Advanced titanium, aluminum, and magnesium alloys are being developed to provide superior functional characteristics in various components in many industries. Specifically, titanium is light, noncorrosive, and structurally strong. However, excessive wear, erosion, and friction of titanium surfaces due to strong metal-to-metal contact, cold welding, and low hardness hinder wider use of Ti alloys for important machine components such as gears, shafts, axles, bearings, etc.

SANOVA developed and patented advanced methods for thermo-chemical processing and heat treatment (LinterProcess and Linheat) of metal surfaces and cores to dramatically improve performance characteristics such as friction hardness, strength, wear, erosion, fatigue, and corrosion resistance. The processes use rapid physical direct heating (inductive, resistive, and contact) of metal parts in contact with active elements extracted from specially formulated cold liquid active medium (LAM). These simple, inexpensive, safe, and highly effective processes create improved diffusion protective surface layers and a strong core on various metal components. These surface layers and core have required performance characteristics achieved with a gradual enhancement of chemical composition, structure, and properties of the metal surface.

The patented treatment technologies are unique and bring many important benefits compared with traditional heat treatment technologies in effectiveness, speed, and cost of treatment. This enables significantly broader, more effective use of Ti alloys in manufacturing lightweight, highly durable, and cost-effective components.

LinterProcess and Linheat technologies are effective, versatile, and tightly controlled. They are equally efficient in treating the entire component, or just a portion. SANOVA’s fully functional prototype production equipment prototype simplifies customization of treatment protocols and serves as basis for design and assembly of custom production equipment to process components made of various metals and alloys including carbon, alloy, and stainless steels; several specialty metals; and some light alloys. Most of these custom technologies have been successfully tested and deployed by customers, with Ti6Al4V alloy technology yielding strong, sometimes unprecedented results. Custom technologies for other Ti alloys, as well as Al and Mg alloys, are under development.

Industry Needs
Companies worldwide continually focus on developing cost-efficient machines and equipment with improved performance. Replacing steel with lightweight Ti, Al, and Mg to achieve component weight reduction and improved performance is getting more attention. However, while these lightweight materials have many useful functional characteristics, they are not without deficiencies. For example, aluminum and magnesium have low melting temperatures, weak wear and erosion resistance, and are highly corrosive, while titanium is soft and prone to cold welding due to strong metal-to-metal contact. Materials scientists are working on developing special treatment processes to improve or...
ABSTRACT

Titanium alloys are light-weight with excellent mechanical properties and superior corrosion resistance. However, they are susceptible to excessive wear and erosion due to low hardness and impractical in friction pairs due to strong metal-to-metal contact and consequent cold welding. SANOVAs has developed and deployed patented liquid internal technologies LINTERPROCESS™ and LINHEAT™, which utilize various liquid active media (LAM) and internal physical heating (inductive, resistive, contact, etc.) for rapid creation (under 30 minutes!) of custom-depth surface diffusion protective layer with superior hardness (65-70 HRC), wear and friction characteristics on Ti components of almost any geometry and size. These unique treatment technologies are applied in production of highly durable lightweight Ti components, enabling significantly wider use of Ti in various industries and applications.

Replacing steel with lightweight Ti, Al, and Mg to achieve component weight reduction and improved performance is getting more attention.

eliminate performance shortcomings of these metals. New effective heat treatment and thermochemical processing methods are vital to achieve these goals, as many traditional technologies fall short due to processing limitations.

Titanium is one of the most promising metals, with low density (40% less than steel), excellent mechanical properties, corrosion resistance, and high structural efficiencies. Also, it does not absorb moisture, does not degrade under UV exposure, and withstands extreme corrosive environments. However, it has a high friction coefficient and is prone to excessive wear, erosion, and cavitation of the surface due to relatively low hardness, which limits its use in applications having component contact and friction. The use of Ti alloys is precluded in applications where its inherent structural advantages would otherwise make it a perfect material choice. Consequently, even though the 21st century brought a growing demand for wide use of Ti alloys in various industries, particularly for lightweight, high-performance components for use in severe conditions, technologies were not available to effectively and safely overcome Ti alloy limitations. SANOVAs LinterProcess and LinHeat technologies solve that problem.

Some existing metal treatment technologies, such as furnace thermochemical processing, plasma nitriding, PVD and CVD, and surface melting by laser or welding electrode are unable to consistently produce high-quality enhanced surface layers and core due to treatment parameter limitations. In addition, these traditional processes are expensive and have inefficiencies due to high equipment and facilities costs, long processing times, extensive energy consumption, expensive labor and materials, as well as frequent maintenance and repair. Furthermore, traditional technologies have health and environmental concerns associated with them, as large quantities of harmful vapors and gases are discharged into the environment. Many of these treatment methods require separate additional heat equipment to obtain desired metal properties, which adds more complexity and cost.

