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Medium Wave Infrared Heater for High-Speed Fiber Placement

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ABSTRACT

Electroimpact, in cooperation with a large airframe manufacturer, has developed Automated Fiber Placement equipment capable of depositing material at speeds in excess of 2000 inches per minute. As the machine lays down each new ply of material, the area forward to machine motion is heated just in advance of pressing the tape against the substrate. A fast-reacting, high-power infrared emitter heats this area quickly and safely. The design of these heaters is the subject of this paper.

INTRODUCTION

With the introduction of the composite wings and fuselage on commercial aircraft, the aerospace industry has created a tipping point in the AFP (Automatic Fiber Placement) machine market. Machines capable of producing small to medium size parts fast enough to meet low-volume military programs are giving way to demands for higher and higher capacity. Equipment available to previous aircraft programs was capable of surface speeds of 100-400 inches per minute. AFP equipment being built today will add and cut tape at 2000 inches per minute or more while meeting all of the same accuracy and quality specifications.

Increasing the surface speed brought with it many challenges. In order for the tow to adhere to the substrate either the tow itself or the substrate must be heated. Heating the tow before it is laid down is undesirable since the softened, tacky resin leads to jams, poor feeds, and fouled cutters. These problems can hold up production in the machine cell for extended periods of time while equipment is cleaned. Instead, it's preferable to keep the tow in the AFP head cool and to heat the substrate material.

Most AFP machines use forced hot air to warm the thermo-set resin to ensure sufficient tack for tow adhesion. Dry air has a low specific heat so high air temperatures and flow rates are required. The heating element in these systems takes several seconds to reach the desired operating temperature so gating and mixing of the heated air is necessary. During this time the waste heat is disposed of, and this contributes to fouling the head. Since the heater must be maintained at high temperature even when the actual output required is low (because of slow thermal response), there is considerable waste heat. Limitations on the "on" and "off" times, as well as the total amount of heat energy that can be delivered to the part substantially limit the lay-down rate of the fiber placement equipment.

High surface speeds require a large amount of energy to be imparted into the material over a relatively short period of time in order to ensure tack. This can be especially problematic at course starts as this is when the heater is needed most and it is just being turned on. The operators will also be able to adjust the speed of the lay-down on the fly so the heating solution needs to be fast acting over the whole output range in order to impart enough heat at all speeds without heating too much so as to begin the curing process of the material already deposited.

Our investigation of heater options has lead us to design a quartz lamp IR heater. The main advantages of the quartz IR emitter we chose are short response time, durability in a manufacturing environment and longest wavelength with high power output. This paper describes the factors that contributed to that choice as well as some of the details of the heater design.

MAIN SECTION

PROBLEM STATEMENT

The task of the heater is to warm the resin in a single layer of pre-preg composite tape while passing over it at 'high speed'. For this paper, we will consider laying down a 200mm (8") width of material at a target speed of 0.85m/s (2000ipm). It is conceivable to pay out tape faster than this, particularly in idealized conditions, but since the heater described scales well, we will assume this starting point.

Material: Torayca 3900-series highly toughened carbon fiber-reinforced epoxy pre-preg in unidirectional narrow slit tape with approximately 60% (by volume) intermediate modulus T800S fiber.

Ambient temp: 22.2 C (72F) Most composite lay-up areas are tightly climate controlled for temperature and humidity, so we will assume that the substrate is at this uniform temperature.

Target temp: 35.0 C (95F) At this temperature, the resin is soft and tacky.

Required temperature rise: $\Delta T = 35.0 - 22.2 = 12.8$ C (23F)

Not-to-exceed maximum temp: 93.3 C (200F) This is a critical factor. If the resin is heated above this temperature, even for a short time, localized curing may weaken the composite part.

DESIGN CONSIDERATIONS

Energy Required to Heat the Material

The heater design began by developing power and irradiance requirements. We started with an idealized calculation: perfect absorption of the entire IR spectrum; uniform power distribution; and no conductive heat loss to the surrounding material or convective loss to the environment.

$$Q = m\,c\,\Delta T$$

With the above assumptions, and an estimated specific heat (c) of 0.93 J/gC, the energy required (Q) to raise the temperature of 1 cm^2 of material by 12.8 C is approximated to be 0.36 J.

