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Title: INTENSE HIGH-FREQUENCY GYROTRON-BASED MICROWAVE BEAMS FOR MATERIAL PROCESSIN

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INTENSE HIGH-FREQUENCY GYROTRON-BASED MICROWAVE BEAMS FOR MATERIAL PROCESSING

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ABSTRACT

Microwave processing of materials has traditionally utilized frequencies in the 0.915 and 2.45 GHz regions. Microwave power sources are readily available at these frequencies but the relatively long wavelengths can present challenges in uniformly heating materials. An additional difficulty is the poor coupling of ceramic based materials to the microwave energy. Los Alamos National Laboratory scientists, working in conjunction with the National Center for Manufacturing Sciences (NCMS), have assembled a high-frequency demonstration processing facility utilizing gyrotron based RF sources. The facility is primarily intended to demonstrate the unique features available at frequencies as high as 84 GHz. We can readily provide quasi-optical, 37 GHz beams at continuous wave (CW) power levels in the 10 kW range. We have also provided beams at 84 GHz at 10 kW CW power levels. We are presently preparing a facility to demonstrate the sintering of ceramics at 30 GHz. This paper presents an overview of our present demonstration processing facility and describes some of the features we have available now and will have available in the near future.

INTRODUCTION

The National Center for Manufacturing Sciences (NCMS) and Los Alamos National Laboratory have entered into a DOE Cooperative Research and Development Agreement (CRADA) for the purpose of exploring commercial applications for microwave processing of materials. Through this program Los Alamos has established a user facility with capabilities over a broad range of microwave frequencies. The ability to process materials at millimeter wavelengths has been a primary focus of this program [1]. Through the close cooperation of The Paton Welding Institute (PWI), and the Salyut Company, Former Soviet Union organizations, Los Alamos has acquired a materials processing chamber and gyrotron equipment capable of providing many kilowatts of continuous, quasi-optical, output power in the 37 or 84 GHz microwave bands. In addition to the quasi-optical equipment Los Alamos has recently installed a 30 GHz processing system produced by the Institute of Applied Physics, Nizhny Novgorod, Russia. This facility incorporates a multi-mode chamber with the capability of precisely controlling the environment in which materials are processed. This paper concentrates mainly on the millimeter wave processing hardware available at Los Alamos National Laboratory. Some material processing examples are included but much of the actual experimental work conducted with this equipment is proprietary in nature and cannot be included here.

PROCESSING SYSTEMS

37 GHz / 84 GHz Quasi-Optical System

Figure 1 is a photo showing the gyrotron equipment and processing chamber associated with the 37/84 GHz quasi-optical material processing system. The system was provided by the Paton Welding Institute, Kiev, Ukraine. The gyrotron tubes were manufactured by the Sayute company in Russia. Replacement tubes now come from GYCOM of Nizhny Novgorod, Russia. The gyrotrons for this system require a superconducting magnet which is the cylindrical structure above the cabinet to the right in Figure 1. The entire system includes high voltage power supplies and a control console not shown here. This system can be operated with an 84 GHz tube or a 37 GHz tube.

The system features a quasi-optical beam which may be tailored to the processing application by combinations of dielectric lenses and metal mirrors. In addition to adjusting the beam distribution the mirrors may be scanned to sweep the beam across a large area sample. Processing is done primarily in an air environment although we sometimes insert the sample within a quartz tube and back fill the tube with an inert gas. A blower system fitted with a HEPA filter draws gas byproducts clear of the processing environment. The process may be viewed through water-filled, microwave-screened, windows. We have a thermal-imaging camera, and other thermal detecting equipment available to document the process. Power may be adjusted from several hundred watts to 10 kW. The system provides a continuous (cw) output but may be gated on and off with pulse lengths and repetition times as short as 0.1 seconds.