By contrast, SANOVAs patented technologies are simple, inexpensive and safe, while extremely effective. They enable creation of overall and local protective diffusion surface layers on various metals, specifically steels and titanium alloys (this article covers treatment of Ti alloys only), significantly increasing material stiffness, strength, and resistance to fretting, wear, and erosion, while preserving crucial qualities such as flexure strength and ductility. Optimum thickness, chemical composition, microstructure, and performance properties of such protective diffusion surface layers, as well as in core, can be obtained in minutes and can be customized to meet specific application requirements.

Results on Ti components are unprecedented in some cases. For example, a hardness of HRC 60+ is consistently achieved, and HRC 70+ has been achieved in some cases. Such components have high wear, erosion, corrosion and fatigue resistance, low friction coefficient, and complete absence of any cold welding tendencies of contact surfaces. These improvements in Ti surface and core properties open the potential use of Ti alloys in many previously limited applications.

Treatment Characteristics

Surface and near surface performance enhancement of metals by precise diffusion of special chemical elements to produce optimum chemical composition, microstructure, and properties plays a crucial role in eliminating deficiencies of various metal components for demanding service conditions. Precision in quality, profile, and concentration of active elements during and after diffusion in such thermochemical processes as carburizing, nitriding, and others is critical in metal surface performance optimization. Unfortunately, such degree of element diffusion precision is extremely difficult and often impossible to achieve using traditional furnace-based treatment technologies. LinterProcess and LinHeat technologies overcome these difficulties.

In these processes, a metal component is subjected to intense direct physical heating (inductive, resistive, contact) and subsequent cooling while contained within a working chamber filled with specially formulated cold liquid active medium (LAM), or liquid protective medium (LPM), which creates a protective surface layer, transition zone, and strong core. The layers are not adhesive coats, but rather are durable diffusion surface layers. The layers are achieved by a gradual enhancement of their chemical composition, structure,
and properties with chemical elements contained in specially dissociated LAM and by application of precise treatment parameters, such as heating and cooling velocities and temperature, process sequence, and treatment duration. Combining wide treatment regime ranges with various LAM compositions creates numerous treatment protocols, which are tested, analyzed, and ranked to identify the optimal treatment parameter combinations to be used later in production.

A family of specialized sub-processes was created based on the LinterProcess technology (Table 1). These sub-processes, originally created for various steels, can be used for other metals and alloys and allow the diffusion of various active elements and combination of elements into the surface of a component to achieve optimal performance characteristics. The sub-processes, originally created for various steels, can be used for other metals and alloys. In addition, specific thermochemical sub-processes (Table 2) using multi-component LAM, are being created and tested to enhance the mechanical and service properties of light and special alloys.

Additional heat treatment of components can be performed after LinterProcess treatment to further improve physical, mechanical, and service properties of the surface, transition zone, and core. Any required heating and cooling rate, active or protective atmosphere mixture and flow rate, and any sequence and duration of operations or their stages can be applied for LinterProcess and LinHeat. It is important to note that all stages of these process technologies can be performed consecutively in an automated cycle without the need to remove and re-insert the component.

Such flexibility creates countless combinations of the two technologies with custom process stage sequences using precisely selected treatment parameters to meet required part specifications. For example, an alloy requiring high wear resistance must have high surface hardness, while the same alloy requiring high erosion and/or fatigue resistance must have small grain size; each result being achieved via different process steps and treatment protocols.

LinHeat can perform any type of heat treatment currently carried out by furnace processes. In addition, due to the application of custom internal heating of parts, it can perform unusual types of heat treatment that are

