VACUUM SYSTEMS
AND TECHNOLOGIES FOR

METALLURGY
HEAT TREATMENT
ALD Headquarters

ALD Vacuum Technologies
Hanau, Germany
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Deep-Rooted Competence

The process and systems know-how available within ALD Vacuum Technologies is based on developments over the past 85 years successfully brought about by the firms Degussa, Heraeus and Leybold. During that period, these companies worked together in a number of ways.

1916
HERAEUS enters the field of vacuum metallurgy when it succeeds in melting chromium-nickel alloys under vacuum conditions.

1930
LEYBOLD starts manufacturing industrial vacuum equipment.

1950
DEGUSSA decides to build vacuum furnaces.

1967
E. Leybold Successors merge with Heraeus-Hochvakuum GmbH to form LEYBOLD-HERAEUS GmbH. Degussa, Heraeus and Metallgesellschaft hold equal interests in Leybold-Heraeus GmbH.

1987
DEGUSSA AG acquires all shares of Leybold-Heraeus GmbH, which is then renamed LEYBOLD AG.

1991
Degussa spins off its Durferrit business including Degussa Industrial Furnaces, while Leybold AG sheds its vacuum metallurgy division. The two spin-offs merge to form LEYBOLD DURFERRIT GmbH.

1994
The vacuum metallurgy and vacuum heat treatment businesses become part of the newly founded ALD Vacuum Technologies.
1998

1999
ALD Vacuum Technologies enters the Own & Operate Business.

2000
Decision about Own & Operate in USA. ALD enters into the vacuum coating business by acquiring all EB/PVD activities from Leybold AG.

2001
Start up of the Own & Operate Business.

2002
Introduction of new heat treatment system, type ModulTherm®.

2003
Cooperation with AFC Holcroft, Wixom, Michigan.

2005
2nd US Own & Operate factory started in Port Huron, Michigan.

2006
ALD Polska, another production site for ALD, started in Czosnow, Poland.
ALD Vacuum Technologies supplies equipment and systems for thermal and thermochemical treatment of metallic materials in solid and liquid form. The company’s competence consists on the one hand of its mastery in vacuum process technology and on the other hand of its know-how in designing custom-tailored system solutions for use in this field.

ALD is noted for its superb know-how basis, high investments in research and development and its strategic alliances. Close collaborations with well-known manufacturers in operator companies have strengthened its position as a supplier of key technologies to major growth markets.

Worldwide Technology and Market Leader

The company is a worldwide technology and market leader in the following fields:

**Vacuum Metallurgy**
This involves designing and supplying systems and processes for treating metallic materials in liquid form – particularly vacuum systems for the melting, casting and remelting of metals and alloys, metals for solar cells as well as special coating equipment for turbine blades.

**Vacuum Heat Treatment**
This includes vacuum furnaces for heat treating metallic materials. Such equipment is used for heat treating of tools, high precision parts for engines and fuel injectors as well as for transmissions. Sintering of high strength cemented carbides and special oxides is also a part of heat treatment.
ALD plants are built for operation around the clock, seven days per week. As and when the need for service arises, a global network is available to send urgently needed spare parts or an experienced service technician. ALD has subsidiaries in 6 countries worldwide and representations in many others. Our marketing and service network and replacement part stocks at strategic locations enable us to react at short notice. Additionally, our headquarters in Germany operate a customer support center with dozens of experts who assist whenever special know-how is required.

ALD services include professional support in emergencies as well as preventive maintenance for plant equipment and the refurbishment of older systems to boost plant availability to the highest possible level. Our services at a glance:

- Delivery of spare parts and consumables;
- Repair services;
- Maintenance and inspection;
- Equipment refurbishment.
VACUUM METALLURGY

The Development of New Vacuum Processes for Metallurgy Drives Technological Advances in Future Markets
Vacuum metallurgy is presently entering a new phase wherein it is assessing the experience gained from continuously developing established processes and joining together new process combinations. Advanced vacuum processes such as steel degassing and ladle metallurgy, melting and remelting, as well as casting and metal-powder technology, have led to high-quality metallurgical products tailored to meet the ever-increasing demands imposed upon them. New processes are being developed that will yield further improvements as well as entirely new products.

The use of these metal-making processes in modern, efficiently functioning production systems greatly reduces costs. The recycling of revert from the processing of costly materials contributes to the economy’s cost-effectiveness. Examples of the products that have been derived from these technologies include highly alloyed special steels and superalloys, refractory and reactive metals with ultrahigh purity and a fine grain structure, precision castings with directional and single-crystal structures, forgings in near net shape, and high-purity powder for homogeneous, high-strength parts.

The resulting materials of high strength and reliability add to demanding applications in the aerospace industries, while the high-purity products contribute to new developments in electronics and offshore and energy applications. Each and every technology has its pros and cons, partially overlapping each other in their techno-economic potentials. Therefore, the proper selection of technology is the most demanding task the plant builder has to solve in close dialog with the producer of the materials and the consumer. This particular challenge is the keystone of the business philosophy of ALD Vacuum Technologies, Hanau / Germany.

Vacuum metallurgy for the airplane of the future. Concealed behind the technical term „vacuum melting and controlled solidification“ as well as „electron beam physical vapor deposition“ are path-breaking technologies for the energy saving airplane of the future. These vacuum metallurgical processes allow large-scale mass production of turbine blades, which reduce fuel consumption by up to 30% and emissions by 15% and more.
Vacuum Induction Melting (VIM/VIDP) Furnaces for Charge Weights from 1 kg up to 30 tons
Vacuum induction melting (VIM) is one of the most commonly used processes in secondary metallurgy applied for refining treatment in the liquid state and adjustment of chemical composition and temperature. To achieve the increasing quality demands on the resulting material and at the same time save raw materials such as alloying elements due to higher yield; and save energy, the application of vacuum in the induction melting process is a must for many specialized materials. For example, vacuum induction melting is indispensable in the manufacture of special alloys, which must be melted under vacuum or in an inert gas atmosphere because of their reactivity with atmospheric oxygen. The process is suitable for the production of high-purity metals within an oxygen-free atmosphere. This limits the formation of non-metallic oxide inclusions. Vacuum induction melting makes possible effective degassing of the melt and extraordinarily precise adjustment of alloy composition, since the temperature, vacuum, gas atmosphere, pressure and material transport (e.g., through stirring of the bath) can be adjusted independently of one another. Besides the exact concentration of alloying elements, the content of trace elements is also important for many alloys.

**Metallurgical Advantages are:**

- Melting under oxygen-free atmosphere, this limits formation of non-metallic oxide inclusions and prevents oxidation of reactive elements;
- Achievement of very close compositional tolerances and gas contents;

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**Current processing route for products cast from VIM/VIDP furnaces**

**Subsequent Treatment**
- Refine
- Purify
- Chemical Control

**Primary Melting**
- Extrude
- Forged Rail

**Wrought Products**
- Billet
- Bar
- Sheet
- Wire

**Secondary Melting Processing**
- Remelt for
  - Microstructural Control
  - Microstructural Control
- Atomize
- Spray Forming
- Investment Casting
- VAR
- ESR
- EB
- Plasma

**Final Processing**
- Powder
- HIP + Forge
- Powder + Extrude
- Extrudable Forge
- Coating
- Thermally Spray Powder

**Precision Cast Products**
- Extruded
- DI-Directional Solidified
- SS-Single Crystalline
- Thermal Barrier Coatings, TBC

**Wrought Products**
- Billet Bar Sheet Extrude Forged Rail to Shape
Removal of undesired trace elements with high vapour pressures;
Removal of dissolved gases e.g. oxygen, hydrogen, nitrogen;
Adjustment of precise and homogeneous alloy-composition and melt temperature.

For this reason, metallurgical operations, such as dephosphorization and desulphurization, are limited. VIM metallurgy is primarily aimed at the pressure-dependent reactions, such as reactions of carbon, oxygen, nitrogen and hydrogen. The removal of harmful volatile trace elements, such as antimony, tellurium, selenium, and bismuth in vacuum induction furnaces is of considerable practical importance.

Exact monitoring of the pressure-dependent reaction of excess carbon to complete the deoxidation is just one example of process versatility using the VIM process for production of e.g., superalloys. Materials other than superalloys are decarburized, desulfurized or selectively distilled in vacuum induction furnaces in order to meet specifications and guarantee material properties. Because of the high vapor pressure of most of the undesirable trace elements, they can be reduced to very low levels by distillation during vacuum induction melting, particularly for alloys with extremely high strengths at higher operating temperatures. For various alloys which must meet the highest quality requirements, the vacuum induction furnace is the most suitable melting system.

Depending on the product and metallurgical process, vacuum levels during the refining phase are in a range of $10^{-1}$ to $10^{-4}$ mbar.

The following methods can be easily combined with the VIM system to produce clean melts:

- Atmosphere control with low leak and desorption rates;
- Selection of a more stable refractory material for crucible lining;
- Stirring and homogenization by electro-magnetic stirring or purging gas;
- Exact temperature control to minimize crucible reactions with the melt;
- Suitable deslagging and filtering techniques during the casting process;
- Application of a suitable launder and tundish technique for better oxide removal.

For particular applications (i.e. rotating engine parts) the quality of the material produced by VIM is the fundamental melting step but it is not sufficient to satisfy the highest requirements with respect to cleanliness and primary structure. The VIM-produced material must undergo a remelting and resolidification step as described in the chapter on ALD’s remelting technologies. For the most advanced quality requirements, the material has to undergo several refining steps such as in a triple melt process consisting of consecutive VIM (vacuum induction melting), ESR (electroslag remelting) and VAR (vacuum arc remelting) processes.
ALD’s Product Range of Vacuum Induction Melting and Casting Furnaces

The casting weight in VIM furnaces by ALD can vary from 1 kg to 30 tons or more, depending on whether the furnace is being used for precision casting or for the production of ingots or electrodes for further processing. A large number of optional items allows a VIM furnace to be tailored for special requirements.

ALD and its predecessor, Leybold-Heraeus, has designed, manufactured and put into operation more than 2000 VIM furnaces worldwide.

VIM Application Advantages

The following advantages have a decisive influence on the high demand for ALD’s vacuum induction melting furnaces in metal production:

- Flexibility due to different batch size;
- Fast change of program for different types of steels and alloys;
- Low losses of alloying elements by oxidation;
- Achievement of very close compositional tolerances;
- Precise temperature control;
- Low level of environmental pollution from dust output;
- Removal of undesired trace elements with high vapor pressures;
- Removal of dissolved gases e.g., hydrogen and nitrogen;
- Choice of vacuum, controlled atmosphere, normal atmosphere or reactive atmosphere;
- Choice of different pumping systems;
- High level of operational safety and good accessibility;
- Broad range of standard accessories and options;
- High reliability and high productivity.

The installation of a programmable control system for automation provides best reproducibility of the melts. In this way, increasing metallurgical demands for cleanliness and homogeneity can be met. In addition, close compositional tolerances can be achieved, as all of the process data are registered, stored and analyzed by a statistical process control.
**VIM Chamber Furnaces Product Line**

The product line is based on the chambertype VIM (Vacuum Induction Melting) or on the compact VIM-VIDP furnace design. Depending on production and economical requirements, the VIM furnace technology can be expanded by different implements. These are:

- **VIM 02-4000** Vacuum Induction Melting in the range of 0.2 to 4,000 liters crucible volume; basic equipment
- **VIM-VIDP** with Mold Treatment
- **VIM-MT** with Vertical Continuous Casting
- **VIM-VCC** with Horizontal Continuous Casting
- **VIM-HCC** with Directional Solidification
- **VIM-DS** with Flakes Casting
- **VIM-HMC** with separate Horizontal or alternatively Vertical Mold Chamber
- **VIM-P** with Over-Pressure Operation
- **VIDIST** with Vacuum Induction Degassing

**Laboratory vacuum induction melting furnace**

The basic equipment is a single-chamber system with a tiltable crucible and an integrated vertical mold chamber, a vacuum pump unit and a melt power supply.

