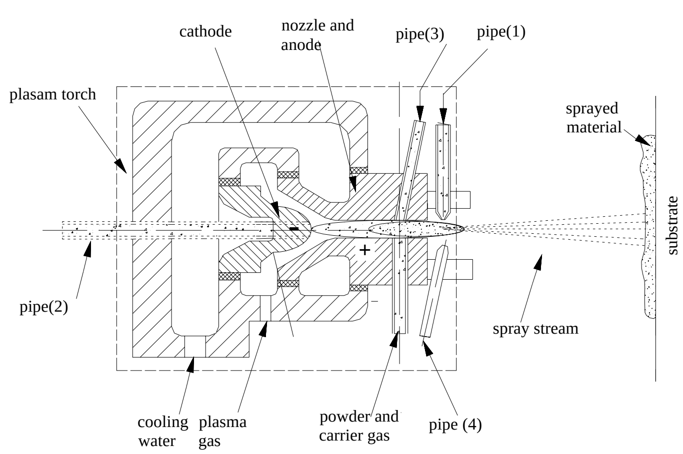

Fig. 1 The schematic sketch of a plasma spray

Plasma spraying is a complicated deposition process, is governed by momentum, heat and mass transfer, and, at the same time, involves physical, chemical, and thermodynamical phenomena. There are up to 50 technical parameters [15], such as feeder parameters, torch characteristics, powder feeding parameters, spraying distance and so on, which affect the quality of plasma spraying and also interact each other. Among them, powder feeding and plasma torch are most important, because they affect directly characteristics of the in-flight particles, such as velocities, trajectories and energies of particles. In turn, these characteristics influence the coating properties and characteristics. To get the better quality of the coating, it should manage to make particles to penetrate the hot region of the plasma, have their mean in-flight trajectory as close to the plasma jet axial as possible and acquire optimal velocity, heat and higher deposition efficiency. Therefore, in this section powder feeding and plasma torch will be analyzed and improved to meet requirements of spreading technology used in the hybrid process.

4.1 Powder feeding

Some researches about powder feeding focus on feeding position and feeding angle [16,20-23] and aim at ensuring that the particles get optimal heat transfer and velocity, then spread onto a substrate, and acquire the better quality of the coatings. There are four different feeding angles, including orthogonal, downstream, upstream, and axial feeding, and two feeding positions: internal feeding and external feeding.

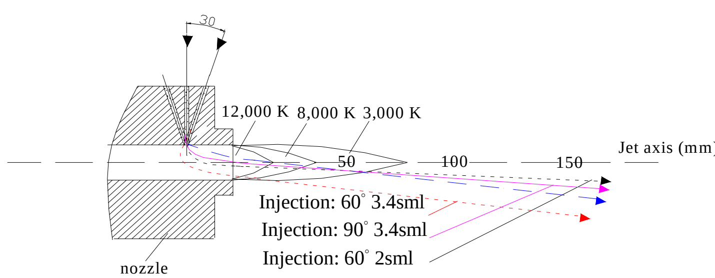

Fig. 2 Mean trajectories injected at different angles

4.1.1 Feeding angles

As shown in Fig. 1, Pipe (1) indicates an orthogonal feeding, where the powders are injected perpendicularly to the jet axis; Pipe (2) is an axial feeding, where the powders are injected along the jet axis; Pipe (3) and Pipe (4) represent upstream and downstream feeding respectively, where the powders are injected at an angle which is not equal to 0 ^{o} or 90^{o} with the jet axis. Different feeding angles would result in different trajectories. Fig. 2 shows a comparison of the trajectories caused by different feeding angles. As for an orthogonal feeding and an upstream feeding, to obtain similar trajectories, the powder carrier gas flowrate of the upstream feeding is lower than that of the orthogonal one; otherwise the mean trajectory of upstream feeding crosses the plasma jet too rapidly, which cause the powders not to be melted enough and decrease the deposition efficiency (the ratio of the weight of coating deposited on the substrate to the weight of expended feedstock) [22]. Although the upstream feeding injection increases particles' residence time in the hottest zone of the jet, this tilting feeding has a drastic influence on the particle's mean velocity, and the lower feeding speed (compared to the orthogonal feeding) cause sticking problems [22]. Thus upstream feeding is seldom selected. Downstream feeding protects the powder material from excessive vaporization because of shorter residence time in the hottest zone of the jet [23], but it is not suitable to spray the material with the high melting point. In any case, special attention has been paid to properly control the feeding velocity and angle of the powder in order to insure that particles penetrate the hot region of the plasma and acquire as close to the axial trajectory as possible.

In fact, the highest deposition efficiency of powder feeding is achieved when the powder is injected along the axis of the plasma jet (pipe 2), which leads to increase in the dwelling time of particles in the hottest zones of the plasma jet and make particles get optimal energies, and at the mean time, form a uniform deposition because of the symmetry spread streams [23]. However, such a solution is rather complex from the viewpoint of design, and therefore, in most cases, the injector is orthogonal to the jet axis either inside or outside the anode-nozzle. But the researchers [20,26,27] have successfully developed the axial powder injection.