**Table 1 — LinterProcess sub-processes for Fe-base carbon and special alloys**

<table>
<thead>
<tr>
<th>Process</th>
<th>Diffusion</th>
<th>Function</th>
<th>Enhanced properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>LinBor</td>
<td>B</td>
<td>Boronizing</td>
<td>Hardness, wear, erosion</td>
</tr>
<tr>
<td>LinCarb</td>
<td>C</td>
<td>Carburizing</td>
<td>Hardness, wear, erosion</td>
</tr>
<tr>
<td>LinNitro</td>
<td>N</td>
<td>Nitriding</td>
<td>Corrosion, hardness, wear, eros.</td>
</tr>
<tr>
<td>LinCarboNit</td>
<td>C, N</td>
<td>Carbonitriding</td>
<td>Corrosion, hardness, wear, eros.</td>
</tr>
<tr>
<td>LinSulfoCarboNit</td>
<td>C, N, S</td>
<td>Sulfocarbonitriding</td>
<td>Friction, anti-cold weld/grip</td>
</tr>
<tr>
<td>LinOxid</td>
<td>O</td>
<td>Oxidizing</td>
<td>Corrosion for steels</td>
</tr>
<tr>
<td>LinAl</td>
<td>Al</td>
<td>Aluminizing</td>
<td>Corrosion, surface incrustation</td>
</tr>
<tr>
<td>LinAlBor</td>
<td>Al, B</td>
<td>Borosiluminizing</td>
<td>Wear, incrustation</td>
</tr>
<tr>
<td>LinSil</td>
<td>Si</td>
<td>Siliconizing</td>
<td>Corrosion in salt, acid</td>
</tr>
<tr>
<td>LinSul</td>
<td>S</td>
<td>Sulfidizing</td>
<td>Iron anti-cold weld/grip</td>
</tr>
<tr>
<td>LinCrom</td>
<td>Cr</td>
<td>Chromidizing</td>
<td>Hardness, wear, corrosion</td>
</tr>
<tr>
<td>LinMet</td>
<td>Metals</td>
<td>Multi-saturation</td>
<td>Hardness, wear, corrosion</td>
</tr>
</tbody>
</table>

**Table 2 — LinterProcess sub-processes for selected metal alloys**

<table>
<thead>
<tr>
<th>Process</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>LinterTitanium</td>
<td>Treatment of Ti alloys</td>
</tr>
<tr>
<td>LinterAluminum</td>
<td>Treatment of Al alloys</td>
</tr>
<tr>
<td>LinterMagnesium</td>
<td>Treatment of Mg alloys</td>
</tr>
<tr>
<td>LinterZirconium</td>
<td>Treatment of Zr alloys</td>
</tr>
<tr>
<td>Lintercobalt</td>
<td>Treatment of Co alloys</td>
</tr>
<tr>
<td>LinterChromium</td>
<td>Treatment of Cr alloys</td>
</tr>
</tbody>
</table>
impractical or impossible to achieve in a furnace.

A family of specialized sub-processes based on LinHeat technology has been created, each with specific designation. The sub-processes enable various treatment steps before, during, or after LininterProcess (or without the LininterProcess) to achieve optimal performance characteristics for a specific alloy and application. All LinHeat processing is performed in special protective atmospheres, which prevent any changes to the chemical composition (e.g., oxidation and decarburization) of the part surface.

In general, the three main stages of any heat treatment are:
- Heating to the selected processing temperature at the required speed
- Soaking at that temperature as necessary
- Cooling at the required speed

Parameter variations in these stages determine the designation and function of a particular LinHeat process, which enhances microstructure and physical and mechanical properties of the treated metal component accordingly.

LinHeat technologies not only can enhance the microstructure of a surface layer, but also the entire component volume if necessary. Thus, the technologies are separated into surface-treatment and volume-treatment subgroups. The main LinHeat sub-processes are LinAnnealing (liquid internal annealing), LinHard (liquid internal hardening), LinTemp (liquid internal tempering), and LinAge (liquid internal aging).

LinAnnealing is used to improve the crystal lattice and microstructure after plastic deformation and/or over-heating of metal. It consists of heating to and holding at a suitable temperature, followed by cooling at necessary rate. Three variations of this treatment, defined by levels of processing temperature, are:
- LinAnnealing(C) - Processing at temperatures higher than \(A_{\text{C3}}\) critical temperature (for steels, for example), resulting in complete annealing
- LinAnnealing(IG) - Processing at temperatures between \(A_{\text{C3}}\) and \(A_{\text{C1}}\) produces incomplete annealing
- LinAnnealing(D) - Processing at temperatures lower than \(A_{\text{C1}}\) is annealing after high/cold deformation

Variations in heating temperature and heating and cooling rates define a further subdivision of this process:
- LinRecrest - Used for recrystallization of metal crystal lattice and grain sizes
- LinNormalizing - Higher cooling rate than LinRecrest and LinHard
- LinAnnealing(SE) - Special annealing process designed to eliminate the carbide network after carburizing by cyclic heating and cooling around critical temperature \(A_{\text{i}}\) (spheroidizing).
- LinHard has cooling rate higher than the critical rate. It also has several variations (similar to LinAnnealing) dependent on heating temperatures:
- LinHard(C) - Processing at temperatures higher than \(A_{\text{C3}}\) critical temperature (for steels), resulting in complete hardening
- LinHard(IG) - Processing at temperatures between \(A_{\text{C3}}\) and \(A_{\text{C1}}\) resulting in incomplete hardening
- LinHard(L) - Local hardening
- LinHard(S) - Surface hardening
- LinHard(D) - Double-hardening
- LinHard(ST) - Combined hardening and self-tempering