**ALD offers a complete product line of VIM furnaces with charge weights varying from 1 kg up to 30 tons for the making of:**

- Semi-finished products, such as:
  - Wires, strips, rods
  - Ingots and electrodes
  - Targets
  - Structural parts
  - Powders

by the following procedures:

- Mold casting
- Continuous casting
- Centrifugal casting
- Powder atomization
- Spray forming
- Vacuum induction distillation

for use in:

- Research & development
- Electronic industry
- Dental applications
- Automotive and aerospace industry
- Ferrous applications
- Non-ferrous applications
- Precious metal industry
VIM-VCC with vertical continuous strip or wire casting

VIM-VMC
The VIM-VMC furnace is a two-chamber design with vertical mold chamber.

VIM-VCC
Vacuum induction melting with subsequent vertical continuous casting technology under inert gas prevents surface oxidation of cast wires, rods or strips.
Comparison of Larger Standard VIM Chamber Systems

ALD specializes in developing and implementing system designs tailored to customers’ specific needs. The furnaces are equipped with accessories for charging, sampling, temperature measurement, melt stirring facilities for melt treatment, turntable or mold carriage for several molds, etc. In addition to these “engineered” solutions ALD offers a variety of basic versions whose designs fundamentally differ from one another:
1 – 20 tons VIM furnace
The VIM furnace one chamber system with horizontal melt chamber and moveable sidedoor for crucible coil service.

VIM with launder system
Two-chamber system with one turntable for short ingots and another for long ingots. Replaceable heated launderers.

VIM with bottom purging
The VIM furnace can be equipped with a tundish preheating unit and a crucible gas bottom purging device in order to treat the melt with gases. Oxygen blowing for R&D purposes is also possible.
VIM with double-door arrangement
Typical charge weights: 5–30 metric tons. Two-chamber system with horizontal melting chamber and two interchangeable induction furnaces.

VIM-V 6, 4/6 t,
Production of Fe-Ni based electric/magnetic materials.

VIM-HMC
Multi-chamber system with a laterally movable door and furnace insert for easy maintenance. Hydraulic tilting device and power cables are arranged at atmosphere.

VIM-V 6, 25 t,
Melt/cast chamber with separate mold chamber for production of superalloys.
The VID furnace has a compact design with small chamber volume, appropriate for steel melt shops and foundries. It is suitable for liquid and solid charging. It is applied for melting and degassing of special steel and non-ferrous metals, pouring at atmosphere into ladles or casting molds. The standard furnace capacity ranges from 1 up to 15 metric tons.
VIDP Vacuum Induction Degassing and Pouring Furnaces

**VIDP Features:**
- Small furnace volume
  - Reduced desorption surfaces
  - Smaller vacuum pumping system
  - Optimum control of the furnace atmosphere
  - Lower inert gas consumption
- High flexibility
  - Through a range of interchangeable lower furnace bodies
  - Variable pouring techniques (ingot casting, horizontal continuous casting, powder production)
  - Unit can be modularly expanded
  - Connection to multiple casting chambers
- Fast furnace change
  - <1 hour with hot crucible
  - High operating availability
  - Increased productivity by up to 25 %
  - Rapid alloy change
  - Separate crucible break out and relining stations
  - Vacuum drying of crucible available
- Easy to maintain
  - Power cables and hydraulic lines are outside the melting chamber – leaks do not affect the vacuum
  - Simplified maintenance of the vacuum pumps with effective filter system
  - Smaller vacuum pumping system
  - Tried and tested components
  - Preventive fault diagnostic
  - No large vacuum chamber to clean

**System Design**

In comparison to conventional VIM chamber furnaces, the VIDP design is characterized by its compact design with a small melt chamber volume, versatile connection capabilities for a variety of casting chambers and a high degree of cost-effectiveness. The VIDP concept is based on a modular design that can be extended to melting and casting in a vacuum or protective gas atmosphere. The casting process is realized by using a ceramic launder which transfers the liquid metal through a pouring tunnel to the casting (mold) chamber.

The vacuum chamber size is reduced to a minimum – the result is lower pressure, shorter pumping time or smaller pump system capacity, better control of process atmosphere, fast replacement of different furnace bodies with shorter downtimes for crucible exchange, high flexibility in

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Basic principle of a VIDP furnace with tilting vacuum furnace
the type of pouring technique, reduced risk of contamination by eliminating all flexible power cables, water hoses and hydraulic lines from inside the vacuum chamber, lower desorption and leakage rates compared to a conventional chamber-type VIM furnace.

The VIDP concept opens the way for economical production under controlled atmosphere of all high-grade metals and alloys commonly processed in chamber-type VIM furnaces. In detail, the system with a capacity range from 1 ton to 30 tons is applied for the production of

- High-quality superalloys or special steels;
- Critical copper alloys and oxygen-free copper.

**Total view of a VIDP production unit for ingot casting**

1. VIDP melting chamber
2. Mold chamber
3. Charging device
4. Launder/Tundish lock
5. Temperature measurement probe
6. Vacuum system
7. Power supply
8. System control desk
ELECTROSLAG REMELTING (ESR)
ESR has been known since the 1930s, but it took approx. 30 years before it became an acknowledged process for mass production of high-quality ingots. The ESR technology is of interest not only for the production of smaller weight ingots of tool steels and superalloys, but also of heavy forging ingots up to raw ingot weights of 165 tons.

**Process Technology and Process Characteristics**

Whereas VAR needs vacuum for refining, in ESR the consumable electrode is dipped into a pool of slag in a water-cooled mold. An electric current (usually AC) passes through the slag, between the electrode and the ingot being formed and superheats the slag so that drops of metal are melted from the electrode. They travel through the slag to the bottom of the water-cooled mold where they solidify. The slag pool is carried upwards as the ingot forms. The new ingot of refined material builds up slowly from the bottom of the mold. It is homogeneous, directionally solidified and free from the central unsoundness that can occur in conventionally cast ingots as they solidify from the outside inwards.

Generally the ESR process offers very high, consistent, and predictable product quality. Finely controlled solidification improves soundness and structural integrity. Ingot surface quality is improved by the formation of a solidified thin slag skin between ingot and mold wall during the remelting operation. This is why ESR is recognized as the preferred production method for high-performance superalloys that are used today in industries such as aerospace and nuclear engineering as well as for heavy forgings. Ingots are obtained with purity levels that were unheard of some years ago. Other branches of engineering are following the examples of the “high-tech” pacesetters and insist on new, high purity levels that can be obtained from ESR with the latest, most sophisticated equipment.
Metallurgy of the Electroslag Remelting Process

Due to the superheated slag that is continuously in touch with the electrode tip, a liquid film of metal forms at the electrode tip. As the developing droplets pass through the slag, the metal is cleaned of non-metallic impurities which are removed by chemical reaction with the slag or by physical flotation to the top of the molten pool. The remaining inclusions in ESR are very small in size and evenly distributed in the remelted ingot.

Slags for ESR are usually based on calcium fluoride (CaF$_2$), lime (CaO) and alumina (Al$_2$O$_3$). Magnesia (MgO), titania (TiO$_2$) and silica (SiO$_2$) may also be added, depending on the alloy to be remelted.

To perform its intended functions, the slag must have some well-defined properties, such as:

- Its melting point must be lower than that of the metal to be remelted;
- It must be electrically efficient;
- Its composition should be selected to ensure the desired chemical reactions;
- It must have suitable viscosity at remelting temperature.

In spite of directional dendritic solidification, various defects, such as the formation of tree ring patterns and freckles, can occur in remelted ingots. Reasons for the occurrence of these defects are the same as in VAR. It is important to note that white spots normally do not occur in an ESR ingot. The dendrite skeletons or small broken pieces from the electrode must pass the superheated slag and have enough time to become molten before they reach the solidification front. This prevents white spots.

The ingot surface covered by a thin slag skin needs no conditioning prior to forging. Electrodes for remelting can be used in the as-cast condition.

Electroslag Remelting Furnaces

Significant advances have been made over the years in plant design, coaxial current feeding and particularly in computer
control and regulation with the objective of achieving a fully-automatic remelting process. This in turn has resulted in improved metallurgical properties of the products. A fully coaxial furnace design is required for remelting of segregation-sensitive alloys in order to prevent melt stirring by stray magnetic fields.

Shielding of the melt space with protective atmosphere has been the latest trend in recent years. Remelting under increased pressure to increase the nitrogen content in the ingot is another variation of ESR. ESR furnaces can be designed for remelting of round, square and rectangular (slab) ingots.

Finally, computer controlled process automation has been developed to perform similarly to ALD’s automatic melt control system (AMC) described under VAR. Important to mention here is that ALD’s electrode immersion depth control into the slag is based on slag resistance or slag resistance swing. Using the resistance parameter automatically decouples the immersion depth and remelting rate control loops which are otherwise cross-influencing each other.

Also for ESR it can be stated that ALD’s automatic melt control system (AMC) is unsurpassed in the world for its inherent features, ease of operation and last but not least its accuracy and repeatability of control, producing ingots with excellent properties, including:

- Homogeneous, sound and directionally solidified structure;
- Free of internal flaws (e.g. hydrogen flakes);
- Free of macro-segregation;
- Smooth ingot surface resulting in a high ingot yield.

### Electroslag Remelting of Heavy Forging Ingots

At the end of the 1960s, the concept of using ESR plants to manufacture large forging ingots gained acceptance. Increasing demand for larger electrical power generating units required forging ingots weighing 100 tons or more for manufacturing of generator and turbine shafts. ALD’s largest ESR furnace, commissioned in the early 1970s, allows to manufacture ingots of 2,300 mm

165 ton ESR furnace
diameter and 5,000 mm length weighing up to 165 tons. The furnace operates with ingot withdrawal employing four consumable electrodes remelted simultaneously in the large diameter mold and replacing the consumed electrodes with subsequent ones and as many as necessary to produce the desired ingot weight.

Directional solidification must be ensured over the entire ingot cross-section and length to avoid interior defects, such as macro-segregation, shrinkage cavities and non-uniform distribution of inclusions. By maintaining the correct remelting rate and slag temperature, directional solidification can be achieved for ingot diameters as large as 2,300 mm. Accordingly, the ESR ingot is free from macro-segregation in spite of the large diameter. The cleanliness and homogeneity of ESR ingots result in excellent mechanical properties as compared to conventionally cast steel ingots.

**Process Variations**

Three ESR process variations have been developed by ALD:
- Remelting under increased pressure (PESR);
- Remelting under inert gas atmosphere (IESR);
- Remelting under reduced pressure (VAC-ESR).

**Pressure Electroslag Remelting (PESR)**

Over the past 30 years, nitrogen has become increasingly attractive as an inexpensive alloying element for enhancing the properties of steel. In austenitic steel, nitrogen, particularly in dissolved form, increases yield strength by forming a super-saturated solid solution. With ferritic steel grades, the aim is to achieve a fine dispersion of nitrides comparable to the microstructure obtained by quenching and tempering iron-carbon alloys. For the production of these new materials, it is essential that a sufficiently high amount of nitrogen above the solubility limit under normal pressure is introduced into the molten steel and that nitrogen loss is prevented during solidification. As the solubility of nitrogen is proportional to the square root of its partial pressure, it is possible to introduce large amounts of nitrogen into the melt and allow it to solidify under higher pressure. This has been verified by the electroslag remelting process at an operating pressure of 42 bar.

