Additive manufacturing and powder metallurgy.
Optimal product quality with tailored gas solutions.
Linde – a world-class gas business.

The Linde Group is a world-leading supplier of industrial, process and specialty gases and is one of the most successful global engineering companies. Linde products, gas solutions and services can be found in nearly every industry, in more than 100 countries.

Wherever you want to go – we are there to help.
<table>
<thead>
<tr>
<th>Page</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Linde – a world-class gas business</td>
</tr>
<tr>
<td>5</td>
<td>Overview of additive manufacturing and powder metallurgy processes</td>
</tr>
<tr>
<td>7</td>
<td>Metal powder production</td>
</tr>
<tr>
<td>9</td>
<td>Additive manufacturing processes</td>
</tr>
<tr>
<td>10</td>
<td>Laser metal fusion</td>
</tr>
<tr>
<td>11</td>
<td>Laser metal deposition</td>
</tr>
<tr>
<td>12</td>
<td>Selective laser sintering</td>
</tr>
<tr>
<td>13</td>
<td>Wire arc additive manufacturing</td>
</tr>
<tr>
<td>14</td>
<td>Thermal spraying</td>
</tr>
<tr>
<td>15</td>
<td>Electron beam melting</td>
</tr>
<tr>
<td>17</td>
<td>Heat treatment and surface cleaning</td>
</tr>
<tr>
<td>18</td>
<td>Sintering</td>
</tr>
<tr>
<td>19</td>
<td>Hot isostatic pressing</td>
</tr>
<tr>
<td>20</td>
<td>Cleaning</td>
</tr>
<tr>
<td>21</td>
<td>Linde – leading in powder metallurgy and additive manufacturing innovation</td>
</tr>
<tr>
<td>22</td>
<td>Linde – world class gas supply options</td>
</tr>
<tr>
<td>23</td>
<td>Linde – the leading gas partner</td>
</tr>
</tbody>
</table>
Powder metallurgy and additive manufacturing

Courtesy of TWI
Overview of additive manufacturing and powder metallurgy processes.

The metal powder industry has grown significantly in recent years due to the development and use of sintered parts and additive manufacturing processes. Linde is at the forefront of research and development not just for the metal powder industry or the metal additive manufacturing industry, but for the entire value chain of powder usage in additive manufacturing. Linde provides powder metallurgy and additive manufacturing with industrial and special gas supply through a wide variety of delivery solutions together with technical support to ensure customer processes are efficient and effective.

The additive manufacturing value chain

Linde plays a major part in providing applications, solutions and supplying gas and equipment to these processes; through our expertise across the whole value chain spectrum, Linde is renowned as the leading gas and joining technologies supplier, providing a complete service approach to customers. Linde’s complete service approach provides customers the following advantages:

- A comprehensive range of industrial and specialty gases and technical support specific to powder metallurgy and additive manufacturing applications:
  - Metal powder production
  - Additive manufacturing processes:
    - Laser metal fusion (LMF)
    - Laser metal deposition (LMD)
    - Selective laser sintering (SLS)
    - Wire arc additive manufacturing
    - Thermal spray surface finishing
    - Electron beam melting (EBM)
    - Sintering
    - Hot isostatic pressing
    - Cleaning
  - High-purity gases produced at ISO 9002-accredited facilities
  - Dedicated support for original equipment manufacturers (OEMs) and customers
  - Optimum process efficiency achieved through dedicated gas control equipment
  - An extensive range of supply options tailored to suit customer requirements
  - Efficient supply schemes, helping to reduce the processing cost of products
  - 24-hour gas ordering services
  - Manufacturing Technology Centres with research and development capabilities to support customer trials and technology exchange

The additive manufacturing value chain

Linde provides applications, solutions, gases and equipment for the following processes:

- Conventional die pressing
- Metal injection molding
- Hot isostatic pressing (HIP)
- Additive manufacturing
- Forming
  - Laser metal fusion
  - Laser metal deposition
  - Selective laser sintering
  - Electron beam melting
- Wire arc & plasma manufacturing
- Thermal spraying
- Metal wire
- Metal powder (production)
- Powders and lubricants
- (Die) pressing
- Molding
- De-binding
- Container manufacturing
- HIP
- Container removal
- Heat treatment
- Surface treatment
- Finished product
Powder metallurgy and additive manufacturing
Metal powder production.

The mechanical properties of a finished product are highly dependent upon the manufacturing process and the characteristics of the powder used in the process. Physical properties of the powder material must be maintained or affected exactly as required.

Linde’s high pressure gas supply schemes and technologies are used to atomize high alloyed metals to powder particles that are spherical in size and of uniform density.