Numerous other hardening process variations may be created based on specific requirements:
- LinTemp is usually applied after normalizing and hardening. Variations of the tempering process defined by processing temperatures are:
  - LinTemp(L) - Low temperature tempering (temperature below 200ºC)
  - LinTemp(M) - Medium temperature tempering (below 400ºC)
  - LinTemp(H) - High temperature tempering (below \(A_{\text{C1}}\), or ~ 600ºC)
- LinAge also has several variations:
  - LinAge(D) - Low temperature process applied to stabilize dimensions for precision friction pairs
  - LinAge(P) - Precipitation aging

The LininterProcess and LinHeat technologies have been used to simultaneously enhance surface and core microstructures and properties of several materials including steels, and Ti, Zr, and Co alloys with positive results. Newly developed technologies have excellent potential for rapid production of stronger, more durable products in a safe, cost-effective manner. These simple to set-up and easy-to-use processes can create a wide range of metal structure and property enhancements on many components made of different materials.

Process Specifications

Key LininterProcess and LinHeat process characteristics are the use of physical heating and liquid active media (LAM) to achieve desired part surface and core properties. Figure 1 shows a schematic and actual equipment of one application. The part to be treated, along with a handling device, IR sensor of the temperature control system, inductive heater (inductor), and sprayer is placed in a working chamber containing liquid active medium having the required chemical composition and physical properties. The selected portion of the part surface (or the entire part) is rapidly heated to the required temperature using (in this case) precisely controlled induction heating method. The part can be stationary, rotating, and/or moving through the inductor (scanning). Even complicated shapes and surface geometries, such as gears, can be treated with precision and consistency.

The essence of the LininterProcess method is the dissociation of LAM components directly in the reaction...
zone of the part. A gas phase containing a large amount of atomized performance-enhancing, highly active alloying element(s) is produced during this stage around the heated part surfaces. Controlled by treatment duration and heating temperature the alloying elements are rapidly absorbed and diffused into the metal surface to the desired depth, creating a protective surface layer with superior hardness, strength, wear, erosion and corrosion resistance, as well as other desired characteristics. The products of the liquid medium dissociation also insulate and protect the treated component from oxidation and contamination by the environment, while significantly decreasing process energy consumption. Various LinHeat sub-processes in the same active or another protective atmosphere can be used, if necessary, to further enhance surface and/or core properties.

Various LAM are used in LinterProcess to alloy the part surface with specific metallic and nonmetallic elements, such as carbon in LinCarb, or carbon and nitrogen in LinCarboNit. Liquid medium consumption during the entire liquid internal process is negligible, since only small amount of LAM is vaporized and dissociated on the treated surface. The rest of LAM mass serves as a confining “blanket,” which keeps active element concentration at high, uniform levels near the part's treated surface, resulting in significantly better results, decreased processing times, and considerably enhanced overall process efficiency.

There are no restrictions in part geometry. In fact, LinterProcess is often the only technology that can effectively treat and enhance surface layers of certain complex-shaped components. Properties of the surface layer and metal core can be customized for various applications by rapid, economical selection of the necessary treatment protocol; i.e., heating method and temperature, active media composition, and duration of processing stages. This allows achieving a wide range of part surface properties, such as hard or soft, flexure-strong, or resistant to friction, wear, corrosion, fretting, erosion and cavitation. The process is fully automated, computerized, and tightly controlled, ensuring high precision, quality, and uniformity of each treated component. All treatment parameters and settings are stored and printed for each treated component (Fig. 2).

LinterProcess and LinHeat treatment parameters and selection of corresponding LAM or LPM depend on the part characteristics and desired surface and core properties. Various treatment conditions and parameters can be used to process parts. All surface and core structures created by liquid internal thermochemical processing can be subsequently heat-treated (if necessary) via LinHeat without the need to relocate the part from the treatment equipment and by using the same active medium and heating device; something not possible with other commercial heat-treatment process.

While many components of the LinterProcess production equipment are the same from application to application, each production treatment machine assembly is customized depending on dimensional and functional parameters of the components to be treated on that machine, and on the production throughput for that component.