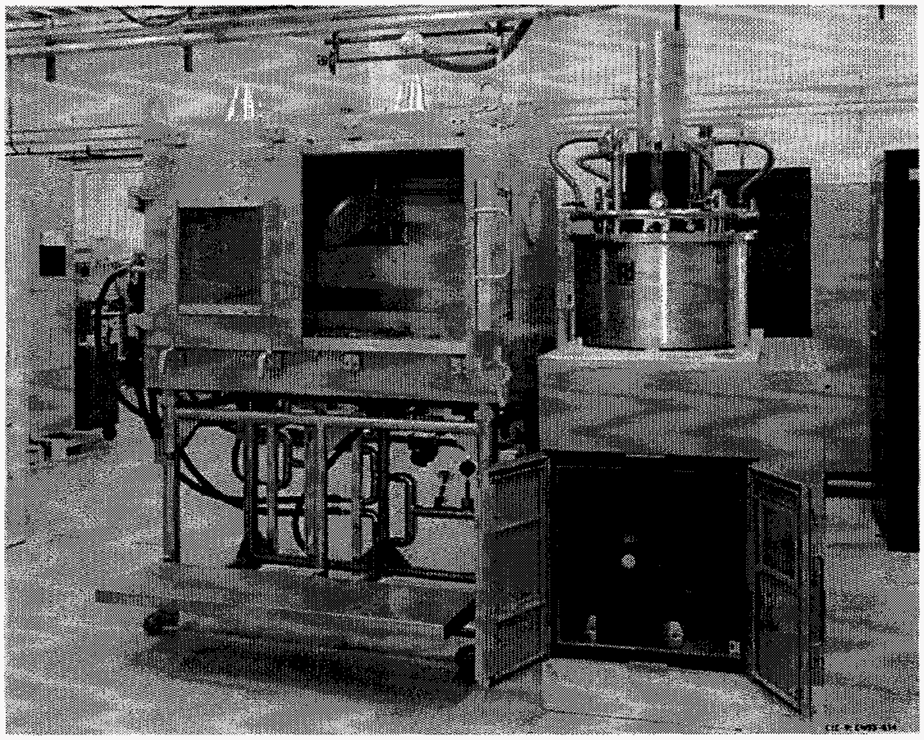

Figure 1: Quasi-Optical Gyrotron Processing System

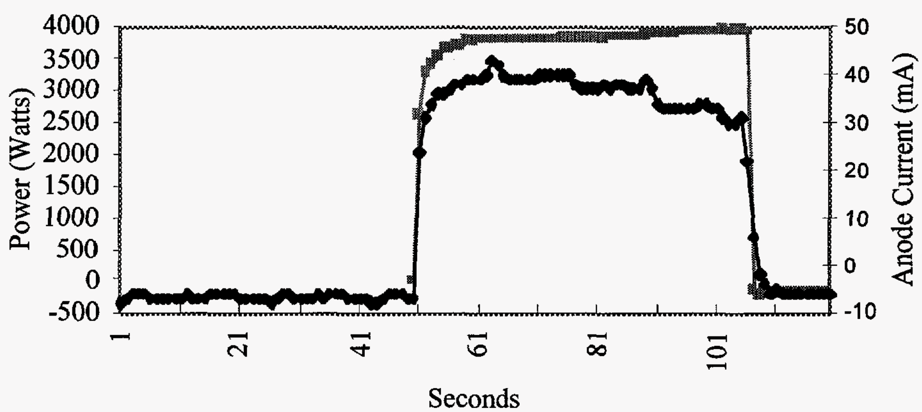

Figure 2: Typical Output Power Pulse (upper trace) and Anode Current

Power can be monitored continuously during processing by observing the power lost in the tube vacuum window. The window is water cooled so temperature rise of the cooling water is a measure of the power dissipated in the window. The window has a time constant of 14 sec. so for short duration pulses the time constant effects must be taken into account. Figure 2 shows a typical power output pulse. A detected microwave signal is also available but is hard to interpret since the output observed by this detector is affected by beam parameters.

An absolute measure of output power can be obtained from a water-load/calorimeter. This device was provided by IAP as part of the multi-mode 30 GHz processing system but can also be installed within the quasi-optical processing chamber. This device utilizes temperature sensors to measure the rise in water temperature resulting from microwave energy absorbed by the load. The device also contains a pair of electrical heater units that are adjusted to provide a temperature rise of a similar magnitude as that observed with microwave power. The comparison technique removes the need to accurately measure the properties of the thermal sensors and the cooling water flow rate.

The quasi-optical nature of the microwave output beam provides some unique processing options. Waveguide is unnecessary. The material to be processed may simply be placed in the chamber and exposed to the beam. A metal mirror, visible in the photo of Figure 1, and other optical elements direct the beam onto the material and can be used to tailor the beam distribution to some particularly desired pattern. The optical elements can be remotely positioned while microwave power is being applied. Features such as raster scanning across a large sample can be accomplished during the application of microwave power. The beam may be focused to a spot or line distribution or metal masking may be utilized to provide more precise patterns. A major advantage for this kind of quasi-optical beam is for dedicated zone heating applications where adjacent materials are not heated.

30 GHz Multi-Mode Cavity System

The 30 GHz multi-mode cavity processing system produced by the Institute of Applied Science (IAP) Nizhny Novgorod, Russia was originally intended for the sintering of ceramics [2]. The processing chamber has a uniform field region of about 1 cubic foot allowing bulk heating of samples in a controlled environment. A computer based control capability offers the unique ability to program a variety of processing cycles with repeatable characteristics.