Emissivity of the Material

When radiant energy hits an object, some energy is absorbed, some is reflected away, and some is transmitted through. The ratio of absorbed energy to total energy is known as emissivity. Since only absorbed energy produces heat in the object, emissivity can be viewed as the 'efficiency' of radiant energy transfer to an object.

Emissivity varies with surface condition, temperature and wavelength. However, because we are dealing with new material with a consistent surface condition in a very narrow range of temperature, only the IR wavelength has a driving effect. To get a proper view of the composite material, we separately consider the epoxy resin and carbon fibers.

The epoxy resin is nearly translucent to visible light and 'near IR' wavelengths below 1um. From there, the absorption increases with wavelength until approximately 8um. It is not practical to produce significant power at wavelengths longer than approximately 4.5um from a quartz emitter. However, it is preferable to choose an emitter with the longest available wavelength to maximize absorption directly into the resin.

The matt black carbon fiber, in contrast, has a high emissivity and almost zero transmissivity over the whole IR spectrum. Because of the high fiber content in the Torayca™ composite material, this means that a large portion of the IR energy will be absorbed in the top layer of the substrate, rather than penetrating deeper in. It also means that some of the heat transfer to the resin will be in the form of conduction from the fiber.

Material testing shows a total 'average' emissivity of the composite of roughly 0.8, with a small dependence on wavelength. This means that 80% of the incident energy on the surface will be absorbed and become heat, while only 20% will be reflected. Due to the opacity of the fibers, almost no IR energy penetrates beyond the first layer of the substrate.

Packaging and Power Density Calculations

To go from energy to power calculations, we must consider heating time. At steady-state, heating time is heated length divided by surface speed, where heated length is the distance, in the material lay-down direction, directly illuminated by the IR emitter. See Figure 1 below. A brief look at packaging considerations is needed to pick a reasonable heated length.

There are several competing constraints on the envelope for the design of the heating unit. Clearance must be maintained in a 15º-draft angle so that the machine can maintain surface normality to the part even in concave geometry or while navigating ramps in parts. The heater can also not be thicker than 2.5" at the base due to process equipment that cannot be moved. Although this gives us a maximum envelope it is best to minimize the heated length. This minimizes the pre-feed lead-in travel required for the substrate can reach the target temperature when material is added.

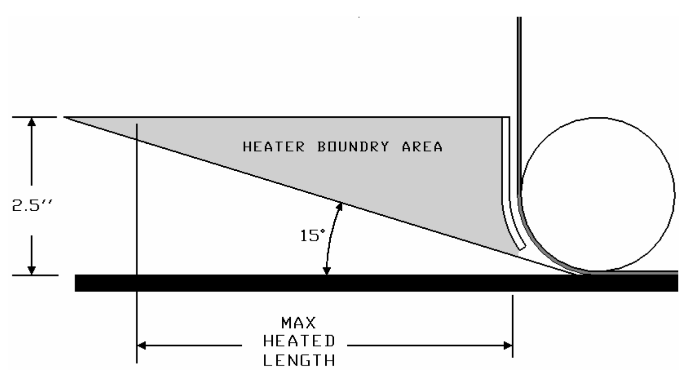

Figure 1. Heater Geometry Constraints

If we consider a heated length of 100mm and a surface speed of 0.85m/s the exposure time is 0.12s. Then by multiplying the estimated energy to heat one square cm of material times the total heated area and dividing by the material emissivity and heating time,

$$\frac{0.36J/cm^2 \bullet 20cm \bullet 10cm}{0.8 \bullet 0.12s} = 756W$$

we calculate that the required power in the target area of the substrate surface is 756W and the mean surface irradiance is 3.8 W/cm2.

Uniformity of the Power Distribution

Of course real IR lamps do not give a completely uniform power distribution. Energy travels outward from the emitter in all directions and must be reflected or guided to the target surface. Figure 2 below shows a ray-traced model of a single IR tube lamp 75mm from a flat target plane.