Figure 3 shows the LinCarb-1 production equipment prototype used by
SANOMA for test-treatment of various production components. Four main components of the system are a high-frequency power supply, a treatment chamber, a programmable control unit, and auxiliary systems (not shown). A custom high-efficiency internal heater, such as an induction coil for example, is a critical component of the effective internal heating process, essentially defining the quality and efficiency of the treatment process. Its design depends on the dimensions and geometry of the treated component, heating pattern, cycle time, power, and frequency requirements (Fig. 4). A variable frequency power supply contains all the necessary instruments to measure, control, and support the operations of the induction coil (heater type in this example). Other types of internal heating devices, such as resistive, contact, etc., can be, and currently are, used effectively. The choice of heating device depends on such particulars as size, form, technical requirements of the component and their effect on treatment results. The quantity of a particular component to be treated also plays a role in determining the choice of heating.

LinCarb-1 is equipped with ancillary devices, sensors and instruments to provide precise, effective and repeatable treatment of the parts with predictable, consistent results. An automatic programmable, computerized system provides both manual and automatic input, control, and regulation of treatment parameters such as processing temperature and times of all process stages, position, rotation, and vertical movement of the treated component, LAM temperature and chemical composition, sprayer positioning, water and compressed air systems operations. The control system is equipped with touch-screen controls and registers all data points of the treatment process. The feedback temperature control system (Fig. 5) precisely monitors and dynamically adjusts the temperature of the treated metal component surrounded by the products of dissociated liquid active medium during processing.

Also included in the system are numerous handling devices for chucking, rotation and linear and/or vertical movement of the treated component, as well as component loading and unloading devices. Holding tanks contain LAM and are equipped with devices for chemical analysis, agitation, circulation, cooling, and filtration of LAM, as well as an emergency response mechanism. A sprayer is used to increase quench cooling velocity for improved surface quenching of the treated component.

While LinCarb-1 is a prototype, it enables SANOMA to treat production samples and real production parts and serves as a functional base to create custom production equipment to treat practically any production component and to achieve desired performance characteristics.

Equipment can be integrated as part of a continuous manufacturing process, requiring minimal space, maintenance, and operator supervision. A single operator can effectively operate several treatment machines. The machines are environmentally friendly, easy to operate and maintain, can be turned on and off in seconds, and produce consistent, repeatable results.

**Ti-Alloy Treatment**

Direct physical heating of metals using cold LAM accelerates all phases of thermochemical and heat-treatment processes compared with traditional treatment processes by enabling rapid heating of only the part, using broader temperature ranges with higher upper limits, and precisely directed and controlled LAM dissociation products onto the part surface. Varying LAM physical properties and chemical composition, the sequence of process stages, and selecting precise processing parameters enable creating custom surface layer and core microstructures and performance characteristics. This allows using LinterProcess and LinHeat processes to quickly and inexpensively produce almost any stable and...
metastable structure on various metals and alloys.

Already successfully treated materials include plain carbon and special steels, powder metallurgy products, various special alloys, and superalloys, all with very short processing times, measured in minutes and even seconds. Treatment specifications, such as protective surface layer shape, thickness, chemical composition, structure, and performance characteristics, can be fully customized to meet specific application requirements.

Especially effective results have been achieved in treating Ti alloys (Ti6Al4V, for example) using LinterProcess and LinHeat treatments, resulting in diffusion surface layers having distinctive structure and superior hardness, strength, wear, fatigue and erosion resistance (Fig. 6). Customer evaluation of treated Ti6Al4V components confirmed that erosion resistance increased by a factor of over three. This property improvement can be extremely valuable in manufacturing various turbine blades and vanes. In addition, the friction coefficient was of such low value after treatment, that similarly treated Ti components can not only be used in structural or frame assemblies, but also to create friction pair components such as bearings, power train gears, and screws.

Expanding Ti-Alloy Applications

There is the possibility to potentially grow the market for titanium alloy use in organizations currently using titanium alloys, such as Boeing, Lockheed Martin, and NASA, with the availability of treated titanium alloys having significantly improved performance characteristics. For example, NASA could use enhanced titanium alloys to make certain spacecraft components considerably lighter and more reliable. Manufacturers in the transportation industries, such as cars, trucks, tractors, trains, etc., also could reduce overall weight, thereby dramatically increasing operating efficiency, which would translate into significant economies of scale in energy consumption.

In medicine, this technology can potentially result in the production of more reliable, longer lasting, and significantly more cost-effective tools and components for invasive orthopedic and trauma procedures. This would result in better quality of patient care and significant savings for the medical insurance industry and eventually for patients.

In construction, this technology could improve building construction and reinforcement techniques and components, resulting in greater durability and the ability to better withstand natural disasters of commercial and residential dwellings.

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