Due to the extremely short dwell time of the metal droplets in the liquid phase during
remelting, the nitrogen pick-up via the gas phase is insufficient. The nitrogen must, therefore, be supplied continuously during remelting in the form of solid nitrogen-bearing additives. The high pressure in the system serves exclusively to retain the nitrogen introduced into the molten steel. The pressure level depends on the composition of the alloy and on the desired nitrogen content of the remelted ingot.

**Remelting under Inert Gas Atmosphere (IESR)**

As a consequence of ALD’s development work in PESR processing, ALD nowadays recommends to conduct the ESR process under a fully enclosed inert gas atmosphere at atmospheric pressure. This is a great step forward in freeing the ESR process from hydrogen pick-up problems and the influence of seasonal atmospheric changes. In addition it allows remelting under oxygen-free inert gas.

The following results have been obtained:
- Oxidation of electrode and slag is completely avoided;
- Oxidizing loss of elements such as Ti, Zr, Al, Si, etc. is almost completely avoided. This is especially important when remelting high Al and Ti-containing alloys, like superalloys with very narrow analytical ranges;
- Better cleanliness in the ingot is achieved;
- When using argon as the inert gas, pick-up of nitrogen and hydrogen is avoided (When using nitrogen as the inert gas, some pick-up of nitrogen is possible).

Due to the absence of oxygen in the furnace atmosphere, desulfurization via the gas phase is no longer optimal. However, sulfur is today taken care of by ladle metallurgy in the making of steel electrodes.

Two furnace concepts are available, one with a protective hood system of relative tightness, the other with a fully vacuum-tight protective hood system that allows the complete exchange of air against an inert gas atmosphere prior to starting the remelting process.
Electroslag Remelting under Vacuum (VAC-ESR)

Electroslag remelting under vacuum is another newly developed process. Remelting is carried out under vacuum as in VAR, however, using a slag. Problems of oxidation of the melt do not arise. In addition, dissolved gases such as hydrogen and nitrogen, can be removed and the danger of white spots, as encountered during VAR, is reduced to a minimum. Thus, the advantages of both ESR and VAR are combined in one process. That is of interest for superalloys or titanium remelting.

Furnace Types

ALD has developed five basic ESR furnace concepts:

Pilot Systems
for stationary and moving mold applications. These are particularly well-suited for experimental and pilot production, and for the performance of high-versatility ESR operation at low investment cost.

Stationary Mold Systems
with two fixed remelting stations and one pivoting furnace head. These are particularly suited for efficient production at high production rates.

Ingot Withdrawal Systems
with central ingot withdrawal station and electrode exchange capability, and two outer stations for remelting in stationary molds. The central station is particularly suited for remelting of large diameter ingots. Smaller diameter ingots may be remelted simultaneously in the outer stations.

Atmospheric Protection Systems
for stationary mold application with closed furnace hood system to remelt under inert gas atmosphere. These systems are particularly recommended when remelting Ti, Al and rare-earth containing alloys or alloys with low Al content (< 0.005).
**Pressurized/Vacuum Systems**
Completely sealed systems for ESR operations under vacuum, inert gas, or increased pressure. These systems are particularly suited for producing ESR ingots with high contents of nitrogen or reactive elements.

**ESR Features:**
- Ingot weights from 100 kg to 165 metric tons;
- Alternating current as remelting energy with melting currents from 3 kA to 92 kA;
- Ingot diameters from 170 mm to 2,300 mm, depending on material being remelted;
- Circular, square and rectangular ingot shapes are possible;
- ALD offers systems for special processes such as remelting under pressure, protective gas or vacuum. A growing market share is anticipated for these processes, especially the IESR process under inert gas atmosphere.

**ESR Applications:**
- Tool steels for milling cutters, mining, etc.;
- Die steels for the glass, plastics and automotive industries;
- Ball-bearing steels;
- Steels for turbine and generator shafts;
- Superalloys for aerospace and power turbines;
- Nickel-base alloys for the chemical industry;
- Cold rolls.
VACUUM ARC REMELTING (VAR)
VAR is widely used to improve the cleanliness and refine the structure of standard air-melted or vacuum induction melted ingots, then called consumable electrodes. VAR steels and superalloys as well as titanium and zirconium and its alloys are used in a great number of high-integrity applications where cleanliness, homogeneity, improved fatigue and fracture toughness of the final product are essential. Aerospace, power generation, defense, medical and nuclear industries rely on the properties and performance of these advanced remelted materials.

**Process Technology and Process Characteristics**

VAR is the continuous remelting of a consumable electrode by means of an arc under vacuum. DC power is applied to strike an arc between the electrode and the baseplate of a copper mold contained in a water jacket. The intense heat generated by the electric arc melts the tip of the electrode and a new ingot is progressively formed in the water-cooled mold. A high vacuum is being maintained throughout the remelting process.

The basic design of the VAR furnace has been improved continuously over the years particularly in computer control and regulation with the objective of achieving a fully-automatic remelting process. This in turn has resulted in improved reproducibility of the metallurgical properties of the products.

**Metallurgy of the Vacuum Arc Remelting Process**

The VAR ingot's solidification structure of a given material is a function of the local solidification rate and the temperature gradient at the liquid/solid interface. To achieve a directed dendritic primary structure, a relatively high temperature gradient at the solidification front must be maintained during the entire remelting process. The growth direction of the cellular dendrites conforms to the direction of the temperature gradient, i.e., the direction of the heat flow at the moment of solidification at the solidification front. The direction of the heat flow is always perpendicular to the solidification front or, in case of a curved interface, perpendicular to the respective tangent. The growth direction of the dendrites is thus a function of the metal pool profile during solidification. As pool depth increases with the remelting rate, the growth angle of the dendrites, with respect to the ingot axis, also increases. In extreme cases, the growth of the directed dendrites can come to a stop. The ingot core then solidifies non-directionally, e.g., in equiaxed grains, leading to segregation and micro-shrinkage. Even in the case of directional solidification, micro-segregation increases with dendrite arm spacing.
A solidification structure with dendrites parallel to the ingot axis yields optimal results. However, a good ingot surface requires a certain level of energy input, resulting in respective remelting rates. Optimal melt rates and energy inputs depend on ingot diameter and material grade, which means that the necessary low remelting rates for large diameter ingots cannot always be maintained to achieve axis-parallel crystallization.

In spite of directional solidification, defects such as “tree ring patterns”, “freckles” and “white spots” can occur in remelted ingots. These defects can lead to rejection of the ingot, particularly in the case of special alloys.

Tree ring patterns can be identified in a macro-etched transverse section as light-etching rings. They usually represent a negative crystal segregation. Tree ring patterns seem to have little effect on material properties. They are the result of a wide fluctuation of the remelting rate. In modern VAR plants, however, the remelting rate is maintained at the desired value by precise computer control of the electrode weight diminution and electrode speed of feed, so that the remelting rate exhibits no significant fluctuation unless caused by electrode defects.

Freckles and white spots have a much greater effect on material properties as compared to tree ring patterns. Both defects can represent a significant cause for premature failure of turbine disks in aircraft engines. Freckles are dark etching circular or nearly circular spots that are generally rich in carbides or carbide forming elements. The formation of freckles is usually a result of a high metal pool depth and sometimes of a rotating pool. The liquid pool can be set in rotation by stray magnetic fields. Freckles can be avoided by maintaining a low pool depth and by eliminating disturbing magnetic fields through coaxial current feeding on the VAR furnace. White spots are typical defects in VAR ingots.
They are recognizable as light etching spots on a macro-etched surface. They are lower in alloying elements, e.g., titanium and niobium in Inconel 718.

There are several mechanisms that could account for the formation of white spots:
- Residues of unmelted dendrites of the consumable electrode in the ingot;
- Pieces of arc splatter that fall into the metal pool and are not dissolved or remelted and get embedded in the ingot;
- Pieces of the ingot shelf region transported into the solidifying interface of the ingot.

All three of the above-mentioned mechanisms, individually or combined, can be considered as possible sources for white spots. This indicates that white spots cannot be avoided completely during vacuum arc remelting, as they are inherent in the process. To minimize their frequency of occurrence, the following conditions should be observed:
- Use of maximum acceptable remelting rate permitted by the ingot macro-structure;
- Use of short arc gap to minimize crown formation and to maximize arc stability;
- Use of homogeneous electrode substantially free of cavities and cracks;
- Use of proper melting power supply to reduce excessive current spikes during drop shorts.

**Process Control**

Close control of all remelting parameters is required for reproducible production of homogeneous ingots, which are free of macro-segregation and show a controlled solidification structure and superior cleanliness.
To fulfill today’s most stringent material quality specifications, VAR furnaces make use of computer controlled process automation. Logic control functions, continuous weighing of the consumable electrode, closed loop control of process parameters (e.g., remelting rate, arc gap based on arc voltage or drop short pulse rate), data acquisition and management are handled by dedicated computer systems. These computer systems communicate via field bus or specific interfaces. An operator interface PC (OIP) acting hierarchically as master of the automatic melt control system (AMC) is utilized as the interface between operator and VAR process. The OIP serves for process visualization, featuring parameter indications, graphic displays and soft keys for operator commands, editing and handling of remelting recipes, data acquisition and storage as well as for generation of melt records. Optionally the OIP can be equipped with an Ethernet network interface which may be utilized for data transfer to other computers connected to the local area network (e.g., supervisory PC, customer’s main frame, etc.).

Established remelting parameters are stored as remelting recipes on hard disk and are available for subsequent VAR production of respective ingot size/material grade combinations to assure reproducibility of the metallurgical ingot quality.

ALD’s automatic melt control system (AMC) is unsurpassed in the world for its inherent features, ease of operation and last but not least its accuracy and reproducibility of control.

**Schematic of the VAR furnace**
1. Electrode feed drive
2. Furnace chamber
3. Melting power supply
4. Busbars/cables
5. Electrode ram
6. Water jacket with crucible
7. Vacuum suction port
8. X/Y adjustment
9. Load cell system
VAR Advantages

The primary benefits of remelting a consumable electrode under vacuum are:

- Removal of dissolved gases, such as hydrogen, nitrogen and CO;
- Reduction of undesired trace elements with high vapor pressure;
- Improvement of oxide cleanliness;
- Achievement of directional solidification of the ingot from bottom to top, thus avoiding macro-segregation and reducing micro-segregation.

Oxide removal is achieved by chemical and physical processes. Less stable oxides or nitrides are thermally dissociated or are reduced by carbon present in the alloy and are removed via the gas phase. However, in special alloys and in high-alloyed steels the non-metallic inclusions, e.g. alumina and titanium-carbonitrides, are very stable. Some removal of these inclusions takes place by flotation during remelting. The remaining inclusions are broken up and evenly distributed in the cross-section of the solidified ingot.

VAR Features:

- Ingot diameters up to 1,500 mm;
- Ingot weights up to 50 tons;
- Electrode is melted by means of a DC arc under vacuum (electrode negative, melt pool positive);
- Remelting currents up to 40 kA;
- Vacuum range: 1–0.1 Pa (some applications up to 1000 Pa);
- Electrode weighing system;
- Stable or free-standing gantry design;
- Coaxial high current feeding system;
- Computer controlled remelting process according to remelting recipes (arc gap control, melt rate control, data acquisition system, print-out of melt records).

