



Role of gases in AM.

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Atmospheric gases: enablers behind the additive manufacturing future.

Additive manufacturing (AM), or the process of creating a product or component part layer by layer instead of using traditional moulding or subtractive methods, is leading a transformation in manufacturing technology. So often used interchangeably with the term 3D printing, the two terms are mistakenly considered synonyms. This is a misnomer, as while AM may have 3D printing at its heart, the process consists of much more, with both pre- and post-production treatments being integral to the overall manufacturing approach. And there are multiple approaches – from laser powder-bed fusion, directed energy deposition (using a laser or an arc), electron beam melting, to binder and material jetting. But behind these various production methods – and the key ancillary processes at either end – are the critical atmospheric gases and gas technologies which are fundamental enablers of this manufacturing revolution.

Once destined primarily for prototyping, AM is now employed increasingly for the development of spare parts, small series production and tooling. Adoption of AM has seen the greatest uptake in industries where its relatively higher production costs can be outweighed by the

advantages AM can deliver, particularly in highly innovative, leading-edge industries such as aerospace, defence, medical and automotive. Such advantages include greater design freedom and customisation, improved product strength and functionality, reduced assembly time for complex components, localised production, rapid time to market, mitigation of wastage, reduced obsolescence, decreased reliance on traditional suppliers and even the creation of new materials with unique mechanical and behavioural properties.

While several analyst reports estimate growth in AM will reach \$20 billion by 2020, McKinsey & Company recently speculated that the overall economic impact could be much greater, with growth valued at \$100 billion to 250 billion by 2025, if adoption of AM continues at the current rate.¹

Despite the excitement and subsequent discourse around AM – its benefits, challenges, its early adopters – one area of discussion that is often under represented is the vital role of atmospheric gases – and equally importantly, the associated gas technologies enabling success across the AM fabrication chain.

Gases for a diverse manufacturing landscape.

The AM technology landscape is a diverse one, with various technologies developed to meet different production requirements including materials used, surface finish and cost. What remains constant is the need for high quality atmospheric gases and the pioneering technologies enabling their application to optimise both the process and resultant product.

Inert gas, typically argon or nitrogen, is central to the function of metal AM as well as peripheral AM processes including pre- and post-production activities, and is the media most often used for quenching during the vacuum heat-treating process. Argon gas is the third most common gas in the Earth's atmosphere, with its name coming from a Greek word meaning 'inactive' as the gas lacks chemical reactions. Colourless, odourless, tasteless, and non-toxic, argon is 38% more dense than air and it can displace the oxygen in an enclosed area. It's often used as a shielding gas in welding, electron beam melting and sintering to prevent unwanted burning and oxidation.

In the AM process, argon gas is used in laser powder-bed fusion as it creates the perfect environment for the process. A major challenge in metal AM is building components in a controlled environment and minimising the introduction of any possible impurities. Inerting is also critical for proper management of the combustible dust arising from the powder metal and printing process. A key reason for a constant gas flow above the powder bed is the removal of projections and fumes generated at the melt pool. Without it the fumes would interfere with the laser and the projections would create defects in the material.

For AM methods such as laser powder-bed fusion to electron beam melting (EBM) inert gases are introduced into the sealed printing chamber to create a highly controlled atmosphere, but there are other atmospheric gases used in a variety of applications vital to the AM process.

Laser Directed Energy Deposition (L-DED) uses a high-power laser beam, connected to a robot or gantry system, to form a melt pool on a metallic substrate into which powder or metal wire is fed. The powder is contained in a carrier gas such as argon and, more rarely, helium or nitrogen, and directed to the substrate through a nozzle concentric with the laser beam. Alternatively, a wire can be fed from the side. The powder or wire is melted to form a deposit that is bonded to the substrate and grown layer by layer. An additional gas jet – comprising of argon or tailored gas mixtures – which is concentric with the laser beam, provides additional shielding or process gas protection.

Selective laser sintering (SLS), which uses polymer powder such as nylon, carbon fibre, glass-filled nylon and fine polyamide, begins with the polymer powder heated to just below melting point. A carbon dioxide (CO₂) laser then sinters the powder in an inert gas atmosphere – usually nitrogen – which is used to protect the heated powder from reacting with ambient air.

A further AM process uses gas-metal arc welding (MIG/MAG) and plasma welding techniques to melt metal filler to form a 3D component layer by layer. Shielding gases such as argon, helium or special gas mixtures are applied to protect the hot substrate against the ambient atmosphere and adjust the metallurgical properties of the component being created. Efficient cooling of the generated component is done via the application of cool gases during the welding process to improve productivity.

Pioneering technology for atmospheric control.

