ABSTRACT

This paper presents a brief history of high-density infrared (HDI) lamp systems and their use in advanced materials development and fabrication. Two types of lamp systems have been developed and are in use at Oak Ridge National Laboratory (ORNL) Infrared Processing Center (IPC), namely, plasma arc lamps and tungsten halogen lamps. The plasma arc lamp is used for processes that require high heating rates or high temperatures. Such applications include sheet fabrication and coatings using refractory metals, traditionally difficult-to-process materials, such as intermetallics and ceramics, thermal forming, and selective heat treating. There are significant cost savings for thin sheet fabrication when compared with standard warm/hot deformation processes. Tungsten halogen systems are used for lower temperature materials. Applications include coatings and claddings, debinding operations, braze joining, tooling preheating, and billet heating. A mathematical model has also been developed for the simulation of infrared heating.

1.0 INTRODUCTION

This paper reviews the history, development and application of high-density infrared (HDI) radiant heating technology at the Oak Ridge National Laboratory. Since the facility began in 1996, it has evolved into a prototype production facility with two plasma arc lamps and two tungsten-halogen systems.

The first tungsten-halogen system developed at ORNL was the circular infrared furnace. The Circular Infrared Furnace is a 33-kW unit that utilizes a circular array of 165-mm lighted length tungsten halogen lamps, providing a maximum attainable temperature of 1200°C for most materials. These bulbs achieve full emission and shut down in 0.75 second. Which, coupled with their cold wall design, allows for very fast processing rates. The system is ideally suited for heat treating, brazing and coating fusing applications. The furnace is PID/fuzzy logic controlled. Inside the array, a 92mm-diameter by 73mm-long quartz tube provides various processing atmospheres, including vacuum (10-mTorr maximum). The heat zone is 82mm x 57mm x 152mm. Figure 1 shows the Circular Infrared Furnace.

The second tungsten-halogen based system is the Flat Bed Infrared Furnace. This 88kW furnace uses a planar array of 36 tungsten-halogen quartz lamps. The main body of the flat bed is made from polished, water-cooled stainless steel plate. This maximizes the amount of radiating power and minimizes the heat absorbed by the furnace body. A drop bottom batch arrangement is placed under the lamp array. The box is used to load specimens into the furnace. The work piece size is not limited to the dimensions of the specimen box. Figure 2 shows the Flat Bed Furnace.

In 1999, the first Vortek (Vancouver, B.C., Canada), plasma arc lamp was installed at the ORNL IPC. The 300,000W lamp can deliver power densities up to 3.5kW/cm². Three interchangeable lamp configurations are available, 10cm-wide, 20cm-wide, and 35cm-wide. For any width lamp, a water-cooled and highly polished line focus reflector redirects the radial radiant energy output to the sample being processed. The lamp and its reflector are mounted on a Cincinnati-Milacron T3-776 5-axis robot system. The flexibility of the robotics allows for the processing of many different sample sizes and geometries. Figure 3 shows the 300,000W plasma arc lamp and Figure 4 shows a schematic of the line focus reflector.
In Fall 2003, the newest Vortek lamp system was installed at ORNL IPC, the 750,000W plasma arc lamp. This newest system is similar to the 300,000W lamp in design and function. This lamp is fixed mounted, fitted with a uniform irradiance reflector, and capable of outputting 460W/cm² over an area 375cm². Figure 5 shows the 750,00W lamp and Figure 6 shows a schematic of the uniform irradiance reflector.

Both of the plasma arc lamps utilize a unique technology to produce extremely high-power densities with a single lamp. Instead of using an electrically heated resistive element to produce radiant energy, a controlled and contained plasma is utilized. A schematic of the lamp is shown in Figure 7.

The lamp is sealed at the ends where the cathode and anode are located. Deionized water mixed with argon or nitrogen gas enters at the cathode side through high-velocity jets impinging at a given angle. Due to the high velocities and pressure, the deionized water is impelled to the wall of the quartz tube and spirals down the length of the tube in a uniform 2-3 mm thick film. This water film serves two purposes: to cool the quartz wall and to remove any tungsten particulates that may be expelled from the electrodes. The gas moves in a spiral fashion through the center of the tube, and a capacitative circuit initiates the plasma. The plasma, which has a temperature in excess of 10,000 K, is stable and produces a radiant spectrum from 0.2-1.4µm [1].

