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Plasmas for Additive Manufacturing Applications

R. Mohan Sankaran
University of Illinois at Urbana-Champaign

The manufacturing of materials is essential to many current and emerging technologies from electronic devices to transportation to textiles and medical devices. Plasmas (ionized gases) have historically played an important role in one or more steps of many of these materials manufacturing processes. For example, in the semiconductor industry, plasmas enable the precise etching or deposition of thin films that make up electronic components. Plasmas are also used to coat or clean the surface of a material, including metal parts in automobiles and aircraft, glass in building windows, and polymers in many consumer products.

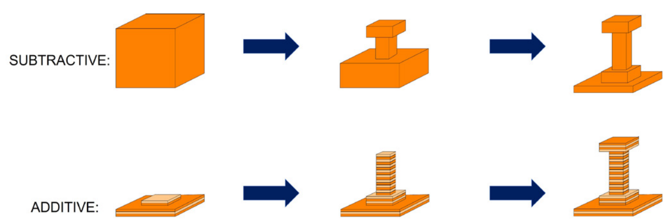

Figure 1. Illustration of subtractive versus additive approaches to materials manufacturing. The subtractive method begins with a larger form of the material and removes areas by machining or cutting. The additive method builds up a material layer by layer. In this example, both methods lead to the same final shape ('I' representing Illinois).

Materials must often be fabricated in a pattern or shape. In general, there are two approaches to materials manufacturing that can lead to either a two-dimensional patterned film such as those that are found in electronic devices, or three-dimensional objects that are found in many polymer (i.e. plastic) products. As illustrated in Figure 1a, the first is termed subtractive and begins with a larger form of the material and describes the removal or shaping of that larger material into a final desired form. A simple example of a subtractive method that is known by many, but may be a remnant of a bygone era, is whittling of wood. To date, many of the manufacturing processes used in industry to produce a material have been subtractive. Examples include machining and laser cutting. Recently, materials manufacturing has been undergoing a renaissance with the emergence of additive approaches. As illustrated in Figure 1b, additive refers to the fabrication of materials by building up layer by layer or block by block, until a desired shape is produced. A simple example of an additive method that is known by most everyone starting even as a child is Legos. At the industrial scale, examples of manufacturing processes that are additive include inkjet printing and 3D printing. The key advantages of additive methods over subtractive methods are that there is much less material wastage and more complex designs are possible. However, additive manufacturing is currently slower and more costly. Nonetheless, as equipment and material options continue to be developed and progress, there is no doubt that additive manufacturing will be implemented more and more in industry.

At the core of any additive approach is the physical and chemical process that leads to the building of a material. Among the various processes, plasmas offer a unique environment. In a low-temperature plasma, the gas is "cold," i.e., near room temperature, while electrons are heated well above room temperature by for example, absorbing energy from an electromagnetic field. These energized electrons can transfer their energy to the gas to excite the molecules and allow chemical reactions to take place without adding heat. Examples of reactions that are made possible by plasmas include surface cleaning, surface functionalization, deposition, etching, and chemical conversion.

In particular, an additive method where plasmas have begun to address important issues is inkjet printing. Typically, inkjet printing relies on a solution containing nanoparticles which is the "ink" that is deposited onto a substrate by flowing the solution through a print head made up of nozzles to produce a patterned thin film. The nanoparticles are usually a metal such as silver and must be coated by an organic in order to suspend them in the solution and prevent them from separating from the solution by precipitation during printing. After the nanoparticles are deposited, the printed film containing them must be heated to remove the organic coatings and sinter the particles, which refers to the fusing of the particle surfaces, so that the printed structures are electrically conductive. However, nanoparticle-based inks have been limited to only a few metals and the heating step can limit what substrates are used, such as those that are temperature-sensitive plastics.

Recently, plasmas have been shown to be capable of converting metal salts dissolved in solution directly to metal nanoparticles. These inks are "particle-free" and not prone to precipitation, making them more stable for storage and printing. Normally, the metal salts would not be useful because unlike metals they are not conductive, and in order to convert

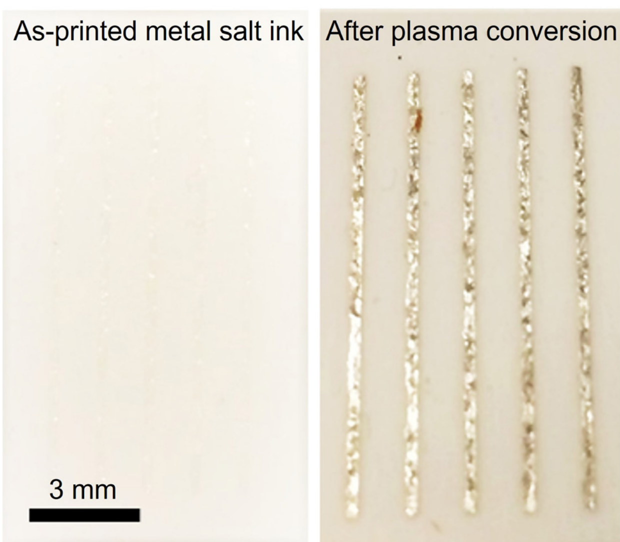

Figure 2. Photos of 'particle-free' ink composed of metal salt (silver nitrate) deposited on paper substrate by ink-jet printing (left) and metallized (silver) lines after conversion by a low-temperature plasma (right).

them to metals would require very high temperatures (>300 degrees Celsius). Since plasmas contain energetic species including hot electrons, the metal salts can be converted to metal at temperatures less than 100 degrees Celsius. As shown in Figure 2, metallized features can thus be fabricated on substrates such as paper. Metal salts are readily available and this approach of combining them with plasma conversion has been extended to many other metals, including gold, platinum, copper, palladium, bismuth, lead, and tin, many of which have not been possible by printing nanoparticle-based inks.

In summary, additive methods have the possibility of changing the paradigm for materials manufacturing by minimizing the amount of raw materials that are needed and fabricating complex parts or devices for a wide range of industries. Plasmas promise to be a part of this exciting future by enabling surface chemistry at low temperatures that is compatible with plastics and expanding the library of materials that is accessible.

Text and images by R. M. Sankaran; Edited by M. Laroussi

Suggested Reading:

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ABOUT THE AUTHOR

R. Mohan Sankaran is the Donald Biggar Willett Professor in Engineering at the University of Illinois at Urbana-Champaign (UIUC). He directs a research program focused on the development of low-temperature, atmospheric-pressure plasmas as a chemical platform for the synthesis of novel materials and small molecules with applications in emerging electronics, medicine, and energy conversion. He has co-authored over 100 peer-reviewed journal articles, edited one book, and contributed several book chapters. He has been recognized for his scientific achievements by the Teacher-Scholar Award from the Camille and Henry Dreyfus Foundation and the Peter Mark Memorial Award from the American Vacuum Society (AVS). He currently serves as an Associate Editor of the Journal of Vacuum Science and Technology and a member of the Editorial Board of Plasma Chemistry Plasma Processing, Scientific Reports, and Plasma Research Express and the Advisory Board of the Journal of Physics D.