Across all these AM approaches, atmospheric gases play a fundamental role in both the core printing process in addition to pre- and post-production processes such as metal powder production and storage. As is well understood and established earlier in this article, the core AM process takes place within a closed chamber filled with high-purity

inert gases such as argon and nitrogen. What is less well understood is that even after the atmosphere is purged, impurities can remain present in the chamber due to incomplete purging or via access through loose connections or the metal powder itself. Even extremely small variations in oxygen content can impair the mechanical or chemical properties of alloys sensitive to oxygen like titanium or aluminium and can affect the composition of the end product, resulting in negative physical characteristics such as discolouration and even poor fatigue resistance. For industries at the forefront of AM adoption such as aerospace, automotive and medical, such negative production outcomes are critically important to avoid.

Linde, a world-leading industrial gases company, has dedicated the past 3 years to developing pioneering technology to overcome these atmospheric impurities in order to give manufacturers optimal printing conditions. The result – ADDvance® O₂ precision – provides continuous analysis of the gas atmosphere, detecting oxygen levels with high precision without cross-sensitivity. Recognising O₂ concentrations as low as 10 parts per million (ppm), the unit automatically initiates a purging process to maintain the atmosphere as pure as needed. The technology is already in use at companies at the vanguard of AM including Liebherr Aerospace in France, leading car manufacturers in Germany as well as other partners – both industrial and academic.



The ADDvance® O₂ precision ensures the atmosphere inside the print chamber.

Metal powder: the beginnings.

The mechanical properties of a finished product are not only highly dependent upon the AM process itself, but the characteristics of the powder used in that process. The quality of metal powders used in AM is critically important as it can impact on the physical properties of the finished product, including tensile strength, brittleness, impact resistance, heat tolerance and resistance to corrosion. Powder quality also plays a vital part in consistency and production repeatability – a key focus area for AM which looks to ultimately apply stringent uniformity for more series-based production. For the delivery of the necessary powder excellence, atmospheric gases play an essential role.

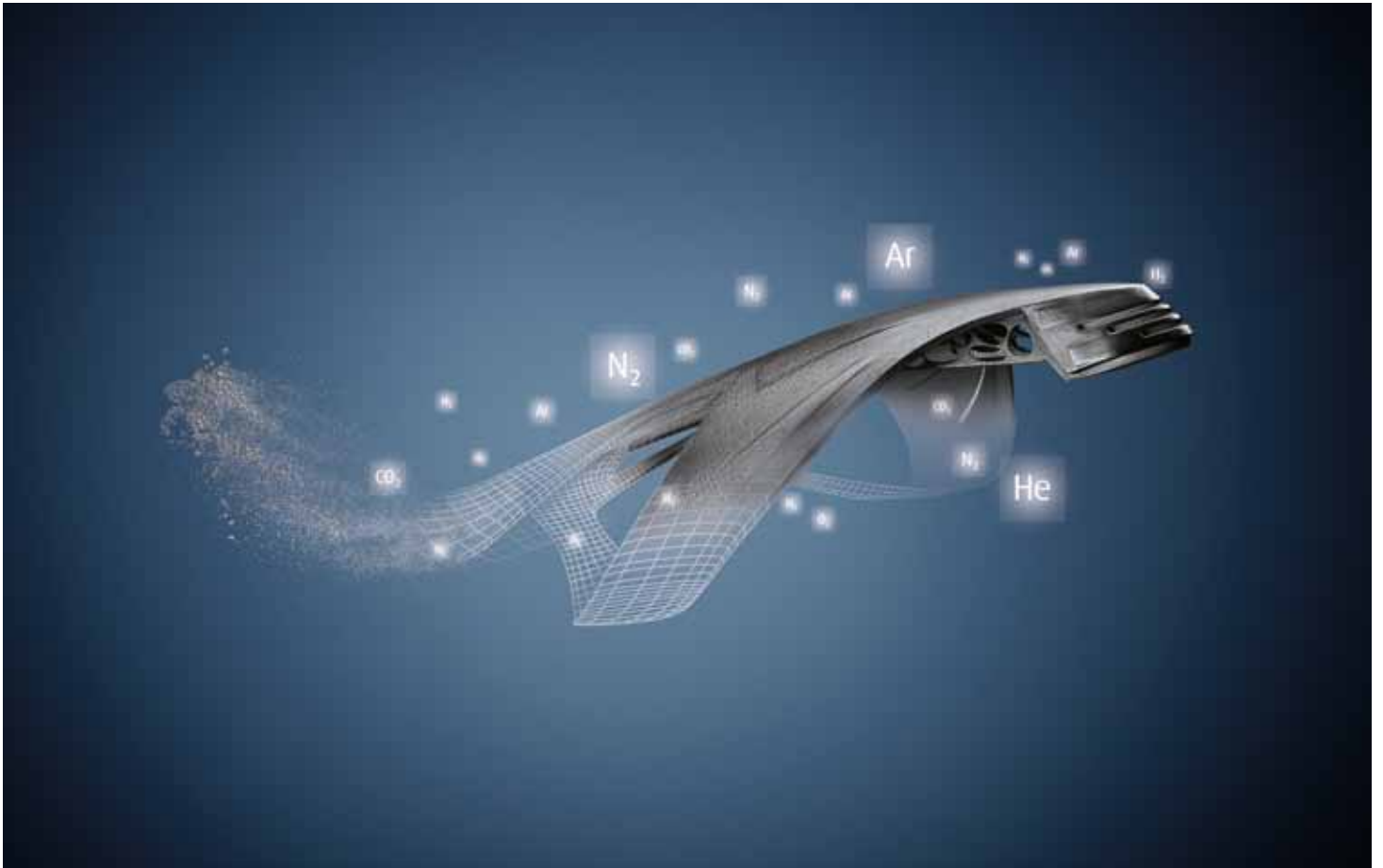
High sphericity of the metal particles is needed so that the metal powder flows smoothly and evenly inside the printer. High powder layer density is also required to produce dense parts with high scan velocities, resulting in high productivity. The density of a powder layer is particularly dependent on particle shape and size, as well as size distribution. Particle shape influences porosity because the greater a deviation from a spherical shape leads to a lower density – and therefore more porosity. Additionally, a spherical shape also offers better flow properties during recoating. Gas atomisation is the most effective approach to metal powder production due to the superior geometrical properties achieved. It requires not only a large supply of inert gases such as argon and nitrogen, but the gas molecule expertise to help manufacturers fine tune the atomisation process to further improve powder characteristics, eliminate rejects – and to do so cost effectively.