The process:
There are many methods to produce metal powders. Atomization has been identified as the best way due to the geometrical properties of the powder particles achieved. For gas atomization, water atomization and direct reduction appropriate gases and gas technologies are required:

- Gas atomization: argon and nitrogen
- Water atomization: hydrogen
- Direct reduction: hydrogen

The Linde solutions for the powder production:
- Argon, nitrogen and hydrogen supply
- Hydrogen supply – oxide reduction after water atomization
- Tailored supply schemes to satisfy customers’ demands for high-quality gases and appropriate gas supply
- Flow control equipment for reliable high-pressure and/or heated gas supply
- Customized process gas blends designed and adapted to the production requirements for special alloyed powder particles
- Fine-tuning of atomization processes to improve powder characteristics, reduce costs and eliminate rejects
Additive manufacturing (AM), often referred to as 3D printing, is rapidly gaining in popularity as it offers a number of compelling benefits. These include material and productivity gains as well as greater design and production flexibility, thus paving the way for mass customization. Linde is well positioned to support the AM industry by providing world-class gases, gas supply solutions and technical expertise for additive manufacturing/3D metal printing processes.

The process:
Additive manufacturing (AM), also referred to as 3D printing, describes the fabrication of 3D components layer by layer from metal powder. As the demand for AM products has been steadily increasing, so have the many technologies which support the industry, including laser metal fusion, laser metal deposition, selective laser sintering, wire arc additive manufacturing, thermal spraying and electron beam melting. Products manufactured through additive manufacturing are typically forged, heat treated or sintered to achieve the quality, finish and mechanical properties desired. Process gases play a vital role in every sequence of the AM fabrication chain.

Linde solutions for AM processes:
- Argon and nitrogen supply – gases for laser metal fusion
- Helium – serving the electron beam melting processes
- Nitrogen – polymer selective laser sintering processes
- Arc and plasma welding gases
- Thermal spraying gas mixtures
- Specialty gases and their mixtures
- On-site support – processes and/or technical support
- Engineering services
- Process specific safety equipment (including PPE)
Additive manufacturing processes.
Laser metal fusion.

Laser metal fusion (LMF) is known by many including metal selective laser sintering, metal laser melting, direct metal printing and direct metal laser sintering. Linde supplies customers with pure gaseous or liquid argon systems to create the appropriate inert atmospheres for LMF processes.

The process:
A high power laser beam is scanned over a bed of powder, sintering the powder in the required shape, in the path of the laser beam. After each layer, the bed is lowered by a short distance and a new layer of powder applied. This technique is suitable for smaller components where precision is a major aspect.

The entire process runs in a sealed chamber with controlled gas atmosphere which is either inert (e.g. argon) or active to fine-tune material / product properties. Typical products cover combustor and fuel injector prototype parts for aerospace, wheel suspension and drive shaft fittings, and prototypes for medical device industries.

Linde solutions for the LMF processes:
- Argon gas supply – design, provision and installation
- Active gas supply – pre- or onsite mixed gases satisfying process demands
- On-site support – process and/or technical support
- On-stream gas system – design and maintenance services
- Gas safety – equipment, safety checks and training
Additive manufacturing processes.
Laser metal deposition.

Laser metal deposition (LMD), alternatively known as near net shape, is a process which 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. Linde supplies customers with gaseous or liquid helium, argon and nitrogen systems to assist with laser metal deposition processes.

The process:
In LMD the powder is contained in a carrier gas and directed to the substrate through a nozzle that is 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, concentric with the laser beam, provides additional shield or process gas protection. The method is suitable for larger components where a higher deposition rate is required. LMD is used for a wide range of applications including cladding and repair carried out for example as mold-to-surface application for high-value parts such as aerospace engine components and military equipment.

Linde solutions for LMD processes:
- Argon, helium, nitrogen gas supply – system design, provision and installation
- Active gas supply – pre- or onsite mixed gases satisfying specific process demands
- On-site support – process and/or technical support
- On-stream gas system – design and maintenance services
- Gas safety – equipment, safety checks and training
Additive manufacturing processes.
Selective laser sintering.

Selective laser sintering (SLS) is a popular additive manufacturing process using polymer powder such as nylon, carbon fiber, glass-filled nylon and fine polyamide. Linde supplies customers with liquid gases and on-site nitrogen generation systems to assist with selective laser sintering processes.

The process:
SLS is popular with prototypers and product designers thanks to its ability to rapidly convert complex CAD geometries into working prototypes.