VAR Applications:

- Superalloys for aerospace;
- High strength steels for rocket booster rings and high pressure tubes;
- Ball-bearing steels;
- Tool steels (cold and hot work steels) for milling cutters, drill bits, etc.
- Die steels;
- Melting of reactive metals (titanium, zirconium and their alloys) for aerospace, chemical industry, off-shore technique and reactor technique.
ELECTRON BEAM MELTING (EB)
Electron beam melting is distinguished by its superior refining capacity and offers a high degree of flexibility of the heat source. Thus, it is ideal for remelting and refining of metals and alloys under high vacuum in water-cooled copper molds. Today the process is mainly employed for the production of refractory and reactive metals (tantalum, niobium, molybdenum, tungsten, vanadium, hafnium, zirconium, titanium) and their alloys. It plays an important role in manufacturing of ultra-pure sputtering target materials and electronic alloys and the recycling of titanium scrap.

**Metallurgy of the Electron Beam Melting Process**

Electron beam guns represent high temperature heat sources which are able to exceed the melting and even evaporation temperatures of all materials at their beam spot. By magnetic deflection and rapid scanning at high frequencies the electron beam can be effectively directed at targets of multiple shapes and is thus the most flexible heat source in remelting technology. The electron beam impinges on the target with typical power densities of 100 W/cm². Depending on the melt material, the power transfer efficiency ranges from approx. 50 to 80%. Since EB melting is a surface heating method, it produces only a shallow pool at acceptable melt rates which positively effects the ingot structure regarding porosity, segregation, etc. The exposure of the super-heated metal pool surface to the high vacuum environment at levels of 1-0.001 Pa results in excellent degassing of the molten material. Metallic and non-metallic constituents with vapor pressures higher than the base material are selectively evaporated thus generating the desired high purity of the ingot material. In other cases, however, this can create loss of desired alloy constituents which must be accounted for.

**Process Variations**

The high degree of flexibility of the EB heat source has spawned the development of several remelting and refining methods.

- **Drip Melting** is the classical method for processing refractory metals such as Ta and Nb among others. Raw material in form of bars is usually fed horizontally and drip-melted directly into the withdrawal mold. The liquid pool level is maintained by withdrawing the bottom of the growing ingot. Refining is based on degassing and selective evaporation as described above.
Mostly repeated remelting of the first melt ingots is required to achieve the final quality. For repeated remelting, vertical feeding is applied.

**Electron Beam Cold Hearth Refining (EBCHR)**

is of great importance for processing and recycling of reactive metals. The feedstock is drip-melted in the rear part of a water-cooled copper hearth from where it overflows into the withdrawal mold. During the dwell time of the molten material in the hearth system gravity separation of high- and low-density inclusions (HDI, LDI) can be achieved in addition to the refining mechanisms described above. The hearth must be properly sized to provide sufficient dwell time of the molten metal in the hearth in order to permit efficient gravity separation of HDIs and LDIs. Larger hearth melting systems are equipped with a larger number of EB guns to provide the required power and energy distribution.

**Button Melting**

is utilized for cleanliness evaluation of superalloy samples regarding type and quantity of low-density, non-metallic inclusions. The equipment features programmed automatic sample melting and controlled directional solidification. Low-density inclusions (normally oxides) float to the surface of the pool and are concentrated in the center, on top of the solidifying button.

**Floating Zone Melting**

Floating zone melting is one of the oldest techniques for the production of metals with highest purity.

**Process Control**

EB furnaces operate in a semi-automatic control mode. Even with the highly sophisticated computer controlled process automation, operator supervision of the process and manual fine tuning are still required.

Process automation includes:
- vacuum pump system scheme;
- vacuum pressure control;
- material feed rate and ingot withdrawal rate;
- processor-based high voltage and emission current control;
- PC-based automatic beam power distribution;
- data acquisition and archiving.

For process-specific power distributions, the beam deflection has to be controlled with respect to location and dwell time. For this purpose, ALD has developed a PC-based electron beam scan and control system “ESCOSYS” for simultaneous control of several EB guns. This system fulfills the highest requirements for complex beam power distribution which is defined in melt recipes by selecting suitable deflection patterns from a variety of available pattern shapes. These can be graphically edited in size and location on the melt geometry and visualized on the computer screen. Patterns are automatically corrected for projected angular distortions on the targets. The active power fraction in each pattern is defined by the dwell time as part of the pattern parameter set. An operation mode for the so-called power distribution management is also included. Here the
actual beam pattern on the target is calculated by the computer based on operator definitions. As part of the furnace commissioning a special teach-in program is evoked for the computer to learn about the melt geometry and its dependency on the deflection frequency. This way, electron beam excursions beyond the melt boundaries are recognized and automatically limited when editing deflection patterns.

**Electron Beam Guns and Melting Furnace Types**

The following systems are available:

- **Electron Beam Guns**
  
  a series of EB guns with 60, 300 and 600-kW beam power at 25–45 kV.

- **EB Drip-Melt Production Furnaces**
  
  for production of refractory metal ingots up to 400 mm in diameter and 3,000 mm length, beam powers up to 2 MW with 2, 3 or 4 guns.

- **EB Cold Hearth Production Furnaces**
  
  for production of reactive metal ingots and slabs, including material recycling. Ingot weights up to 15 tons, total beam power above 3 MW with up to 6 guns.

- **EB Pilot Production Furnaces**
  
  permitting both dripmelting and cold hearth refining, equipped with all facilities to conduct these processes. Total beam power 200–500 kW with 2 guns.

- **EB Laboratory Furnaces**
  
  for research and development.

- **EB Button Melting Furnaces**
  
  for producing test buttons of 30 mm Ø; 8 mm height; 0.7 kg weight (Ni-based superalloys), required EB-power 30 kW.

- **EB Floating Zone Melting Furnace**
  
  rods up to 20 mm in diameter and 300 mm length can be treated. An annular electron beam system of 10 kW is employed.

**EB Features**

- ALD offers electron beam guns of 60, 300 and 600 kW power with highly advanced beam deflection controls;
- System designs are implemented with melting powers of up to 3,600 kW;
- Ceramic-free melting process for circular, square and rectangular ingot shapes.

**EB Applications**

- Remelting of high-purity refractory materials such as Nb and Ta;
- Titanium production for the chemical and aerospace industries;
- Zirconium production for the chemical industry;
- Production of high-purity metals for electronic applications (e.g., sputtering targets).
VACUUM INVESTMENT CASTING (VIM-IC)

- Vacuum Induction Melting and Casting with Ceramic Crucibles
- Liquid Metal Cooling for DS/SC Solidification
- Cold Crucible Induction Melting and Casting
- Vacuum Arc Melting and Casting
Vacuum Induction Melting and Casting Furnaces with Ceramic Crucibles

The majority of vacuum investment castings like turbine blades and vanes for the aircraft and industrial gas turbine industries are made from Ni-base superalloys and are produced in a vacuum induction melting and precision casting furnace. In vacuum precision casting furnaces, a master alloy composition is inductively melted and then cast into an investment mold. The solidification structure of the casting can be adjusted to be equiaxed (E) (uncontrolled, from outside to inside) or, through the use of an additional mold heater, directionally solidified (DS) or single crystal (SC).

The DS/SC solidified components have increased strength at high temperatures close to the melting temperature of the alloys.

General System Design

ALD’s furnace concepts can be tailormade to fit every customer’s needs. ALD’s competence includes tilt pour as well as crucible versions with bottom-pouring techniques, static and centrifugal casting techniques are applied.

Depending on the required solidification structure and the size of the components, ALD offers vertical and horizontal furnace designs. For casting capacities up to approx. 20 liters/150 kg and mold sizes
up to a diameter and height of approx. 800 mm the vertical furnace design is the most cost-effective solution.

For higher casting weights and larger molds, the pouring geometry and the handling of the molds become more complex and require alternative furnace concepts.

Here the horizontal furnace design, with the mold loading station outside the furnace, allows easy loading of large and heavy molds. 2-axial motion systems for either the mold or the induction coil enable centric pouring into the pour cup at minimized metal drop heights.

Liquid Metal Cooling for DS/SC Solidification

For the production of large directionally solidified (DS) and single crystal (SC) components high thermal gradients are required. In order to provide the highest temperature gradient and a flat solidification front, ALD’s patented “central baffle with heat sink” may be applied. The “central baffle with heat sink” provides an improved thermal environment during solidification of particularly large DS/SC components.

A further improvement of the solidification conditions for large DS/SC components is provided by the liquid metal cooling (LMC) process. In the LMC process, the mold is immersed for solidification of the components into a liquid cooling bath, either consisting
of aluminum or tin. The heat extraction from the component is based on heat conduction and convection, which is remarkably better than the radiation heat extraction of the conventional DS/SC process. Larger temperature gradients are especially important for the production of large DS/SC parts, e.g., for turbine blades and vanes for stationary gas turbines.

ALD has built several LMC furnaces for R & D and pilot production of directionally solidified and single crystal structures by the LMC process with tin as well as with aluminum as cooling agent.

In total, ALD has built more than 100 vacuum precision casting furnaces for customers all around the world and the largest mold heater (48” x 60” / 1,200 mm x 1,500 mm) ever used for the production of DS/SC components.
Cold Crucible Induction Melting and Casting

LEICOMELT® Furnaces System Design

When reactive materials such as titanium, zirconium, superconductors and hydrogen storage materials, shape memory alloys, magnets, intermetallic alloys and high temperature materials are to be processed with stringent requirements towards cleanliness and structural control, the cold crucible induction melting and casting method is the solution to overcome major limitations of the induction melting method with ceramic crucibles.

- The copper crucible avoids any contamination of the charge material;
- Electromagnetic stirring of the melt provides excellent thermal and chemical homogenization of the melt.

The cold wall induction crucible is made of a plurality of water-cooled copper segments that allows the induction field to couple and heat the charge material. The induction field creates a vigorously stirred melt throughout the entire melt time with excellent chemical and thermal homogenization. Because LEICOMELT® furnaces are basically induction melting furnaces, they can be charged with casting revert scrap, turnings and sponge rather then utilizing expensive round ingots. One of the salient features is the combination of the alloying itself and subsequent pouring in one temperature.

ALD is marketing LEICOMELT® furnaces with melt volumes within the range of some cubic centimeters up to 30 liters. Tilt pour and bottom-pouring systems are applied. Static and centrifugal investment molds or permanent molds made of special alloys complete the range of casting techniques.

Applications:
- Titanium golf club heads;
- Titanium aluminide automobile valves;
- Structural and engine parts (titanium castings) for the aerospace industry;
- Implants for human medicine;
- Hot-end turbo charger wheels;
- Production of reactive metal powders;
- Zirconium pump casings and valves for the chemical industry and offshore drilling.

Cold crucible

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Cold crucible
Vacuum Arc Melting and Casting

Because of titanium’s high affinity for oxygen, melting and casting of this highly reactive material must be done under a vacuum. A consumable titanium electrode is melted with an electric arc into a water-cooled tiltable copper crucible. When the desired fill level in the crucible is obtained, the electrode is automatically and quickly retracted and the molten titanium is poured into a precision casting mold. The melting process is automatically controlled and can be remotely observed via a monitor.

Crucibles of appropriate sizes can be used for different pouring weights. One electrode allows several pours. The basic version of the standard systems is the single-chamber version where crucible and mold are located in the same chamber. This version can be extended by adding a mold-cooling chamber to raise the system’s productivity. The systems may also be equipped with a centrifugal-casting unit to improve mold filling of shapes with small and complex cross sections. An argon cooling system, offered as an option, can be applied for enhanced mold cooling and further reduction of furnace cycle time.
POWDER METALLURGY

- Vacuum Induction Melting and Inert Gas Atomization
- Ceramic-Free Metal Powder Production
- Sprayforming
- Inert Gas Recycling
Metal powder technology is one of the most established production methods nowadays in all kinds of industries.