It is essential to maintain the correct atmosphere during storage in order to avoid humidity. Humidity will lower the flowability of the powder and will increase the amount of O₂ during printing. The latest addition to Linde's AM solutions now includes Linde's ADDvance® powder cabinet to ensure optimal conditions for powder storage.



The ADDvance® powder cabinet provides the optimal storage environment for metal powders.

Enhanced post-processing: the final touch.



Gas-enabled excellence - from powder to precision parts with Linde.

As stated earlier, versus just 3D printing, AM comprises a sum of production processes and nowhere is this more evident than in the finishing of printed parts, with gases continuing to play a leading role. The many advantages enabled by AM strengthens the need for ensuring that parts created have similar or even superior mechanical properties than traditionally manufactured parts produced through casting, forging, milling, cutting and welding.

Most AM components require a heat treatment step to reduce stress. Hot isostatic pressing (HIP) is an advanced material heat treatment process utilising elevated temperatures in a contained high-pressure atmosphere to eliminate internal porosity and voids within cast metal materials and components. The work-pieces are treated thermally in a vessel under high isostatic pressure with high-purity argon typically used to provide the inert atmosphere necessary to prevent chemical reactions that might adversely affect the materials being treated. The smallest impurity in the argon will at this pressure – easily up to 1,000 bars – create oxidation. This is a key challenge for the gas supply. Under the high temperature/high pressure HIP process conditions, microporosity and voids are reduced or eliminated by plastic deformation, creep and diffusion bonding, improving mechanical properties and fatigue performance of manufactured parts. The reliability and service life of critical high-performance components are optimised. Typical HIP applications include gas turbine components, automotive engine parts, turbo charger wheels, aerospace structural parts, medical implants, prosthetics and near net shape components.

Binder jetting is an additive manufacturing process in which a liquid binding agent is selectively deposited to join powder particles and is applied in alternate layers with the material to be bonded. The build chamber is filled with an inert gas such as argon to prevent oxidation of the metal, but once the build is completed and the object separated from the build plate – called a “green component” – it has poor mechanical strength and high porosity. This can be rectified by the sintering process, with the part being fed slowly through a special high-temperature furnace to bond the metal particles together.

During any of the AM processes, blast powder residue or unfused powder can build up on the part being printed. Removing particles from holes and cavities can represent a particular challenge in the case of small, elaborate parts and components with complex geometries, especially as melting metal residue requires potentially damaging high temperatures. Depending on the application in question, a number of different surface finishing treatments can be applied to remove or reduce the surface roughness of AM parts including barrel finishing, abrasive flow machining, plasma polishing, micro machining and electrochemical polishing.

Linde has developed a highly effective solution to improve cleaning. ADDvance® Cryoclean technology creates dry ice particles, or “snow”, by expanding liquid CO₂ and using compressed air to accelerate the particles up to sonic speed, shooting them onto the surface to be cleaned. The cleaning effect relies on flash cooling, kinetic energy, embrittlement and gas impact. If needed, a further abrasive agent can be added to the dry ice particles to remove more stubborn powder residue.