The SLS process commences with the polymer powder heated to just below melting point. A CO₂ laser then sinters the powder in an inert gas atmosphere.

Once the first layer build has been completed, the build platform drops down before the leveling roller pushes fresh powder onto the platform. Nitrogen is frequently used to protect the heated powder and material from further reactions with ambient air.

Linde solutions for SLS processes:
- Nitrogen or argon gas supply – design, provision and installation
- On-site support – process and/or technical support
- On-stream gas system – design and maintenance services
- Gas safety – equipment, safety checks and training
Additive manufacturing processes.
Wire arc additive manufacturing.

Gas-metal arc welding (MIG/MAG) and plasma welding techniques are used to melt metal filler to form a 3D component layer by layer. Gases are applied to protect the hot substrate against the ambient atmosphere and to adjust the metallurgical properties of the component.

Linde offers a wide variety of specialist welding gas solutions to protect and fine-tune material properties.

The wire arc AM process:
As in standard MIG/MAG welding, metal wire is added as the electrode melts in the arc and its droplets form layers on the substrate. Processes with lower heat input, such as controlled short-circuit metal transfer, are preferred given the heat sensitivity of most materials used in additive manufacturing. Shielding gases protect the layers against ambient air.

The plasma process:
Plasma additive manufacturing is similar to laser metal deposition; powder is guided towards the substrate in a gas stream and fused by the plasma heat.

Linde solutions for the arc processes:
→ Argon and helium gas supply – design, provision and installation
→ Active gas supply – pre- or onsite mixed gases satisfying specific process demands
→ Plasma gases – required to generate the plasma
→ On-site support – process and/or technical support
→ On-stream gas system – design and maintenance services
→ Gas safety – equipment, safety checks and training
Additive manufacturing processes.
Thermal spraying.

Thermal spraying involves a well-established range of industrial coating technologies used to improve component properties such as wear and corrosion resistance by adding a layer of desired composition. Linde supplies customers with argon, helium, nitrogen and gas mixtures in either gaseous or liquid form.

The process:
Molten, heated powder particles or droplets from molten wires are accelerated in a gas stream towards the substrate, where local adherence is ensured by kinetic energy and heat.

When used for additive manufacturing, thermal spraying is applied layer by layer to build up components without geometrical complexity, e.g. tubes or reducers. Process gases protect the hot material against ambient atmospheric gases and help to fine-tune material properties.

Linde solutions for thermal spraying processes:
- Argon, helium and nitrogen gas supply – design, provision and installation
- Active gas supply – gases mixed in advance or on site satisfying specific process demands
- CO₂ gas supply – spot cooling of sensitive layers
- On-site support – process and/or technical support
- On-stream gas system – design and maintenance services
- Gas safety – equipment, safety checks and training
Additive manufacturing processes.
Electron beam melting.

Electron beam melting (EBM) is described as a powder bed fusion process using an electron beam in a vacuum. EBM processes are similar to direct metal laser sintering, with a higher build-up rate and lower surface quality.

Linde supplies customers with pure gaseous or liquid helium systems to assist with EBM build cooling processes.

The process:
Electron beam melting grows complex parts in a vacuum chamber and is thus suitable for materials sensitive to reaction with air gas components such as titanium. The electron beam melts the metal powder bed, growing the component part layer by layer. The process temperature can be as high as 850 °C.

Orthopedic manufacturers use electron beam melting processes to make bespoke and standard titanium implants. In the aerospace and defense industries, EBM is ideal for non-critical prototype components as it reduces both weight and costs by eliminating the need for conventional machining methods. Inert gases such as helium are applied for cooling during the component build process.

Linde solutions for EBM processes:
- Helium gas supply – design, provision and installation
- On-site support – process and/or technical support
- On-stream gas system – design and maintenance services
- Gas safety – equipment, safety checks and training
Powder metallurgy and additive manufacturing

The processes:
Most AM components require a heat treatment step to reduce stress. High-performance parts such as aerospace and turbine components will go through the HIP process. CRYOCLEAN® Snow is a technology for cleaning, pretreating and finishing surfaces. The dry ice particles for the cleaning process are simply produced on demand.

Linde solutions for heat treatment and surface cleaning processes:
- Nitrogen and nitrogen/hydrogen mixtures for sintering
- Argon for HIP in an inert atmosphere
- Hydrogen, argon and nitrogen for heat treatment processes such as annealing
- Various inert and active gases and mixtures customized for LINSPRAY applications
- CO₂ for CRYOCLEAN dry ice cleaning and LINSPRAY spot cooling
- Gas supply systems and gas mixing units
- Gas control equipment and monitoring systems

Heat treatment and surface cleaning.