### 2.0 TUNGSTEN HALOGEN LAMP APPLICATIONS

Infrared heating has many advantages over commonly used heating techniques. Infrared heating provides: (1) an inherently clean non contact heating method; (2) high heat fluxes resulting in heating rates up to 200°C/s, materials dependent, due to the fact that only the sample is heated to the desired temperature; (3) high heat fluxes; (4) controlled temperature gradients through thick-section material; and (5) a precise process, which is essentially shape independent, utilizing proper furnace design.

#### 2.1 Circular Infrared Furnace

Due to the above features of infrared heating, ORNL has worked in conjunction with industry to further develop infrared processing applications. Joining of advanced materials, such as, TiAl, FeAl, and titanium matrix composites has been achieved. Automotive part heat treating and coatings have been developed. Titanium bonding to steel for armor and other applications have benefited from infrared heating. Debinder and pre-sintering operations for powder metallurgy processing have benefited from infrared heating [2-4]. The clean heating environment, precise fuzzy logic controlling, and high heating rates allow for tape cast metal powders, such as, Ni, Ti, and TiAl to be debindered quicker and cleaner than in conventional vacuum furnaces.

#### 2.2 Flat Bed Infrared Furnace

Applications include rapid preheating of die blocks, billet preheating, preferential tempering, predetermined hardening, and preheat for powder metallurgical sheet and steel [5,6]. In the many cases mentioned, the infrared processing technique results in tremendous cost savings through reduced processing time, reduced operating cost, and environmental friendliness. The underpinning materials science has been developed at ORNL and published for many applications.

### 3.0 PLASMA ARC LAMP APPLICATIONS

Processes requiring higher heating rates, higher temperatures, or a combination of both over large areas are perfectly suited applications for the plasma arc lamps. Heating rates of 2000°C/s and peak temperatures well above 3000°C are possible. This heating capability allows for the processing of powder metal precursors for coatings/claddings or forming of dense sheet. Preferential heat treating of materials has also been investigated.
3.1 750,000W Plasma Arc Lamp Applications

The 750,000W plasma arc lamp has the unique capability to illuminate a large area with a uniform power density. Thin gage sheet processing of traditionally difficult-to-process materials has been successfully demonstrated with this system [2,4,7]. Due to the lack of room temperature ductility of refractories and inter metallics that limits their ability to be rolled into sheet, a new process in which powder metal precursors are liquid phase sintered and formed into thin gage sheet has been developed using the plasma arc lamps. Nickel, titanium aluminide, and rhenium sheet have all been successfully produced. The process starts by tape casting a metal powder. The tape cast structure is laminated and warm pressed to a desired thickness. The compact is then debindered/pre-sintered in the circular infrared furnace. The resulting precursor is then rapidly heated and liquid phase sintered under the plasma arc lamp. In the case of Ni, the HDI-processed sample is repeatedly cold rolled then flash annealed under the lamp until the desired thickness and surface condition is obtained. For more difficult-to-process materials, such as rhenium and gamma titanium aluminide, the HDI-processed sample is centerless ground resulting in usable material. Figure 8 shows various sheet product and resulting microstructures that were obtained by processing under the plasma arc lamps.

3.2 300,000W Plasma Arc Lamp Applications

HDI offers a unique solution to controlling deformation of crumple zones in the event of an automobile crash. In a recent joint effort with Ford Motor Company, the heating of an extruded aluminum tube at periodic intervals with the plasma arc lamp was explored. Square, extruded 6063-T6 aluminum tubes were heated with the 300,000W plasma arc lamp in order to locally reduce the hardness according to Ford model predictions for appropriate crush behavior [8]. The material in the heat-affected zone showed a 50% reduction in hardness and corresponding changes in the microstructure. Recent work by Shibata et. al. [9] demonstrated induction hardening of steel members to locally increase strength in steel body panels. While this method could be applied to aluminum frame rails, HDI holds a critical advantage over induction heating in that HDI is a more shape and size flexible system.