Reviewing the printed part.

Collaboration with the Manufacturing Technology Centre.

The Manufacturing Technology Centre, or the MTC, was established in 2010 as an independent research and technology organisation with the objective of bridging the gap between academia and industry for the advancement of British manufacturing on the global stage. Based in Ansty Park in Coventry, it represents one of the largest public sector investments in UK manufacturing. The MTC develops and proves innovative manufacturing processes and technologies in what is an agile, low risk environment. It provides integrated manufacturing system solutions for customers large and small, across sectors as diverse as automotive, aerospace, space, rail, food & drink, construction, oil and gas, and defence. Operating some of the most advanced manufacturing equipment in the world, and employing a team of highly skilled engineers, many of whom are leading experts in their field, ensures a high-quality environment for the development and demonstration of new processes and technologies on an industrial scale. The organisation's advanced facilities include the UK's National Centre for Additive Manufacturing (NCAM), for which BOC, the UK subsidiary of The Linde Group, is a founding member.

Working with dozens of companies across the UK, the NCAM facilities focus on research, development and testing of the variable elements of an AM process to ensure optimal operational conditions for production of the final product. The objective of the NCAM is to accelerate the uptake of AM by developing the technology and systems required to address the key challenges within the AM value chain. To achieve this, the process needs to be stable and repeatable to ensure the same high-quality result each time, with a view ultimately towards successful series production.

One of the key challenges in the AM process is ensuring optimal conditions within the printing chamber. As stated earlier, even extremely small variations in oxygen content can impair the mechanical properties or chemical composition of the end product, resulting in negative physical characteristics such as poor fatigue resistance. For MTC's customers, many of whom are at the frontline of AM adoption – a high quality and reliable

production process is critically important. Taking the aerospace sector as an example, there has been a lot of investment in AM by the aerospace primes but there remains a challenge to establish a robust aerospace AM supply chain in the UK to actually produce the parts required. To address this, the MTC is leading a large £14m government-funded project (DRAMA) specifically intended to provide the facilities and knowledge that the aerospace supply chain need to build their AM capabilities.

While vendor agnostic, one of MTC's recent technology adoptions has been Linde's ADDvance® O₂ precision, providing continuous analysis of the gas atmosphere within the print chamber – detecting oxygen levels down to 10 ppm – and purging when required. "All AM machines will purge air but ADDvance® O₂ precision does so to a much higher degree", said Kevin Withers – Senior Research Engineer. The system was used to provide greater control over the print chamber's atmosphere, which for some machines is particularly important given differences in gas management and leakage concerns.

Another Linde technology in use at MTC is their ADDvance® Cryoclean which is used – either alone or in combination with an abrasive agent – to blast off any remaining metal particles on the surface of the manufactured part as well as any other impurities like grease or fingerprints. This system has been evaluated by the MTC through use on electron beam melted AM parts.

The AM work being done at MTC also relies on a dependable, safe and high-quality supply of key atmospheric gases for the different AM processes. A key focus of MTC's technology research is around laser metal deposition (a directed energy deposition process) which, as discussed earlier, relies on the supply of a carrier gas such as helium to deliver the powder to the substrate through a nozzle. An additional gas jet – comprising of argon or nitrogen – which is concentric with the laser beam, provides additional shielding or process gas protection.



Post processing in action. With thanks to Trumpf.

Conclusion.

In addition to creating highly complex and customised parts, Linde believes AM will prove transformative for industry more widely. We are already leveraging the process to manufacture products, such as burner nozzles, avoiding the design and production constraints associated with subcomponents that traditionally have been welded together.

As the AM industry develops, with new materials being used, demand for increasing quality and series production, Linde will continue to lead research and development across the whole AM value chain.

For more information please contact
info-additivemanufacturing@linde.com or visit www.linde-am.com

References.

1. Jörg Bromberger & Richard Kelly; September 2017; Additive manufacturing: a long-term game changer for manufacturers, McKinsey; page 61

Getting ahead through innovation.

With its innovative concepts, Linde is playing a pioneering role in the global market. As a technology leader, it is our task to constantly raise the bar. Traditionally driven by entrepreneurship, we are working steadily on new high-quality products and innovative processes.

Linde offers more. We create added value, clearly discernible competitive advantages, and greater profitability. Each concept is tailored specifically to meet our customers' requirements – offering standardized as well as customized solutions. This applies to all industries and all companies regardless of their size.

If you want to keep pace with tomorrow's competition, you need a partner by your side for whom top quality, process optimization, and enhanced productivity are part of daily business. However, we define partnership not merely as being there for you but being with you. After all, joint activities form the core of commercial success.

Linde – ideas become solutions.

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