Powder metallurgy processes turn formed metal powder parts into useful components. Internal porosity and voids within the cast metal powder parts have to be eliminated. In addition, specific material properties such as extended hardness may be required. After the production of AM components, heat treatment processes are necessary to achieve the final desired functionality.
Heat treatment and surface cleaning.

Sintering.

Sintering and sinter hardening are powder metallurgy processes which turn metal powders into useful components. Powder metallurgy techniques enable manufacturers to produce net-shape components with complicated geometries without subsequent machining. With a material usage rate of almost 100%, sintering results in little or no scrap.

Linde supplies customers’ sintering processes with liquid nitrogen or nitrogen and hydrogen gas mixtures, complementing these with SINTERFLEX® technology for precise control of gas atmospheres.

The process:
Powdered metal is compacted at room temperature in a press die that is shaped like the final component. After the mass of powder is compacted into a shape and ejected from the press (“green component”), it is fed slowly through a special high-temperature furnace to bond the metal particles together. The green component then goes through a series of thermal processes in the production chain. The key heat treatment processes are sintering, where parts become solid metal components ready for service, or sinter hardening, where parts become solid metal components and are then hardened in the same process cycle.

SINTERFLEX® ACS:
The atmosphere control system (ACS) was developed in close cooperation between Linde and Höganäs AB. Together, Linde and Höganäs offer a complete package of high-performance powders, control equipment and gases, which can be easily adapted to any existing sintering process. Linde’s additional patented Atmosphere Zoning Technology gives precise control of different atmosphere zones in different parts of a continuous furnace.

The Linde solutions for sintering processes:
- Nitrogen or nitrogen/hydrogen – gas mixture system design, provision and installation
- SINTERFLEX® – atmosphere zoning technology and control equipment to support the sintering process, design and installation
- On-stream gas system – design and maintenance services
- Gas safety – equipment, safety checks and training
Heat treatment and surface cleaning.

Hot isostatic pressing.

Hot isostatic pressing (HIP) is an advanced material heat treatment process utilizing elevated temperatures in a contained high pressure atmosphere, to eliminate internal porosity and voids within cast metal materials and components.

Linde supplies customers with liquid argon gas systems to create the appropriate inert atmospheres for HIP processes.

The process:
The work-pieces are treated thermally in a vessel under high isostatic pressures during the HIP process. High purity argon is typically used to provide the inert atmosphere necessary to prevent chemical reactions that might adversely affect the materials being treated.

Under the HIP process conditions of high temperature and high-pressure, micro porosity and voids in cast products are reduced or eliminated by plastic deformation, creep and diffusion bonding. This improves mechanical properties and fatigue performance of manufactured parts. The reliability and service life of critical high performance components are optimized. Typical HIP applications include gas turbine components, automotive engine parts, turbo charger wheels, aerospace structural parts, medical implants, prosthetics and, near-net shape components.

Linde solutions for HIP processes:
→ Argon gas supply systems – design, provision and installation
→ Atmosphere control – commissioning and provision of controlled atmosphere technology and appropriate control equipment to support the HIP processes
→ On stream gas system – design and maintenance services
→ Gas safety – equipment, safety checks and training
The process:
CRYOCLEAN® Snow is a technology for cleaning, pre-treating and finishing surfaces. The dry ice particles for the cleaning process are directly produced on demand. By feeding liquid CO₂ into a specially designed snow chamber, extremely solid dry ice particles are created and shot onto the component surface using compressed air.

CRYOCLEAN Snow combines CO₂ snow and abrasive material for difficult to remove residues. CRYOCLEAN Snow can be utilized as either a manual or automated solution.

CRYOCLEAN Snow in additive manufacturing:
- Removal of unfused powder in laser-fused AM
- Removal of surface oxides in steel, aluminum, etc.
- Removal of flash from post-machined parts
- Cleaning of molds, dies and fixtures
- Cleaning during post-machining processes
- Removal of small residues from drilled and tapped holes

Linde solutions for CRYOCLEAN® processes:
- CRYOCLEAN Snow – provision, installation and commissioning of a manual or automated cleaning system
- Liquid CO₂ supply – design, provision and installation of a liquid carbon dioxide gas system
- PRESUS® pressure control – CO₂ pressure control system
- On site support – process and/or technical support
- On stream gas system – design and maintenance service
- Gas safety – equipment, safety checks and training
Linde – leading in powder metallurgy and additive manufacturing innovation.