The alloy types which can be manufactured by powder metallurgy cover a broad spectrum, ranging from soldering and brazing alloys for the electronics industry, nickel, cobalt and iron-base superalloys for the aircraft industry, hydrogen storage and magnetic alloys, up to reactive alloys such as titanium for the sputter target production.

The process steps involved in the production of metal powders are melting, atomizing and solidifying of the respective metals and alloys. Metal powder production methods such as oxide reduction and water atomization, are limited with respect to special powder quality criteria, such as particle geometry, particle morphology and chemical purity.

Inert gas atomization, combined with melting under vacuum, therefore is the leading powder-making process for the production of high-grade metal powders which have to meet specific quality criteria such as:
- Spherical shape;
- High cleanliness;
- Rapid solidification;
- Homogeneous microstructure.

ALD has the capability to combine various melting technologies with inert gas atomization which enables the production of superalloys, superclean materials and additionally reactive metals.

**Metal Powder Applications:**
- Ni-base superalloys for the aviation industry and power engineering;
- Solders and brazing metals;
- Wear-protection coatings;
- MIM powders for components;
- Sputter target production for electronics;
- MCRLY oxidation protection coatings.

**Production-scale Inert Gas Atomization System** The system has a vacuum induction of 35 l effective volume. It is equipped with a high-vacuum pumpset and a cyclone particle separator.
Vacuum Induction Melting and Inert Gas Atomization

The standard design of a vacuum inert gas atomization (VIGA) system comprises a Vacuum Induction Melting (VIM) furnace where the alloys are melted, refined and degassed. The refined melt is poured through a preheated tundish system into a gas nozzle where the melt stream is disintegrated by the kinetic energy of a high pressure inert gas stream. The metal powder produced solidifies in flight in the atomization tower located directly underneath the atomization nozzle. The powder gas mixture is transported via a conveying tube to the cyclone where the coarse and the fine powder fractions are separated from the atomization gas. The metal powder is collected in sealed containers which are located directly below the cyclones.

ALD has developed atomization systems where a variety of melting processes can be combined with inert gas atomization. The atomization systems built by ALD have a modular design and are applicable from laboratory scale (1 – 8 l crucible volume), through pilot production (10 – 50 l crucible volume) up to large-scale atomization systems (with 300 l crucible volume).
Large Scale VIGA Atomization System

The photo on this page shows a large scale inert gas atomization system. The melting crucible of this production atomization system has a maximum capacity of 2 tons. The atomization tower is connected to a melt chamber with a double-crucible door arrangement. Each furnace door is equipped with a vacuum induction melting furnace. This design allows very fast crucible changing. While one crucible is in production the second crucible can be cleaned or relined in stand-by position. This minimizes the down time for furnace change operations. Additionally, the double-door design enhances the production flexibility, because different furnace sizes can be used in the same equipment. The melting chamber is equipped with a bulk charger, two temperature measuring devices and a redundant tundish system.

Each pouring tundish, including the gas nozzle arrangement, is mounted on a tundish cart. The tundish cart can be moved sideways to a location for loading and unloading without venting the system and without breaking the ambient atmosphere. The redundant tundish configuration allows a high flexibility in case clogging of the outlet nozzle occurs. In that situation, the second preheated tundish nozzle system which is in stand-by position can be moved into the atomization position to continue the process.

Schematic design of a large scale atomization system with a double-door melting furnace chamber

Double-door crucible VIGA atomization unit
Each vacuum induction furnace has a rated batch capacity of 2,000 kg. A gas recycling system recovers the inert gas for reuse.
Ceramic-Free Metal Powder Production

The “standard” design of a vacuum induction melting inert gas atomization system is equipped with a ceramic melting crucible and also ceramic material for the tundish and the melt outlet nozzle arrangement. Due to the contact between the melt and the ceramic lining and nozzle material, ceramic inclusions in the melt can occur, which influence the material properties of high-strength PM-components in a negative manner. Reactive metal powders, such as titanium based alloys, cannot be produced with this method at all, due to the reactions between the reactive melt and the ceramic lining. In order to overcome the “ceramic problem” it is necessary to use melting techniques where the melt is not in contact with ceramic lining material. Additionally, a refining of the melt during the melting process would be desirable. Typical materials that need ceramic-free production processes are refractory and reactive materials, such as Ti, TiAl, FeGd, FeTb, Zr and Cr.

EIGA

In the EIGA (electrode induction melting gas atomization) process, prealloyed rods in form of an electrode are inductively melted and atomized without any melting crucible at all. The melting of the electrode is accomplished by lowering the slowly rotating metal electrode into an annular induction coil. The melt stream from the electrode falls into the gas atomization nozzle system and is atomized with inert gas. The EIGA process was originally developed for reactive alloys such as titanium or high-melting alloys. It can also be applied to many other materials.

PIGA

For the production of ceramic-free powders and for the atomization of reactive, and/or high-melting alloys, melting can also be accomplished by means of a plasma jet in a water-cooled copper crucible. PIGA stands for plasma-melting induction-guiding gas atomization. The bottom of the PIGA crucible shown above is connected with an inductively heated discharge nozzle, also made of a copper base material. This ceramic-free discharge nozzle system guides the liquid metal stream into the gas atomization nozzle, where it is disintegrated by the inert gas.
**VIGA-CC**

Reactive alloys like titanium or intermetallic TiAl alloys can also be melted in a copper-based cold wall induction crucible which is equipped with a bottom pouring system. The bottom pouring opening of the cold crucible is attached to a CIG system.  

CIG stands for cold-wall induction guiding system and is exclusively patented by ALD. VIGA-CC stands for vacuum induction melting based on coldwall crucible melting technology.

**ESR-CIG**

High performance superalloys for the aircraft industry are typically produced via the so-called “triple melt process”. In the triple melt process the refining of the material is carried out by the reactive slag in the ESR melting step. The combination of the ESR remelting technique with a ceramic-free melt guiding system (CIG) represents a process technology to produce powder material with a high level of cleanliness and chemical homogeneity. In the ESR-CIG (electroslag remelting cold-wall induction guiding) process, the material to be atomized is fed in form of an electrode. The electrode is lowered into the metallurgical refining slag. As the electrode tip is melted at its point of contact with the slag, droplets of the refined metal are formed and these droplets pass down through the reactive slag layer.

The refined metal droplets which pass through the reactive slag form a liquid melt pool underneath the slag layer. The melt pool is enclosed by a water-cooled crucible made of copper. The refined liquid metal is guided through the cold-wall induction guiding system and is disintegrated by a high kinetic inert gas stream in a free-fall-type gas nozzle.

**Sprayforming Technology**

Beside the conventional powder-processing route, sprayforming became more and more important during the last decade. This unique process enables the direct fabrication of semi-finished products. A number of process steps related to compaction can be eliminated, the pick up of oxygen is minimized and the risk of contaminatin is dramatically reduced compared to the powder-HIP (Hot Isothermal Pressing) route.

The principles of sprayforming technology are to atomize the molten metal into droplets and to solidify them rapidly onto a collector. By moving this collector the build up of semi-finishes product is established. Due to the high cooling rates, which occur during atomization, a fine micro-structure with no macro-segregation is achieved.
Depending on the design of the atomizer, the movement of the spray nozzle(s) and the collector design various shapes, such as billets, rings, tubes and bars can be produced.

The produced semi-finished products are subjected to secondary processing steps, such as heat treatment, rolling, forging, extrusion or HIP. The process is used extensively to manufacture billets for a wide range of applications in aluminium alloys, copper alloys, special steels and superalloys.

**Inert Gas Recycling**

At a certain batch size of the atomization system, recycling of the inert gas is recommended, to reduce the total inert gas consumption and thus achieve a more economical production process. ALD offers two different process technologies to recycle the inert gas.

**Inert Gas Recycling Based on Compressor Technology**

One method of reusing the inert gas is to “drive” the gas in a closed gas circulation loop, using a suitable compressor system. Behind the cyclone and the filter system, the “dust-free” gas is repressurized using a 2-stage compressor unit. The compressors have to be gastight to prevent contamination of the recirculated inert gas. After each compressor, a gas buffer tank is used to minimize pressure fluctuations during the atomization process. This results in stable atomizing process conditions with respect to atomization pressure and gas-flow rate.

In case the permissible impurity levels in the atomization gas are set very low, the oxygen, hydrogen and nitrogen contents can be monitored at several locations in the gas circulation loop.

For large-scale atomizing systems this type of gas recycling is economically operated in a pressure range up to 50 bar.

![Spryforming process using an “OSPREY” twin-atomizer](image-url)
Argon Recycling Based on Liquefaction

If a higher gas supply pressure is required, the recycling concept described above has to be changed to the principle of reliquefying the argon by using evaporating liquid nitrogen as the refrigerant. In this situation, the 2-stage compressors with the pulsation buffer are replaced by a concurrent flow argon liquifier and a set of high-pressure liquid argon pumps.

The high-pressure liquid argon pumps feed the liquid argon through an evaporator into high-pressure gas receivers. Based on this technology a gas supply pressure of approx. 100–200 bar can be achieved.

Operational experience with large scale atomization systems equipped with the recycling systems described above, shows that the yield of the recycled gas for both recycling systems is in the range of 90–95 %. 
VACUUM TURBINE
BLADE COATING (EB/PVD)

Electron Beam / Physical Vapor Deposition (EB/PVD) of Protective (MCrAlY) and Thermal Barrier Coatings (TBC)
Increasingly stringent demands are being imposed on the efficiency of gas turbine engines employed in the aerospace and power generation industries. This is driven by the requirement to reduce consumption of fossil fuels and thus operating cost. The major means for improving turbine efficiency is by increasing operating temperatures in the turbine section of the engines. The materials employed must withstand the higher temperatures as well as mechanical stresses, corrosion, erosion and other severe conditions during operation, while providing extended lifetime as required by the end users. This is an area where EB/PVD coating processes make a significant contribution today.

**Increase of Turbine Efficiency**

Turbine components have been continually improved over decades, specifically with respect to temperature resistance. Initially the focus for improvement was as the blade material itself and its temperature capability. Large improvements have been achieved since the sixties by continually refining the casting methods, developing new Ni-base alloys, optimizing component shapes, component dimensions, grain structures and finally by applying special cooling methods to the components. This process continues today, but gains in temperature and efficiency have reached the limits set by the laws of physics. Since the seventies, metal base vacuum coatings (e.g. MCrAlY) have been applied to protect the Ni-base alloy component surface against corrosion by hot gas. The success of these coatings marked the starting point for the development of non-metallic coatings with thermal insulation properties. Today these coatings are an integral part of the design of all modern aircraft turbine engines.
Coating of Blades and Vanes

Turbine blades and vanes manufactured in accordance with the latest state-of-the-art methods are currently composed of:

- Specially shaped, precision cast, super-alloy, single crystal components with cooling air passages;
- A bond coating;
- A diffusion barrier;
- A thermal barrier coating.

**EB/PVD Coating Applications**

Among various vacuum coating methods, electron beam / physical vapor deposition is characterized by the use of a focused high-power electron beam, which melts and evaporates metals as well as ceramics. The high deposition rate results in many cost-effective applications. EB/PVD coatings are used in the field of optical coatings for lenses and filters, in the area of semiconductor manufacture, for the coating of packaging web and many other high-volume applications. A system for coatings of turbine components was first introduced at Leybold-Heraeus in the late sixties.
a separate step by electroplating, then a final heat treatment process is utilized in order to create the PtAl coating with required properties. Both coatings are used today with comparable quality. The use of MCrAlY or PtAl depends on the specification established by the original equipment manufacturer (OEM).