The fusing of sprayed coatings and claddings with the plasma arc lamp has recently been investigated [1]. The high heating rate processing available from the plasma arc lamp makes it a natural tool for the fusing of coatings. Coatings investigated thus far are NiCr on steel, WC with Ni-P binder on steel, Cr$_2$C$_3$ with Ni and Cu based binders on 319 aluminum, WC with Ni-P binder on aluminum, Fe-29Cr on steel, and Fe-Cr-B-Mn-Si on steel. The NiCr coatings were deposited by the high velocity oxygen fuel (HVOF) thermal spray process. The WC and Cr$_2$C$_3$ coatings were mixed with their respective binder and a proprietary carrier and deposited at room temperature using an industrial paint spray gun. Fe-29Cr and Fe-Cr-B-Mn-Si coatings were deposited using a two-wire arc spray method. Partner companies on these projects have included Ametek, Crucible Research, Carpenter Powder Products, Lund International, and Caterpillar. NiCr and Ni-P coatings are used to improve corrosion resistance. Carbide coatings are used in cutting tools. And, the Fe-based multi-component systems are used as functionally graded materials. That is, the coatings properties can be tailored through the thickness, i.e., the coating can be ductile at the interface and hard at the surface. In addition, Ni-P coatings can form an amorphous layer if adequate undercooling is achieved. It is important to carefully choose a method of coating application to obtain a favorable microstructure in both the coating and the substrate. Rapid thermal processing techniques, such as laser or weld overlay, cause large convective stirring currents and cause the degradation of the coating and unwanted mixing of the substrate and coating. Although the gross power of the plasma arc lamp is rated at 300,000W, the power densities are two to three orders of magnitude less than that of laser or weld overlay. The HDI process offers more control over the interface reaction between coating and substrate when compared with tradition fusing methods. Figure 9 shows various coatings fused by plasma arc lamp processing.

Using a plasma arc lamp to fuse coatings for wear and corrosion resistance has been shown to be a viable alternative technique. Micro structural analysis shows that the coatings are fully dense and well bonded to the substrates. The reaction zone between the coating and substrate was narrow and showed little mixing. Also, HDI processing only slightly degrades the carbides and produces coatings that resist delamination during bending.
Investigations have also been undertaken involving the surface treatment of ceramics [10]. In these experiments, refractory ceramics were surface treated using the 300,000W plasma arc lamp in order to reduce the corrosive damage that occurs in energy-intensive applications. The refractory in this study was a commercially available aluminosilicate with low cement content and a nominal composition of 60% aluminosilicate, 30% Al₂O₃, 8% SiO₂, and 2% calcium aluminate. The aluminosilicate was processed at a lamp power of 1700W/cm² and a scan speed of 1mm/s. After processing, melting on the surface was apparent. Micrographs in Figure 10 show the cross section of the as-HDI-processed and furnace heat treated samples. Conventionally furnace heat treated material (1500°C, 1hr) consisted of large aggregates bonded together with finer materials. The HDI-processed samples show a 1-2mm thick melted surface coating and 1-2mm thick reaction zone. Residual porosity remains trapped near the underlying reaction zone.

4.0 NUMERICAL MODELING

In order to assist in experimental design, a numerical heat transfer model was developed to simulate the operation of the arc-lamp. One of the main difficulties in using computer models for the thermal analysis of the arc-lamp process is the lack of constitutive equations for thermophysical properties of the material. Material property measurements were conducted to compile a complete set of data for use as input in computer simulation software.

In order to solve the energy equation, data on density, thermal conductivity, surface emissivity, specific heat and latent heat release due to phase transformations are needed. Specific property measurements were conducted to determine properties intrinsic to roll-compacted powder materials. The nickel powder material system was investigated.

The density of powder compacted materials can be determined indirectly from hardness indentation test data [11-14]. The density can be correlated very well with the indent size or hardness. In order to obtain data on thermal conductivity, the thermal diffusivity of the green sheet precursor was measured at room temperature using a laser-flash technique. The thermal diffusivity was measured in direction normal to the sheet, \( \alpha_n \), and in direction transversal, \( \alpha_t \), to the sheet. The effective thermal conductivity, \( \tilde{k} \), can be determined based on the thermal diffusivity results using the following relationship \( \tilde{k} = \alpha \rho C_p \).

For the sake of simplicity, the spectral properties of the sheet surface are neglected in the calculation of radiant heat transfer. The sheet surface is considered to be diffuse-gray. The absorbed heat flux at the sheet surface is considered to be proportional to absorptivity. Based on Kirchhoff's law for diffuse-gray surfaces, the absorptivity and emissivity have equal values and are considered in this study to be equal to the total hemispherical emissivity of the sheet surface.