4.1.2 Feeding position

As for feeding position, there are two methods [25]: the internal feeding (i.e. pipe (3) and pipe (2) shown in Fig.1) and the external feeding (i.e. pipe (1) and pipe (4) shown in Fig.1). The internal feeding introduces powder through the nozzle wall ensures maximum powder particle entrainment at the point of highest energy within the plasma stream, providing injected particles with optimal heat transfer, particle velocity, and no oxygen, and thus creating higher deposition efficiency [21,23,25]. But this nozzle structure is more complicated. External feeding injects powders outside the nozzle wall and is easier to realize, but the deposition efficiency is lower than that of the internal feeding. Generally the quality of the coating by the internal feeding is better than that by the external feeding [21, 23,25,28].

Although internal feeding can acquire higher deposition efficiency, if adopting non-axis feeding angle (e.g. orthogonal, downstream and upstream feeding), their mean trajectories are not symmetry (as shown in Fig.2) and the spread streams are also not symmetry, which causes to form an uneven deposition. Especially when the powders are composed of a heterogeneous mixture of two or more kinds of different powder densities, particle segregation can take place, resulting in the deposition of the different powders on the different location [22]. One remedy that could be used is the symmetry multi-port injection, and the injection velocity of each powder has to be individually controlled to form a uniform deposition [22].

Based on the above analysis, the axial, multi-port and internal feeding is the suitable selection in this research.

4.2 Plasma torch

The plasma torch (or plasma gun) is one of the important factors, which influences the plasma jet and the in-flight particle characteristics [12-19]. The geometry of the torch directly determines the powder feeding. The conventional torch is shown in Fig. 1, and the ionization of plasma gases in the electric arc between the negatively charged cathode and positively charged anode is in a high-energy state of plasma. This structure of the torch can only allow non-axial powder feeding such as orthogonal, downstream and upstream feeding, with which the deposition efficiency is lower and the deposition is not uniform. In order to obtain high-quality products, it is necessary to develop new plasma torches with excellent performance. Thus, some novel torches with axial powder feeding, such as hollow cathode torch [20], high-performance-type [26], and Axial III [27], have been developed. Such torches have higher power, and thus both the temperature and velocity of spray particles are increased simultaneously, which increase uniform of coating and the deposition efficiency, and improve the quality of products. [24-31].

Compared with these torches, high-performance-type [26] is the more suitable one for this application. It permits axial powder injection, and the powder particles introduced into the nozzle are efficiently heated in the arc and then symmetrically ejected from the nozzle [26,30,32]. In addition, it can sustain a stable and clean plasma jet during powder loading, and the thermal efficiency is higher than that of a conventional plasma torch. This device consists of a plasma electrode-type plasma jet generator and a feed pipe on the nozzle axis [26]. The anode and cathode of the axial feeding torch are set up in each electrode chamber and installed perpendicularly rather than coaxially in the nozzle, as shown in Fig. 3, which makes the structure of torch simpler and the maintenance easier. Besides it has four kinds of nozzles and each of them has different diameter, these multi-choices are more available to spread different kinds of materials. However, it cannot directly spread multi heterogeneous materials and inclusions of composites simultaneously, and must be made an improvement to satisfy the basic requirements for spreading technology.