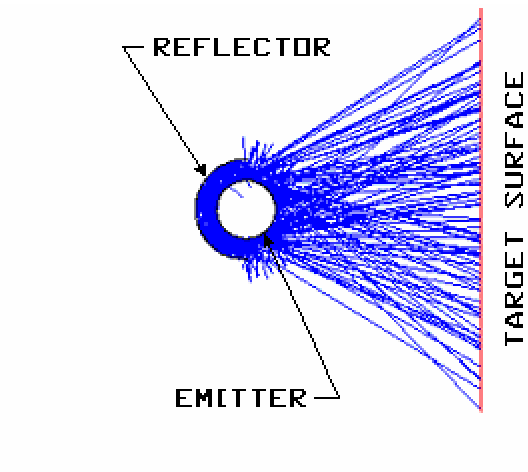

Figure 2. Ray-traced Model of IR lamp and reflector

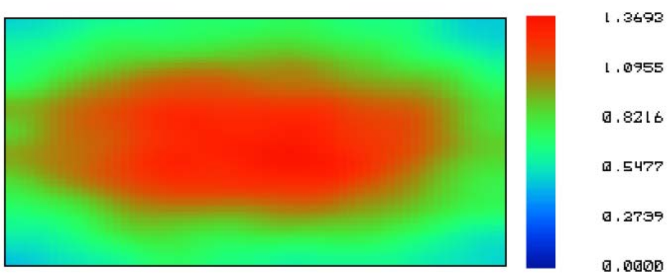

Figure 3. Irradiance on Target Plate

Figure 3 shows the resulting irradiance of the plate. The lamp modeled has a heated length of 200mm and the plate area shown in Figure 3 is 200mm x 75mm. This is a poor design as the power density drops off by 50% at the ends and corners of the image. Through ray-traced models and empirical testing, it is possible to create a multi-lamp array with appropriate reflectors which fits the packaging constraints and has a 90% uniform power distribution. This is critical since our goal is maximum heating without hot spots which might exceed the 93C upper temperature limit.

Reflected Energy and Waste Heat

Ray tracing clearly illustrates that the emitted light will not be perfectly constrained to the target area. To give uniform heating, the heated length of the emitter must be greater than the width of the tape path and there is spill-over and reflection from the surface. Not only does this mean that the selected heater will need to have more capacity to allow for 'fringe effects'. Some of this energy is reflected back and, if not accounted for, will produce undesirable heating of the tape laying equipment. Figure 4 below illustrates this.

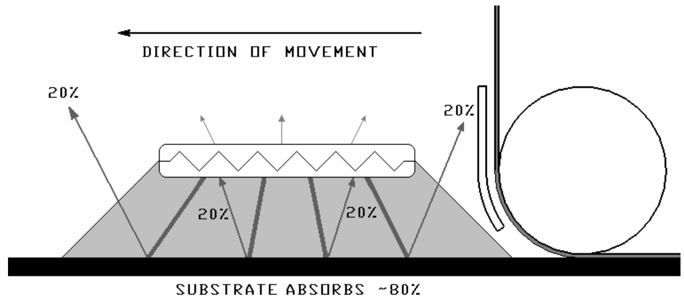

Figure 4. Undesirable Reflected IR and Waste Heat

It is important that the IR emitter incorporate a high-efficiency primary reflector, as implied in the ray-traced model shown. Most commercially-available quartz lamps offer a gold-film reflector which will do an excellent job of directing most of the emitted energy in a useful direction. However, a secondary heat shield will very likely be needed to prevent reflected IR and convected heat from reaching the tape laying equipment.