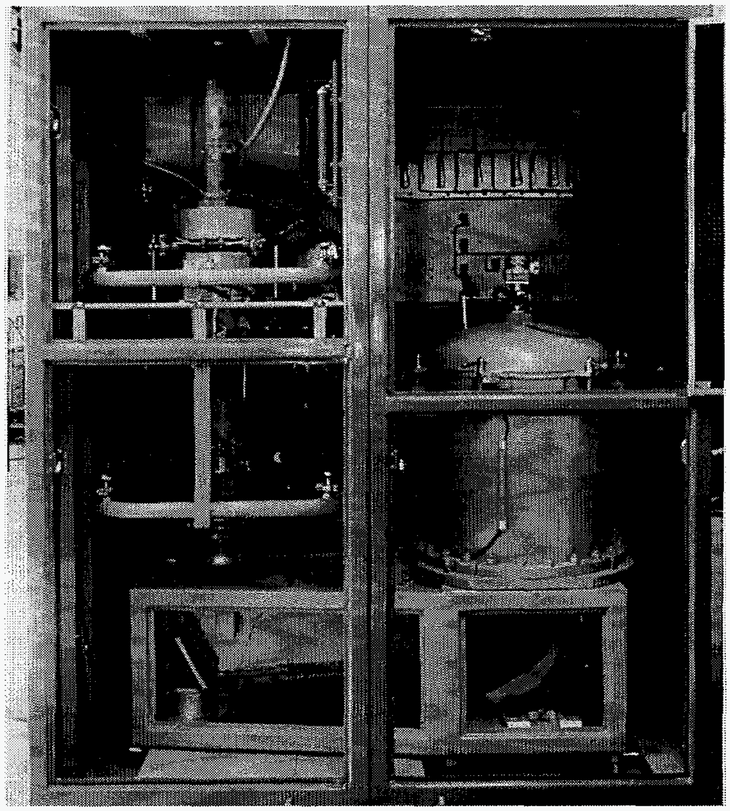

Figure 3: Overall view of the Gyrotron Sintering System

Figure 3 is a photo showing the 30 GHz gyrotron sintering system. The system is shown here with the doors open and covers removed. The gyrotron is located in the left bay. The cathode insulating structure is at the top and its output is at the bottom. The housing that fills the bottom of both bays is an optical transmission line. Gyrotron output is converted from a TE02 mode to a quasi-optical pseudo-gaussian mode to transport it to the processing chamber. The bottom surface of the transmission line is covered by microwave lossy tiles to absorb energy reflected from the processing chamber. The processing chamber fills most of the right hand bay.

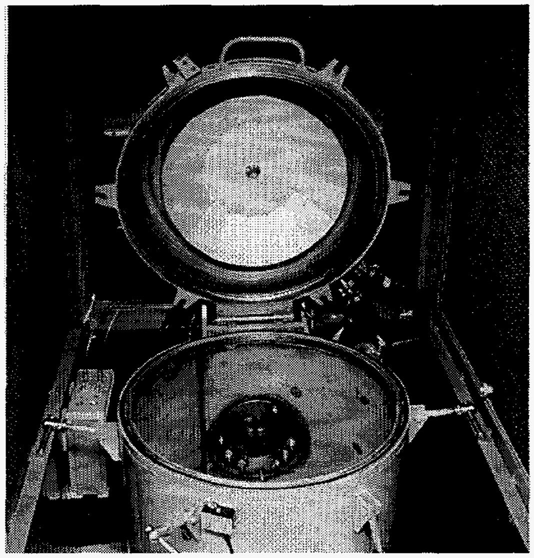

Figure 4: Multi-Mode 30 GHz System Processing Chamber

Figure 4 is a close-up of the processing chamber shown with its lid in a raised position. The structure in the lid forms a mode stirrer to enhance the uniformity of energy distributed within the chamber. The chamber has been designed as a pressure vessel to allow operation either under vacuum or at a positive pressure. The microwave window, located at the bottom of the chamber, presently limits positive pressure to around 2 atmospheres. Electrical feedthroughs, specifically intended for thermocouples to monitor the temperature of materials being processed, are provided at the rear of the chamber.

The 30 GHz Multi-Mode system operates under complete computer control. A digital feedback loop senses the temperature of the part being processed and adjusts the microwave power to follow an operator determined heating schedule. A sample temperature profile showing the actual temperature of the processed part as it follows a programmed function is included here as Figure 5. Power control is achieved by adjusting the cathode voltage.