**Diffusion barriers** are employed between the bond coating and the thermal barrier coating (TBC) for enhanced adhesion between the two layers. The diffusion barrier consists of a thin Al₂O₃ ceramic zone on top of the bond coating. This is an ideal condition for applying TBC. It is created just prior to the TBC coating inside the EB/PVD machine by oxidizing surface aluminum of either the MCrAlY or the PtAl bond coating.

**Thermal barrier coatings (TBCs)** are employed as the final layer that protects turbine components against high temperatures. The paper-thick coating allows high gas temperatures, which can be 100 to 150°C higher than the melting temperature of the Ni-base superalloy component. Yttria-stabilized ZrO₂ has been proven to be the ideal material for these TBCs. The dendritic structure of the TBC produced by EB/PVD, the firmly anchored roots and the loose tips allow the coating to absorb high mechanical stresses which are induced by the severe, rapidly varying, thermal cycling of aircraft and stationary gas turbine engines. The EB/PVD method for producing the TBCs has been the exclusive choice in aircraft turbine components from their introduction until today. An alternative method for TBCs, air plasma spray (APS) has recently been developed. The air plasma spray (APS) method has advantages as well as limitations compared to EB/PVD. Advantages include: atmospheric process and no need for vacuum, relatively low investment in coating equipment, the ability to quickly coat large components and good thermal barrier properties of the coatings. Disadvantages include a platelet structure of the coating which is inferior in terms of bonding and thermal cycling properties, the closing of cooling holes by the powder particles, roughness of the coating which requires the surface to be smoothened after coating and finally the fact that the process is a step by step process. Various OEMs have chosen APS as the preferred TBC coating method for large components of power generation turbine engines. This is due to the simplicity of the process and the comparably low operating cost. Aircraft components from the same OEMs are coated by EB/PVD, due to its superior quality and reliability.
EB/PVD-Production Systems

Coating Machines

Mass production EB/PVD systems are equipped with one central coating chamber incorporating two electron beam guns and a reservoir of zirconia ceramic for the coating process. Preheating chambers are connected on either side of the coating chamber. Each preheating chamber allows the connection of up to two alternately actuated parts loading chambers. Each loading chamber is equipped with a carrier and drive system for the parts to be coated. This system carries the parts from the loading position to the preheating station and finally to the coating position. In the coating position, parts can be rotated, tilted or both at the same time, matching the part geometries and the specified coating thickness distribution requirement. Vacuum valves are installed between the coating and heating chambers. This allows the coating of parts loaded from the left side of the machine, while at the same time the next lot of parts is preheated in the right side heating chamber. As soon as the coating process is finished, the left side parts are moved out to the unloading station while the just preheated parts from the right side are moved into the coating chamber for coating. During the coating process, the left side parts are unloaded and replaced by new parts, which are then moved into the preheating position. The modular design of the EB/PVD coating system offers the possibility to install up to four loading chambers for the highest productivity requirement, two loading chambers for medium-size capacity or only a single loading chamber for pilot production or a small-size capacity requirement as needed by repair and overhaul shops today.
Family of EB/PVD-production systems

Mass production system with four loading stations

Production system with two loading stations

Coater for pilot production and repair coatings

Development coater for R&D with only one EB gun

Loading chamber  Preheat chamber  Coating chamber
**TBC Process**

The diffusion barrier mentioned earlier is created during the preheating process just prior to TBC coating. The major factor determining the quality of the TBC is the process that takes place in the coating chamber. A homogeneous cloud of vapor must be generated. In order to accomplish this, the coating material must be dosed in the right quantity, sufficient reactive gas must be added, the right scanning patterns of the electron beam over the molten material selected and last but not least the parts must be moved inside the vapor cloud in a preprogrammed motion.

**Process Control**

The easy-to-use process controllers of ALDs EB/PVD systems provide both optimal and fully reproducible control over parts manipulator and drive motions. Controls for heating, coating, feeding of new material, vacuum system, valves, interlocks, safety and other items are provided at state-of-the-art level of modern production equipment. An ESCOSYS® (electron beam scanning computer system) computer controls the scan of the electron beam over the molten ceramic ingot. Only in the rare event that the coating process departs from its optimum course will operator interaction be required. In this case, a mouse click is all that is needed to make the corrections and return the process to its ideal course. The process is then stabilized by means of preprogrammed algorithms in the ESCOSYS® computer. This type of control system involving infrequent operator intervention, has proven to be the most reliable and most successful means for mastering the EB/PVD coating process and reaching high yield levels. The main process controller employed allows thorough documentation of all parameters affecting the coating of each individual item involved. From the time components to be coated arrive at the weighing station, before being loaded, until the time they are unloaded and weighed again, all stations involved are networked. The course of processing at each and every stage is fully documented for quality-assurance, a must for critical components employed in the aircraft industry. The entire system may be integrated into the operator’s host-computer environment.
**Future Advances**

Opportunities for making further improvements arise when the general designs of components and system operators’ manufacturing chains are taken into consideration. Stand-alone processes that are separated today may be combined in the future. This could reduce the complexity, increase the quality, as well as reduce the cost of the end product. Examples of their applications, such as applying TBC to turbine blades, demonstrates the great potential that EB/PVD coating technology harbors for further improving the efficiency of turbines. Development efforts currently underway are aimed at investigating the deployment of new types of ceramic materials that have even better thermal barrier properties than the material used today. Multilayered coatings and custom-tailored combinations of various ceramics that yield better thermal barriers and exhibit better adhesion to bonding layers are also being discussed.

**Operator’s cockpit at an EB/PVD-production coater**
SOLAR SILICON MELTING AND CRYSTALLIZATION TECHNOLOGY
Several government programs support the shift towards renewable energy sources. In 2050 about half of the energy worldwide is supposed to be produced from sources such as water, wind and solar power.

Sunlight is changed into electricity by means of photovoltaic cells. The raw material for these cells is silicon.

Market growth in production of solar grade silicon and solar modules is remarkable.

ALD contributes with metallurgical know-how to the cost-efficient and industrial production of solar grade silicon ingots which are processes into wafers, solar cells and modules.

The SCU400 is a stand-alone furnace for melting and crystallization of up to 400 kg solar silicon ingots in a fully automatic cycle.

ALD has many years of experience in this field and a large installed base with solar industry leaders.

**SCU400 Features:**
- Stand-alone furnace for melting and crystallizing one 400 kg solar-grade silicon ingot
- No movement of mold during the process
- Fully automatic melting, crystallizing and annealing
- Bottom and top heater system for controlled crystallization
- PLC-controlled system for industrial production
- Various proven safety provisions implemented in furnace hardware and software
- Furnace concept lends itself to upgrade of future quartz crucible sizes
- Furnace cycle time independent of crucible size

**SCU 400 Solar Silicon Melting and Crystallization Unit.**
The system produces up to 400 kg solar silicon ingots in a fully automatic cycle of less than 45 hours.
HOT ISOTHERMAL FORGING

Vacuum Isothermal Forging for "Near Net Shape" Technologies
A final consolidation step in powder metallurgy is used to achieve full density and full strength. The more common consolidation methods are:

- Sintering;
- Hot isostatic pressing;
- Forging;
- Hot extrusion.

Parts from metals and alloys, such as titanium and various superalloys, that are hard to shape and are used in jet-engine parts subjected to high stresses, as well as metals such as molybdenum which retain high strength at high temperatures are usually finished by hot isothermal forging (HIF). Hot isothermal forging (HIF) has developed in recent years into an important – and for many applications indispensable – process for producing high-quality parts in “near net shape”.

**Isothermal Forging System Design**

A prerequisite for such metallurgical “constancy” of the workpiece is the superplastic deformation, which can be achieved with extremely low deformation rates in a narrow temperature band. If the forging is done under superplastic conditions, maintaining certain parameters, only small stresses occur in the workpiece and the grain size remains nearly unchanged. Another advantage of this deformation method is the “near net shape” potential and the related savings in materials plus a greatly reduced need for subsequent machining. HIF systems from ALD feature:

- The multizone billet heating furnace;
- The multizone die-heating system;
- The microprocessor-controlled system for temperature control.
INDUCTION HEATED QUARTZ TUBE FURNACES (IWQ)

Induction Heated Quartz Tube Furnaces
IWQ furnaces are suited for many common heat-treatment, melting and distillation processes in which reactivity or the special properties of the material, metal-based alloy or mixture require a complete or partial treatment under vacuum or protective gas.

**IWQ Furnaces – System Design**

The induction heated quartz tube furnaces, essentially types IWQ 300, IWQ 500, IWQ 700 and IWQ 800 have an extremely modular design and can be adapted to many special applications. The IWQ furnace has been modified for use in processes such as heat treatment, sintering and metal distillation.

**Material**

Materials heated in an IWQ furnace have a high degree of purity and better properties due to the fact that an induction coil, located outside the useful space, serves as heat source. It can couple in its energy either via a susceptor (different materials) or directly via the charge carrier.

The furnaces offer a high degree of axial and radial temperature constancy.

**Features:**

- Outboard induction coil guarantees no electrical flashovers;
- No possibility of water leaks from the coil into the useful space;
- Vessel material is resistant to aggressive gases such as Cl, F and HF at T 600°C;
- Standard quartz tubes with length of 2,000 mm and diameters up to 1,000 mm;
- Induction coil with and without pitch compensation, which directly heat the susceptor or the charge or preheat the mold;
- Medium-frequency power supply for the induction coil;
- A pumping system whose standard version can achieve operating pressures from 10^-1 mbar down to <10^-5 mbar;
- Process temperature 1,500 – 2,000 °C depending on the application;
- A control panel containing all necessary controls.

**IWQ Applications:**

- Rare-earth metal production;
- Melting and casting of alloys;
- Refining of optical coating materials;
- Battery recycling;
- Production of Sm, Y, UAl, etc.;
- Sintering of ceramics;
- Distillation of metallic scrap and metals;
- Production of ultrapure materials for the semiconductor device industry and fiber-optic data transmission;
- Heat treatment of metals;
- Heat treatment of ceramics and glass.
HIGH VACUUM RESISTANCE FURNACES (WI)

for Special High-Temperature Processes
ALD’s WI high-vacuum resistance furnaces are specially designed and built for applications in industry and research with extraordinary requirements in high-temperature processes, such as:

- Vacuum annealing, degassing and refining
- Sintering of metals and ceramics
- Liquid-phase sintering and metal impregnation
- Vacuum brazing and active-metal brazing
- Vacuum material testing

Each WI furnace is sized and configured for a specific process and application with respect to furnace size, layout, vacuum system, hot zone and charging system.

High-vacuum can be achieved by diffusion pumps or completely dry turbo-molecular pumps. ALD also has industrial experience with and provides safe solutions for high-temperature hydrogen furnaces.

For ultrahigh-vacuum applications, a special ALD double-chamber concept has been proven to permit an ultimate vacuum in the heat treatment chamber of <10⁻⁸ mbar at 1850 °C.

All furnaces are equipped with state-of-the-art PLC process control and visualization.

**WI 800/1100 High Vacuum resistance furnace - bottom loading system**
VACUUM HEAT TREATMENT

Vacuum Technology is the Basis for Process Innovation in Heat Treatment.
Heat Treatment is the process in which metallic/steel parts are exposed completely or partially to time-temperature sequences in order to change the mechanical and/or corrosion properties. There are numerous application areas, e.g.:

- Annealing
- Hardening
- Tempering
- Aging
- Case hardening
- Nitriding

to achieve a higher strength of the material, better wear resistance or to improve the corrosion behaviour of the components.