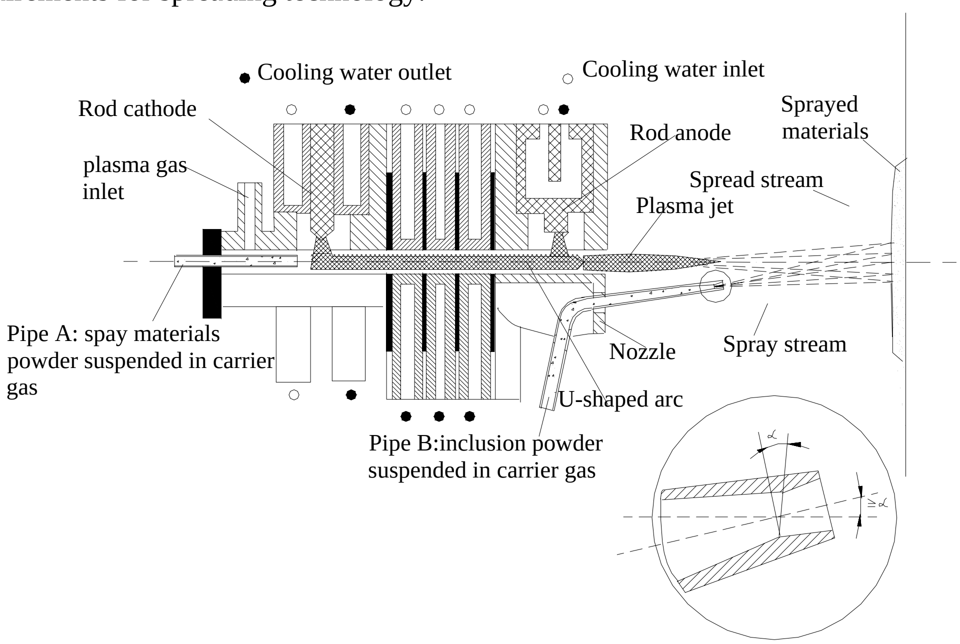

Fig. 3: The schematic sketch of the spray torch

5. The scheme of the implementation

According to the above analysis, the new plasma spraying unit is designed as shown in Fig. 4. It consists of powder feeders and plasma torch, which adopts multi-pipe, axial and internal powder feeding. The axial powder feeding can increase the dwelling time of the particles in the hottest zones of the plasma jet, thus powder can get the highest energy and optimal heat transfer, which can lead to increase deposition efficiency. At the same time, the axial powder injection has the symmetry-spread streams, which can form the uniform deposition. The multi-pipe injection can finish spreading heterogeneous material simultaneously. The improved structure of the torch as shown in Fig.3 mainly includes a plasma electrode-type plasma jet generator and two feed pipes. Pipe A is connected with the axial main powder feeder, which is used to spread different kinds of materials simultaneously, such as functionally graded materials, the matrix of the composite, and the soft metal which fills the void of the periodic microstructure. The main feeder has three even-distribution feeders (set at 120° around the jet axis.), which can contain different materials respectively as shown in Fig. 4. Each feeder is driven by a step motor. Hence, the feed rate of powder material is easily controlled by changing the rotational speed of the motor. The feeder structure is shown in Fig.5. The powder is supplied without stack by two rollers rotating in opposite direction. Scrapers can prevent powder from adhering to the groove of the roller. The different kinds of powder particles are mixed in the blender. There is a tangent pipe inside the blender as shown in Fig.4. With the tangent pipe, the compressed air is formed into the spiral airflow. The mixings of powders with the precise volume of different materials are blended enough and then transported by the spiral carrier gas flow from the blender into the feed pipe A. Pipe B is connected with the feeder of inclusion and only used to spray the inclusion, and its nozzle is away from the high temperature zone of the plasma jet in order to prevent the inclusion from melting. The new design of the plasma spraying can satisfy the requirement for the manufacturing a multiphase perfect material technology.

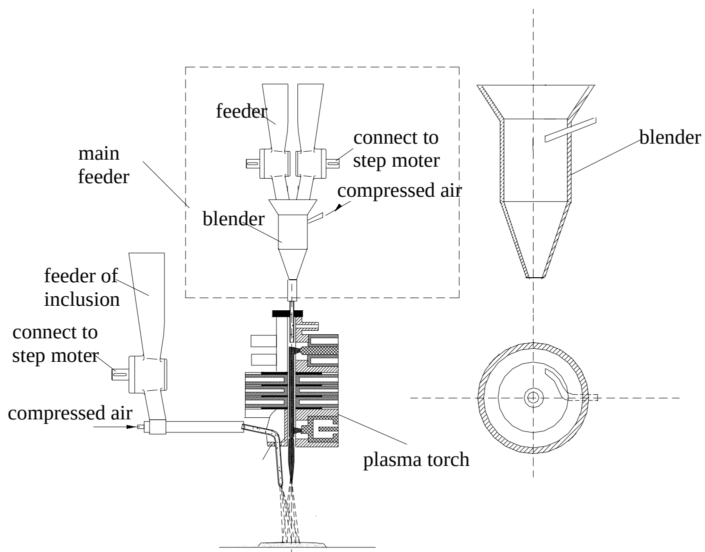

Fig. 4: The schematic sketch of plasma spraying

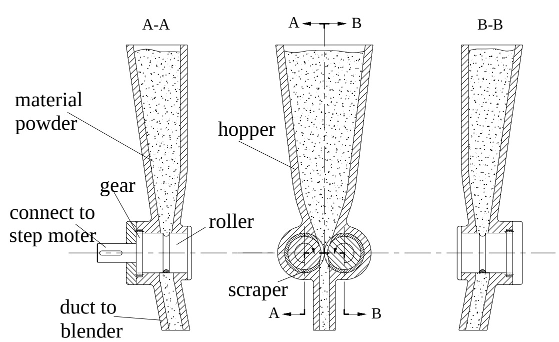

Fig.5: The structure of the feeder

6. Conclusions

This paper further develops the spreading technology of the manufacturing technology for the components made of a multiphase perfect material----plasma spraying, analyzes some important design parameters, including plasma torch and the powder feeding, improves the existing structure of the plasma torch, and presents the novel implementation of this technology. The increase of the pipe B can spray the inclusion of composite material regions. The main feeder with multi-feeder can spread different materials simultaneously with the precise volume. Such implementation can meet all the basic requirements, and fabricate the components made of a multiphase perfect material.

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