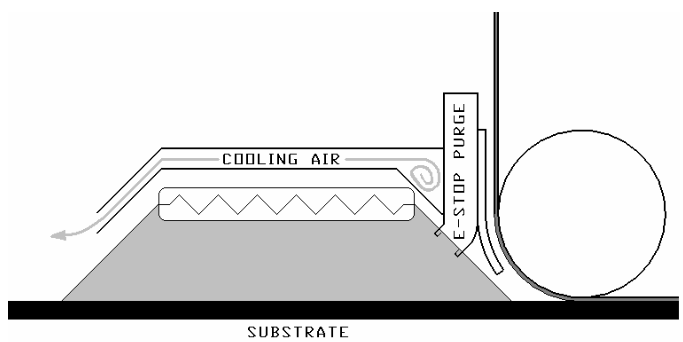

Figure 5. Secondary Heat Shield

Figure 5 above shows an efficient design for a dual-layer heat shield. A low-flow air purge is directed between the layers of the shield to direct waste heat away from the equipment. The inner and outer surfaces of the shield are only connected via insulating material around the edges to minimize conductive heat transfer and keep the outer surface cool. The IR emitter itself is held using ceramic and high-temperature plastic mounting for additional insulation.

Various materials and coatings were investigated for the inner surface of the shield. By far the most IR-reflective surface coating tested was LaserGold™ coating by Epner Technologies. This proprietary coating is nearly 99% reflective in the wavelengths produced by a quartz IR lamp. An inexpensive alternative is polished aluminum. However, with an aluminum surface, care must be taken to avoid oxidation of the surface, which is common and accelerated with heat. Plating stainless steel with commercially pure aluminum and polishing the surface yields better than 85% IR reflectivity.

Preventing Over-Heating During an Unexpected Stop

One major concern for any heating system in this application is overheating during an emergency stop. If the heater is producing maximum output because the machine is moving at top speed over the part and an unexpected event causes the machine to stop suddenly, the heating system must not overheat the substrate. Quartz lamps shut down quickly, but they do continue to emit IR for a time after the electrical power is removed. If input power is cut at time T=0, the relative output of a typical 'fast responding' IR lamp is shown in Figure 6.

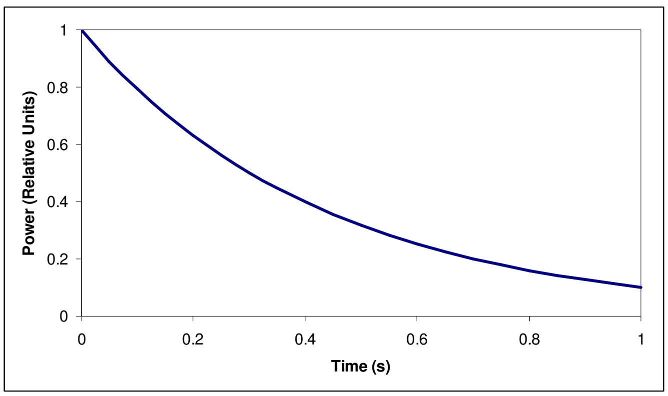

Figure 6. Relative Power Output vs. Time

After 1s, the output power is down to 10% of peak. However, if the peak output is able to heat the part by 12.8C in 0.12s, and one assumes only natural convective cooling to the atmosphere, the maximum material temperature will be exceeded in approximately 0.5s unless other measures are taken.

One way to mitigate this risk of overheating would be to close a mechanical shutter to reflect the IR away from the substrate for a short time during a sudden stop. However, a simpler design is to provide an air blast to rapidly cool both the IR emitter and the substrate. To make the system fail-safe in the event of a total power failure, a normally-open spring-return valve can be used in conjunction with a small pressure reservoir. The stored energy is small enough not to pose a safety risk to personnel servicing the equipment.

TESTING AND QUALIFICATION

In order to validate the computer models on which we based our design, we used an optical thermopile (power meter) mounted on an X-Y sled to map out the irradiance profile. See Figure 7 below. Using this setup it is possible to test different emitter types to compare power output as well as reflector geometry and coatings.

Since start-up and shut-down time are so important in this application, we were also very interested in measuring the transient response of the emitter. Power output was measured with an amplified InGaAs detector. The input current to the emitter was measured with a current transformer. By tracking both signals with an oscilloscope, we were able to characterize the response time of the emitter for both power-on and power-off.