Catapult center and research facility member:

Linde is proud to be members of the Manufacturing Technology Centre (MTC) in Ansty, Coventry, Nuclear Advanced Manufacturing research Centre (NAMrC), Sheffield and also the Welding Institute.

Linde is engaged in a number of development projects within powder metallurgy and additive manufacturing processes, aimed at shaping the future of additive manufacturing.

ACCLAIM project

Linde is proud to be an active member of the ACCLAIM project consortium. The ACCLAIM (Accelerated Cladding and Integrated Machining) project received approximately £700,000 of support from the UK’s innovation agency, the Technology Strategy Board.

With this support, ACCLAIM aims to address current challenges facing the additive manufacturing (AM) sector, in particular limiting factors such as the cost, time and resources involved in finishing parts after an AM build and ways to improve the mechanical performance of AM-built parts.

In-house R&D and customer trials:

Linde has installed a 3D printing unit to extend its own knowledge of the effect of gases, gas purities and gas supply options on AM outcomes. Close cooperation with one of the leading AM machine suppliers further helps Linde to satisfy customer demands and to develop customized solutions.

The 3D printing machine is also used for private customer research, test and trials, to optimize customer processes and support new applications.
Linde – world-class gas supply options.

Linde offers a complete range of gas supply options available which include single gas cylinders, manifold cylinder pallets, liquid deliveries and on-site generation of nitrogen (where applicable). In addition, Linde provides advice and guidance to help customers select the most effective supply solution to meet their process, quality, productivity and cost targets. Linde remains committed to developing and tailoring its services to customer needs, now and in the future, and to helping support increased productivity and growth.

Linde can tailor a gas supply system to the purity, pressure and flow rates required, taking into account the specific application and the constraints of the working environment.
Environmental commitment

Linde recognizes that all industrial and chemical processes impact on the environment and thus actively engages in various activities to reduce environmental impact. Linde works with many customers to help them improve their environmental performance, including assisting them to reduce greenhouse gas emissions, maximize the efficiency of their processes and improve waste water treatment processes.

Cylinder gases

Linde supplies atmospheric gases such as oxygen, argon, nitrogen, fuel gases, and other gases such as hydrogen, helium and carbon dioxide in gas cylinders. Cylinders are the ideal means of supply for smaller volumes of gas, offering flexibility of demand.

Bulk deliveries

For large-volume users, a bulk cryogenic storage vessel, filled regularly, eliminates cylinder handling and the need for delivery assistance. Liquefied industrial gases (nitrogen, oxygen and argon) are produced in large quantities at our air separation units (ASUs). These gases are produced by liquefying and distilling the air into its component parts at cryogenic temperatures. Liquefied carbon dioxide is recovered from a variety of sources including ammonia and hydrogen plants, and then purified.

On-site gas generation

For some customers, the economical, environmentally sound, flexible and reliable solution of on-site gas generation is the best choice. Oxygen, nitrogen and hydrogen, can be generated on-site in purities from 90% to over 99.9%.

Special products

Linde supplies an extensive range of special gases, chemicals and refrigerants as well as gas control equipment. The gases portfolio is supported by a full range of services including gas handling, and safety training courses.

Key areas of expertise are:

→ Specialty gases: High-purity gases (including helium), process and calibration gas mixtures and gases specifically for the electronics industry.
→ Refrigerants: The full range of fluorocarbons, plus ammonia, hydrocarbons and other natural refrigerants to meet the changing legislative demands of the automotive, refrigeration and air-conditioning markets.
→ Chemicals: A wide range of gaseous chemicals for many fundamental industry sectors including water treatment, chemical manufacturing, materials science, foam manufacture, aerosol propellants, utilities and pharmaceutical manufacturing.
→ Liquid helium: A special service for the supply of liquid helium, typically for nuclear magnetic resonance (NMR) or magnetic resonance imaging (MRI) machines, supplied in low-temperature dewars (vessels containing between 20 liters and 1,000 liters).
→ Safety products: Linde offers an extensive range of safety products. Gas equipment and gas safety are core areas of excellence.
→ Development centers: Linde is running a number of development centers in various countries focusing on cutting-edge technologies, improving manufacturing processes to satisfy the demands of the marketplace and delivering customer efficiencies. Close cooperation with leading R&D institutes and OEMs ensures customer oriented application development and gas supply solutions.
Getting ahead through innovation.

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

Linde offers more. We create added value, clearly discernible competitive advantages and greater profitability. Each solution 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 leader in industry technology by your side for which top quality, process optimization, and enhanced productivity are part of daily business. Linde will not only be there for you … but with you. After all, working together to solve problems forms the core of commercial success.

Linde – ideas become solutions.