The emissivity of the sheet surface depends on its surface condition, i.e., surface morphology and state of oxidation. In general, the emissivity is a function of the surface temperature, \( T \). However, when liquid appears on the surface, the emissivity depends on the surface characteristics of the liquid. Since the liquid has a continuum surface without voids, unlike that of the powder compact, the emissivity of the liquid surface is typically much less than that of a powder compact material. Thus, a non-uniform distribution of the radiant heat flux is expected due to the presence of the liquid (see Figure 11). The surface morphology, which includes the fractional area of material on the surface, will affect the overall emissivity of the sheet surface. The surface emissivity of the powder compact, \( \varepsilon_{pc} \), can be taken to be an area fractional average of the emissivity of the material itself, \( \varepsilon_{Ni}(T) \), and that of the void, \( \varepsilon_{void} \) [13]:

\[
\varepsilon_{pc}(T) = \varepsilon_{Ni}(T) a_{Ni} + \varepsilon_{void}(1 - a_{Ni})
\]  (1)
where \( a_{Ni} \) is the fractional area of the metal on the powder compact surface. In general, the emissivity of the surface voids depends on the shape of the void. For the sake of simplicity, the emissivity of the void spaces is taken to be \( \varepsilon_{\text{void}} = 1 \).

For arc-lamp processing, a sample from the debindered nickel was machined to a size of 102 mm long x 38.1 mm-wide x 3.82 mm-thick. These dimensions were chosen to limit the influence of edge effects so that the ends of the compact during processing would remain at close to room temperature. After machining, two small holes were drilled along the centerline of the width of the sample near each end. These holes were used in conjunction with a laser mounted on the plasma arc lamp for accurate sample locating prior to processing. Five thermocouples were attached to the backside of the sample. An S-type thermocouple was spot welded to the center of the compact along with four K-type thermocouples spaced 0.5-cm apart down the centerline of the width of the sample.

Preliminary results indicate that the numerical simulation results are very sensitive to the emissivity. Temperature results are presented in Figure 12. There is very good agreement between the measured and computed temperatures at locations of 0, 0.5, 1.0, and 1.5 cm away from the center of the lamp. Higher temperatures are computed at the other location (2 cm).

There is poor temperature agreement at the 2 cm location and very good agreement for the other locations. The fact that this temperature is not in good agreement is likely to be due to the omission of sintering effects. As shown in previous sections, the sintering phenomena yield surface morphology changes and variation of thermal conductivity within the material in regions where high heat flux is absorbed by the sheet surface. These sintering phenomena are not considered in this study.

5.0 CONCLUSIONS

High density infrared processing has been shown to be a cost effective technique for rapid, clean, and non-contact high temperature processing of materials. The Circular Infrared Furnace can be used for the joining of materials, heat treating, and debinding operations. The Flat Bed Infrared Furnace can be used for heating of die blocks, billet preheating, preferential tempering, predetermined hardening, and preheat for powder metallurgical sheet, steel, and wire. The 750,000W Plasma Arc Lamp is useful in processing materials including refractory metals, Ni, Ti, and Ti alloy cladding/coating/sheet over large areas. The 300,000W Plasma Arc Lamp is a flexible and high power density processing tool that is useful for preferentially heat treating materials and for fusing of coatings and claddings.

6.0 REFERENCES


Fig. 1. 33kW Circular Infrared Furnace

Fig. 2. 88kW Flat Bed Furnace
Fig. 3. 300,000W Plasma Arc Lamp

Fig. 4. Line Focus Reflector

Fig. 5. 750,000W Plasma Arc Lamp
Fig. 6. Uniform Irradiance Reflector

Fig. 7. Schematic of high-power density lamp and its operation principle

Fig. 8. Plasma arc lamp processed a) Ni sheet, b) Re sheet, c) TiAl sheet, and resulting microstructures d) Ni sheet, e) Re sheet, and f) TiAl sheet
Fig. 9. Coatings fused by plasma arc lamp a) WC with Ni-P binder on steel (RXN=reaction), b) HVOF sprayed Cr$_2$C$_3$ on steel, c) WC with Ni-P binder on aluminum, d) two-wire arc sprayed Fe-29Cr on steel, and e) two wire arc sprayed Fe-Cr-B-Mn-Si on steel
Fig 10. Aluminosilicate refractory ceramics processed by a) conventional furnace heat treatment and b) HDI.

Fig. 11. Schematic of the absorbed heat flux on the material surface due to melting
Fig. 12. Temperature evolution at five locations on the back side of the sheet assuming a surface porosity of 21%. Position of thermocouples from the lamp center is indicated on the legends [cm]