In order to check for uniformity in the heating area after the machine has passed over an area a thermal imager can be used. This can also be used to identify hot spots on the heater as well as any problem areas that may be transferring energy from the heater to the head. Though the temperature cannot be directly measured with this device it can be used to refine the design of the heater.

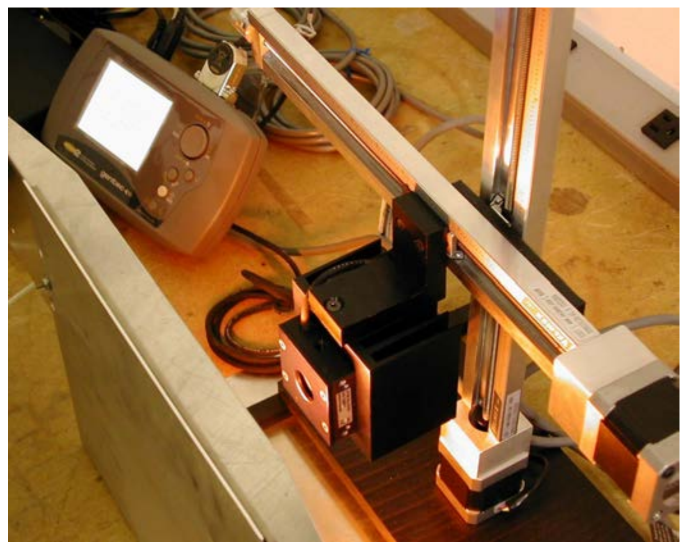

Figure 7 Power Meter on X/Y Stage Measuring Irradiance

Qualification for manufacturing is driven by the requirements of the material and the properties of the tape lay-down equipment itself. As surface speeds continue to increase, the qualification process is being re-written. One simple example of this is the traditional maximum temperature test.

Since this material cannot exceed 93.3 C (200F) without danger of premature curing, the manufacturer specifies that during qualification testing the measured temperature cannot exceed 82.2 C (180F). For this test, the heater is passed at various speeds over thermocouples adhered to the surface of a carbon fiber test piece. This test works well for low surface speeds, but at extremely short heater exposure times, there is a strong concern that peak temperatures will be missed because of the slow response of the test equipment.

Although the transient response of available thermocouple amplifiers is limited, it can be characterized through standard liquid-quench tests. Once the time response of the test equipment is known, heater trials at various speeds allow one to estimate peak temperatures even at extremely high power and short durations. This is just one example which illustrates the new considerations faced in qualification testing.

In addition to the qualification issues for all systems posed by increased power and short exposure times, infrared heat presents its own challenges. A prime example of this is the tendency of reflected radiation from the surface to invalidate non-contact surface temperature measurements. Non-contact thermometers are actually very sensitive infrared detectors which measure the small amount of IR radiating from the substrate surface. Without careful design, even small amounts of reflected energy will saturate these devices. After a few iterations, we were able to incorporate non-contact sensing of the surface temperature into the equipment, but the additional shielding requirement should be noted.

CONCLUSION

Increases in carbon fiber laydown rates achieved through higher machine speeds in excess of 2000ipm have created a need for new heating options to adhere the tow to the substrate. Electroimpact has developed an easily scaleable system using IR emitters to heat the substrate immediately before the application of tow. This allows for highly controlled localized heating of the area in a small package.

CONTACT

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EPNER CONTACT INFORMATION:

For additional information on EPNER Technology's Laser Gold™ IR Reflective Coating visit: http://www.epner.com/

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFP: Automatic Fiber Placement

CFRP: Carbon-fiber reinforced plastic

Tow: Flat, thin bundle of carbon fibers and uncured resin. Commonly ~0.0075 inches thick and 1/8 inch wide. For widths greater than 1/8 inch, the manufacturing process changes and the material is referred to as "slit tape". For this paper, however, the term "tow" will envelope a multitude of sizes.

IR: Infrared is radiation emitted between 750nm to 1mm in wavelength

Laydown Rate: Amount of material applied to mold per unit time (typically pounds per hour).

IPM: Inches per minute

Nip point: Tangent point between part and compaction roller