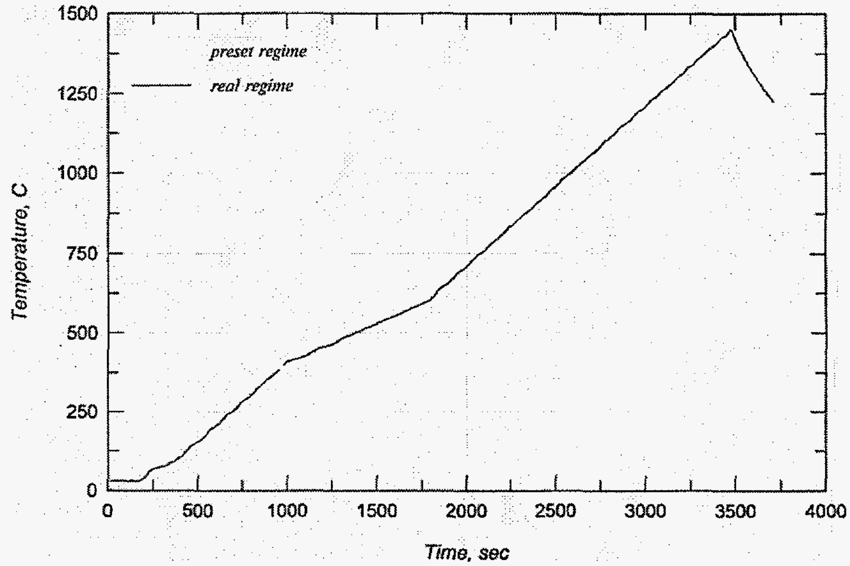

Figure 5: Temperature Profile Taken During Ceramic Sintering Cycle.

PROCESSING EXAMPLES

The photo of Figure 6 shows a typical material processing fixture [3]. This particular fixture was designed for a silicon carbide joining experiment. The fixture holds two cylindrical pieces of silicon carbide under tension. Tension can be adjusted by installing an appropriate spring. The motor to the right rotates the disks allowing the gyrotron beam access to all sides of the material. The video image of Figure 7 shows the material being heated by the gyrotron beam. The beam was focused to a spot of about 1 cm in diameter and directed at the joint region between the two cylindrical samples.

Figure 8 shows another processing fixture[3]. Here a hairpin spring is used to hold the sample in place. The sample is metallic and is indirectly heated by directing the beam onto a microwave lossy material surrounding the sample.

References

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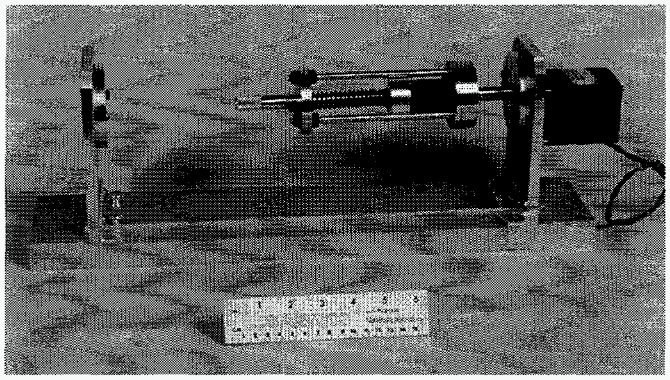

Figure 6: Silicon Carbide Joining Fixture

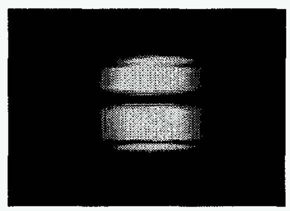

Figure 7: Video frame showing the heating pattern produced by a 37 GHz beam spot focused onto the silicon carbide samples shown in Figure 9a.

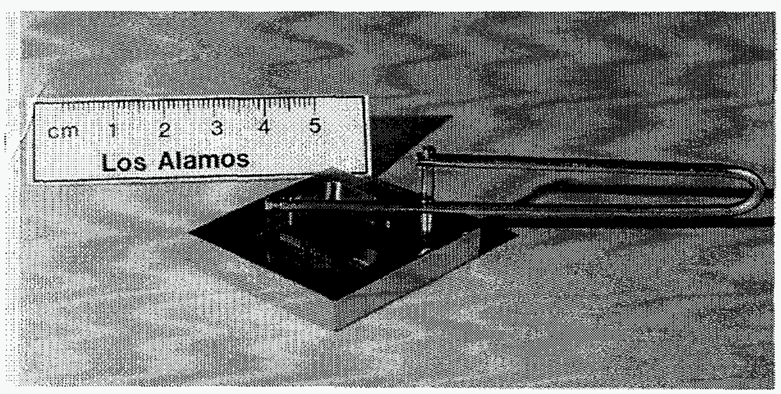

Figure 8: Material Joining Fixture