All of these processes need a temperature up to 1.000 °C and higher as well as especially developed furnaces to achieve such ranges. From the past there are well-known technologies for the above processes, e.g.:

- Technology using molten salt
- Furnace for protective and/or activated atmospheres

Oxidation occurs on the part’s surface when exposed to the atmosphere (air). This results in costly and time-consuming post treatments. Therefore, heat treatment is preferably conducted in an oxygen-free atmosphere. In addition to the use of high-purity protective gases, vacuum allows the best protection against oxidation, thus being the most cost-efficient atmosphere.

Such furnaces are also used for high temperature brazing, a well established joining process.
**Hardened steel structure Martensite**

Annealing is one type of heat treatment comprising heating up to a specific temperature, holding and cooling down slowly. Such processes are generally used to obtain a softer structure of the part and to optimise material structure for subsequent working steps (machining, forming).

Parameters depend on the material and the desired structure.

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**Piezo-Common-Rail diesel injection system**

**Modular vacuum heat treatment furnace (Company Wegener)**

**Hardening and Tempering**

Hardening is a typical heat treatment process combining heating to specific temperatures (mostly above 900 °C) and direct fast cooling or quenching of the part. The requirements are selected to change the materials’ structure partially or completely into martensite. The part undergoes tempering treatment after hardening in order to obtain high ductility and toughness.

**Case Hardening**

One of the important processes is the case hardening or carburizing process. Parts are heated up to 900 °C - 1,000 °C and by adding specific gases (hydrocarbons) into the atmosphere of the furnace the part’s surface is enriched by absorbing carbon. Following this treatment the part is quenched in order to achieve the required properties. This results in higher resistance to stresses and friction on the component’s surface. The core of the part remains somewhat softer and more ductile which allows the part to carry high stresses through its entire life. For example, all gear parts for transmissions are treated this way.

**Brazing**

Brazing is a process for joining components, whereby a filler melts under temperature and joins the components together after solidification. In this process, the solidus temperature of the parts to be joined is not reached. In high temperature brazing (above 900 °C) which ideally happens in vacuum, the atmosphere (vacuum) takes on the duties of the fluxing agent.
Advantages of Vacuum Heat Treatment

**Vacuum as "Protective Atmosphere"**
- No toxic protective gases containing CO
- No health hazards in the work shop
- No danger of explosion or open flames
- No furnace conditioning
- Use of inert gases (nitrogen or helium)
- No CO₂ emission

**Vacuum Carburizing**
- Use of various processes
- Use of different gases
- Shorter carburizing cycles than in conventional technology
- Higher carburizing temperatures offer potential to further reduce process time
- Small gas consumption l instead of m³

**Surface Influences**
- Free of surface oxidation
- No surface decarburization
- Bright, metallic, shiny parts

**Plant Operation / Installation / Maintenance**
- No idling over the weekend
- No continuous gas consumption
- Short heat-up times
- Fast access to installed modules
- No fire detection or sprinkler system
- No open flames
- No flammable gas mixtures
- Cold-Wall Technology
- No gas emission
- Minimum energy loss
- No heat radiation to atmosphere

**Gas Quenching Instead of Oil Quenching**
- Clean, dry parts after hardening
- No washing required - no disposal of washing water
- No maintenance of washing equipment
- No complicated washing water chemistry
- Saves space
- Cost benefits
- Quenching intensity is controlled via gas pressure or gas velocity
- No vapor blankets during quenching
- Homogeneous quenching
- Reduced distortion

**Auxiliary Equipment of Protective Gas Plants are no longer required, such as:**
- Fire safety equipment
- Sprinkler system
- Exhausters
- CO₂ extinguisher for the oil bath
- Measuring CO concentration in the shop
- Smoke exhaust in the roof (automatic opening and closing)
- Oil-proof floor or tank
- Methanol storage
VACUUM HARDENING, TEMPERING

- Vacuum Heat Treatment of Tool Steels
- Single-Chamber Vacuum Heat Treatment Systems in Horizontal and Vertical Design
- Double-Chamber Vacuum Furnaces, Type DualTherm®
- Linked Multi-Chamber Furnace, Type ModulTherm®
The process of heat treatment has been used for centuries in order to specifically change the properties of components. In the course of development, the processes have fundamentally changed. Up to the early 20th century the processes were conducted in a normal atmospheric environment. The use of protective gases has further improved the quality of the components.

Heat treatment development experienced a significant boost with the introduction of vacuum technology. At first, this technology was only used for special materials in aviation technology but soon widely spread to harden high alloyed tool steels.

The following reasons are essential for the change to vacuum technology:

- Reduced distortion
- Clean and dry parts, no oxidation
- Simple and reproducible treatment of parts
- Fully automated processes
- Hardening and tempering in one system

For the heat treatment, parts are loaded in batches into the vacuum furnace. The vacuum furnace is a pressure vessel, equipped with insulation as well as a heating system. After loading the furnace, the vessel is evacuated, thus the air and at the same time any potential for oxidation is removed from the furnace. The parts can be heated either in vacuum or under convection. When using convective heating, an inert gas, usually nitrogen up to 2 bar, is filled into the furnace after evacuation. By circulating the gas during heating, excellent temperature uniformity is reached, which has a positive effect on reducing distortion. Convective heating up to 900 °C also shortens the cycle time. Subsequently, the load is heated in vacuum to the required austenitizing temperature. After an adequate soaking time at austenitizing temperature the parts are cooled using gas quenching.

The type of gas used and the necessary pressure depends on the part (material, geometry) as well as on the required treatment results. Most parts of cold and hot work tool steels as well as high-speed steels can be hardened with nitrogen at a quenching pressure up to 10 bar.
Double-Chamber Vacuum Furnace, Type DualTherm®

The double-chamber vacuum furnace, type DualTherm® ideally combine heating and quenching processes. This furnace has been especially developed for case hardening in vacuum.

This two-chamber system operates according to the in/out principle and its design is similar to conventional sealed quench furnaces. At the beginning of the process, the fore chamber of the furnace serves as the loading chamber and after heat treatment as the gas quenching and unloading chamber. After placing the charge into the fore chamber, it is transported to the treatment chamber via an internal transport system.

The design of the treatment chamber is based on a conventional vacuum heat treatment furnace and it is kept constantly under vacuum and at temperature during furnace operation. The furnace is equipped with a convective heating system to guarantee uniform and rapid heating of the parts. This double chamber vacuum furnace may be equipped with a vacuum carburizing system for heat treating of all case hardening steels. In addition to case hardening, vacuum heat treatment processes up to 1,250 °C may be conducted in the treatment chamber. The "cold quenching chamber" may be operated with a quenching pressure up to 20 bar.

Mid and some low alloyed tool steels, such as ball bearing steel 100 Cr 6, require quenching gases with better thermal properties such as helium, or higher quenching pressures up to 20 bar. Most of the low alloyed steels like case hardening steels are requiring increased quenching speeds which may not be achievable in single-chamber vacuum heat treatment furnaces. These parts have to be quenched in a "cold quenching chamber". ALD has developed such furnace types:

- Double-chamber vacuum furnace, Type DualTherm®
- Linked multi-chamber furnace, Type ModulTherm®
- Special furnaces
Linked Multi-Chamber Furnace, Type ModulTherm®

The ModulTherm® is based on a modular design concept. The design offers solutions to the complete satisfaction of the customers. It meets their specific demands and can be expanded for increasing production capacity.

The basic version consists of a rail-mounted shuttle system, comprising the transfer module and the quenching chamber. This shuttle moves between two or more stationary treatment chambers where the number of chambers can be adjusted to capacity needs. Easy access to all components is guaranteed by the modular design. This innovative furnace concept combines modular components and system availability with flexibility and maximum reproducibility of the heat treatment process.

The treatment chambers can be equipped/used for neutral hardening, annealing, carburizing, brazing etc. to allow:

- Expandability according to customer's requirements
- Different processes, like annealing, hardening, case hardening, tempering, brazing, etc.
- Different processes in different treatment chambers at the same time
- Convective heating
- Short and identical transfer times between treatment and quenching chamber
- Quenching with reversed gas flow
- The transport system is not exposed to heat or thermo-chemical reactions
- Easy access to all system components
- Maintenance during production
ModulTherm® Components

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<tr>
<th>Module</th>
<th>Purpose</th>
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<tr>
<td>Quenching chamber</td>
<td>High-pressure gas quenching</td>
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<tr>
<td>Transfer module</td>
<td>Load transport between treatment/quenching chamber and</td>
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<td>loading/unloading of the treatment chambers</td>
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<tr>
<td>Treatment chamber</td>
<td>Heat treatment processes</td>
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Individual modules may be additionally equipped, according to the required applications with, e.g. convective heating or gas flow reversing during quenching. The complete system may comprise further peripheral components, such as tempering furnaces (continuous or batch-type tempering furnaces, load storage devices, pre-oxidizers, pre-washing machines, sub zero treatment, nitriding units etc.).
**Special Furnaces**

In addition to the furnaces for hardening, tempering, case hardening, annealing, sintering and brazing processes, ALD is particularly experienced in the production of special systems. These special applications accrue from various industrial sectors and include annealing treatments for special alloys in the aviation industry as well as furnaces for the treatment of special materials.

Such systems are developed and manufactured according to the specifications and requirements of our customers.

ALD not only designs and builds the furnaces and systems but also serves as a strategic partner for the customer. Thus, in joint projects, processes are optimized and suitable special systems are designed and built.
VACUUM CASE HARDENING

- Vacuum Carburizing
- High-Pressure Gas Quenching
One of the most important processes of heat treatment is the case hardening or carburizing process. Parts are heated up to 1,000 °C and by adding specific gases (hydrocarbons) into the atmosphere of the furnace the part’s surface is enriched by absorbing carbon. Following this treatment the part is quenched in order to achieve the required properties which results in higher resistance against stress and friction on the component’s surface. The core of the part remains somewhat softer and more ductile which allows the part to carry high stresses through its entire life. For example, all gear parts for transmissions are treated this way.

The traditional way is to run this two step process (carburizing and quenching) in furnaces working under specific CO but also oxygen containing atmospheres for carburizing and is using specific oils for quenching.

This process has some disadvantages, such as reduced product quality, high energy consumption, distortion of the parts, washing problems to remove the quenching oil, but also fire and explosion risks as well as negative influences on the environment like CO\textsubscript{2} emission. These disadvantages can be clearly eliminated by using vacuum carburizing and high pressure gas quenching.

**Vacuum-Based Carburizing**

**Processes**

Vacuum and plasma carburizing are processes where the carburizing gas remains under an absolute pressure of a few mbar. Carburizing gases are hydro-carbons such as methane, propane or acetylene, whereby primarily acetylene is used for vacuum carburizing.

Methane requires an additional plasma activation in order to obtain adequate carburizing results. Plasma carburizing with methane has its advantage, if the parts need partial carburizing. In this case, a simple and easy removable metallic mask is placed on that part of the workpiece which should not be carburized. This process is easier than using paste which is difficult to remove afterwards.
Vacuum-Based Carburizing Processes

In vacuum carburizing, propane or acetylene are usually selected for all carburizing processes without any specific geometrical requirements. However, it has been proven that acetylene offers better carbon efficiency compared to propane because of its instability and higher carbon content per mol of gas. Therefore, by using acetylene, densely packed loads, especially parts with complicated shapes can be carburized at high, reproducible quality.

Small quantities of carburizing gas are introduced in the hot zone and are drawn-off by the vacuum pumps. Process parameters like temperature and gas flow are selected according to the parts requirements and are used for the process control. To achieve the specified carbon profile, the carburizing is done in alternating steps for carburizing and diffusion, followed by a final diffusion step. These sequences are also parameters for the process control.

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<thead>
<tr>
<th>Carburizing Gas</th>
<th>Carbon-content*</th>
<th>Carbon-yield**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane CH₄</td>
<td>75 %</td>
<td>&lt; 3 %</td>
</tr>
<tr>
<td>Propane C₃H₈</td>
<td>82 %</td>
<td>~ 25 %</td>
</tr>
<tr>
<td>Acetylene C₂H₂</td>
<td>92 %</td>
<td>~ 60 %</td>
</tr>
</tbody>
</table>

* in weight-%
** % of carbon transferred from gas into load

Typical load of vacuum-carburized gear parts
**Process Advantages**

Compared to the processes using atmospheric conditions, vacuum carburizing has a lot of advantages. Due to a higher carbon mass-flow rate the cycle time is considerably reduced. Vacuum furnaces easily allow higher temperatures, thus process times can be reduced dramatically, especially for bigger case depths.

Because of the absence of oxygen (air), the quality and properties of the parts surfaces are improved.

**Advantages of Vacuum Carburizing**

- Fast carbon transfer
- No surface oxidation
- Good case depth uniformity
- Integration into manufacturing lines
- Small consumption of carburizing gas
- No formation of furnace atmosphere
- High carburizing temperatures possible

**Vacuum carburizing and gas quenching process**
High Pressure Gas Quenching

For many years now, gas quenching has been the preferred process in the heat treatment of high-speed steels and hot and cold working tool steels.

With the development of separate gas quenching chambers, it is often possible to replace oil quenching with high-pressure gas quenching using nitrogen or helium for heat treating case hardening steels or other low alloyed materials.

The success of this dry quenching technology is based on its environmental and commercial efficiency. Quenching gases such as nitrogen or helium are absolutely inert and without any ecological risk. They leave no residues on the workpieces or in the hardening furnaces. Therefore, investments in equipment such as washing machines or fire monitoring systems are redundant. This, in turn, reduces operating costs for hardening. When helium is used as a quenching gas, appropriate recycling systems for unlimited repeated use of the helium are available.

There is a difference in the quenching pattern, using gas quenching vs. oil quenching, because of the laws of physics. The following diagram shows the different
phases which occur during quenching in liquid media: film boiling, bubble boiling as well as the convection phase. The individual phases are characterized by very different heat transfer coefficients, which lead to big temperature gradients in the part, causing distortion of the part. Gases don't show phase changes during quenching. Heat transfer all over the part is more homogeneous and the risk of distortion is reduced. Excellent process control for the entire quenching process is guaranteed by the control of gas pressure and gas velocity. With these parameters, the quenching speed can be adjusted to the parts requirements.

**Heat transfer and temperature distribution during immersion cooling**

**Heat transfer and temperature distribution during high-pressure gas quenching**
Process Advantages
The main advantages of high pressure gas quenching are reduced distortion which mostly helps to avoid hard machining steps and dry and clean parts afterwards. After gas quenching the parts surface is free from quenching media, dust or other residuals, which is the required condition for further process steps like coating.

Gas Quenching Pressure

<table>
<thead>
<tr>
<th>20 bar</th>
<th>ALD-Patented</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Ball Bearing Steels (Small Sizes) 100Cr6 (SAE 52100) 100CrMn6</td>
<td>- Low Aligned Case Hardening Steels 16MnCr5, 20MnCr4, SAE 8620</td>
</tr>
<tr>
<td>- Heat Treatable Steels 42 CrMo4 HH (4140 HH)</td>
<td>- Ball Bearing Steels (Medium Sizes) 100 Cr6 (SAE 52100)</td>
</tr>
<tr>
<td>10 bar</td>
<td></td>
</tr>
<tr>
<td>- Hot/Cold working Steels X15CrMo12 1(D2) X38 CrMoV5 (H13)</td>
<td>- Al-, Ti-Alloys</td>
</tr>
<tr>
<td>- High Speed Steels 1.3343</td>
<td></td>
</tr>
<tr>
<td>- Ni-Alloyed Case Hardening Steels 18CrNi8, 17CrNiMo6</td>
<td></td>
</tr>
</tbody>
</table>

Nitrogen \(v_{gas} \approx 15 \text{ m/s}\)  
Helium \(v_{gas} \approx 24 \text{ m/s}\)

Material, Part Dimension and Hardness Specification determine Quenching Process Parameters
Advantages of Gas Quenching

- Reduction of hardening distortion and/or variation of distortion
- Quenching intensity adjustable by control of gas pressure and gas velocity
- Process flexibility
- Clean, non-toxic working conditions
- Integration into manufacturing lines
- Reproducible quenching result
- Clean and dry parts, no washing
- Simple process control

Distortion after heat treatment
SINTERING

- Vacuum and Overpressure Sintering
- HIP-Sintering Furnace, Type VKP
- Sintering of Magnets
- Sintering of Nuclear Fuels
Introduction

For more than 50 years, ALD and its predecessors have manufactured sintering furnaces for hard metals, cermets, magnets, MIM products and special oxide ceramics.

The sintering process consolidates particles in a coherent, pre-determined solid structure. Mass transport in the atomic range happens during this process. Single-phase powders are sintered at 2/3 to 4/5 of their melting temperature, multi-phase powders (mixtures) are sintered near the solidus of the lowest melting phase.

Dewaxing Process

In order to produce PM parts, the powder (powder metal mixture) is pressed into near net shape before sintering. To reduce friction and press force, additives, such as paraffin, PEG and others, are added to the powders. They have to be removed in a dewaxing process before sintering, thus obtaining a pore-free and chemically predetermined material structure.

The Sintering Process

The sintering process happens in vacuum or under protective gas at the appropriate temperature for the material. A defined, reproducible sintering atmosphere without atmospheric oxygen is important. At certain pressures and temperatures the process gas feed during sintering with argon, N₂, H₂, CH₄, CO₂ and others may influence the structure and chemical composition of the workpieces.
Overpressure Sintering (HIP)

Following the vacuum sintering process, 6 to 10 MPa Argon gas is introduced into the furnace at sintering temperature to further reduce porosity and to ensure the material quality of high-performance hard metal tools and other sintered parts.

Applications of Sintering Furnaces

Dewaxing, vacuum sintering and/or overpressure sintering at 6 to 10 MPa for hard metal materials and powder metallurgical products.

- Dewaxing, vacuum sintering and overpressure sintering of wear and tear parts
- Sintering of hard metal tools and micro drills
- Sintering of MIM parts (metal injection moulded)
- Dewaxing and sintering of UO₂ and MOX pellets for nuclear fuel elements
- Sintering and heat treatment of rare earth permanent magnets.

Furnace line VKPgr

The features of this furnace line are:

- One single furnace performs up to 4 different dewaxing processes
- High temperature uniformity
- Special graphite felt insulation with long service life
- Graphite heating with integrated, closed graphite muffle
- Two integrated and one external rapid cooling systems to reduce cycle time
- Metallurgical treatment of workpieces using process gases
- Operating pressure 6 MPa or 10 MPa
**Furnace line VKUgr**

The new VKUgr furnace line meets market demands for a "fast sintering furnace" for small and medium loads and various types of dewaxing processes and process parameters.

The features of this furnace line are:
- One single furnace performs up to 4 different dewaxing processes
- High temperature uniformity
- Graphite insulation
- Graphite heating
- Integrated, controllable rapid cooling system
- Metallurgical treatment of workpieces using process gases

**Furnace line VKMQ**

The features of the VKMQ furnace line are:
- Rated temperature up to 1300 °C in vacuum or under convection.
- Durable graphite heating with hard felt insulation
- Integrated, large-sized heat exchanger with fan for high-pressure gas cooling to be used for rare earth magnet sintering.

**Vacuum dewaxing and sintering furnace type VKUgr**

**Furnace line GWSmo**

Pusher type furnaces with hydrogen atmosphere, ceramic brick lining for insulation, molybdenum heaters for sintering of UO₂ pellets or MOX pellets, being used for nuclear fuels.

**Pusher furnace for sintering of MOX pellets type GWSmo**

Example of the use of up to 100 magnets in high-quality cars
**OWN & OPERATE**

**Furnace Manufacturing and Service – a good match?**

The economic efficiency of the ‘New Technology’ (vacuum case hardening and high pressure gas quenching) became apparent in heat treatment in the 2nd half of the 1990’s and a growing number of projects demanded vacuum or plasma carburizing with high pressure gas quenching. Following 6 years of continuous success we finally decided to develop our Own & Operate strategy and since then have taken over the heat treatment for our customers in selected projects.

Thus, two objectives are pursued: on one hand, the customer benefits from our process know-how while immediate investments for new technological equipment are not required.

On the other hand, the prompt feedback of operating knowledge and experiences is invaluable to our technical departments for further development of our furnace technology.

**ALD as commercial Heat Treater?**

It is not our intention to enter the market as a commercial heat treater. On behalf of one customer at a time we are acting to achieve a solution to a problem which is not yet economically solved in the market. The market development of ‘commercial heat treatment’ is part of the strategy of our customers, however, we do not consider this business area a core competence. The strategy rather caters to products with customer specific growth potential, since the ‘New Technology’ is entailing a high added value of the parts to be produced.
ALD Thermal Treatment, Inc.
in Columbia, SC, USA

In 2001, ALD Thermal Treatment, Inc. was established to cover the heat treatment requirements on the US market. Since then, the company has been acting as a service provider for various heat treatments.

New customers were gained in the service sector who benefit from solutions that the ‘New Technology’ is lately providing. Furthermore, the possibility to sample parts locally was very well accepted and was even conducive for the furnace business. As a result, customers like DANA, Visteon and Stackpole could be added to our customers reference list.

VACUHEAT GmbH – Germany’s first ‘New Technology’ Center

In co-operation with ‘Heat Gruppe’ the first project was realised in 1999 in Limbach-Oberfrohna, close to Dresden, Germany. VACUHEAT took over the heat treatment of fuel injection components, like injection nozzles. The Piezo technology for nozzle injection systems promises a high growth rate while demands on precision and cleanliness are accomplished by the ‘New Technology’ only.

Today, almost all well-known manufacturers of nozzle injection systems belong to our client base.

Production facility Columbia, SC
New Factory in Port Huron, Michigan, USA

ALD has been chosen by GM Powertrain for the heat treatment of all 23 parts of the latest six gears automatic front drive. This is one of the biggest orders ever placed for heat treatment in the US.

In June 2006, the new operating site in Port Huron, MI, started its production. Three lines of ALD’s type ModulTherm® with 6 treatment chambers each were installed for GMPT’s first phase, heat treating 1,500 gears per day.

ALD captures Mexico and China

A further order was received for heat treatment of additional 1,500 gears per day. This time the production site is Mexico where the start of production is planned for March 2008 with 3 ModulTherm® lines.

Contract negotiations with a well-known supplier in China’s automotive market are almost concluded. Start of production is scheduled for the near future.

ALD Service – Expertise in New Technology

Since 2005, ALD has been the market leading heat treatment specialist for vacuum carburizing and high pressure gas quenching. As per today the following systems have been installed world-wide:

- 10 DualTherm®-furnaces
- 8 ModulTherm®-furnaces
- 2 Continuous Plants with Plasma Carburising
- 1 Vacuum Brazing Furnace

During the past years the success of our ‘Own & Operate’ service strategy has also been beneficial for our furnace business due to product innovations and new product developments.