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HIGH POWER DIODE LASER-ASSISTED FIBER PLACEMENT OF COMPOSITE STRUCTURE

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Abstract

The hot-gas heating systems used on today's production fiber-placement machines provide limited heating efficiency and poor process control response that prevents placement machines from achieving the full production rates. We have has demonstrated high power diode laser-based heating system, that provides photons for the most efficient heating method radiative. This yields higher processing rates, high control bandwidth, and lower maintenance cost than existing heating technologies. The standard high power direct diode laser integrated with an infrared pyrometer for nit-point temperature control, was demonstrated placing epoxy prepreg materials on production fiber placement machines. The precise and rapid control of the laser energy through a feedback loop maintained a constant material temperature at the nit-point during high machine speeds, rapid process changes, thereby improving tack quality, ply adhesion and process control.

Introduction

Historically, advanced composites have been manufactured by hand lay-up of prepreg to produce composite parts that are then consolidated and cured in an autoclave. This manual process results in high fiber volume fraction, void-free, well-consolidated composite structures with excellent mechanical properties. However, the costs of these structures are high due to the labor and material costs. There is also limitation to part size and shapes for hand lay-up processing [1,2]

Automated fiber placement is currently the accepted technology in aerospace composite manufacturing industry because the process has achieve a significant reduction in labor and material costs in addition to offering increase design flexibility. There are currently over 100 automated fiber placement machines installed worldwide. See Figure 1. Through production implementation, baseline material, process specification, and part design rules were established for several material types, typically epoxies using various fiber placement systems. A wealth of data has been generated through different military and commercial applications, and a fundamental understanding of fiber placement has been established.

2002 Automated Fiber Placement and Tape Laying Machine Market			
Aerostructures Corporation	2	Gencorp	6
Agusta Helicopter	1	GKN	1
Aldila, Inc.	1	Harsco Corporation	2
Alenia	4	Hoechst AG	2
Amalga Composites, Inc.	1	Kawasaki Heavy Industries	1
American Poly-Therm Company, Inc.	2	Lockheed	1
ARC Propulsion	1	Mitsubishi Heavy Industries	1
ATK	7	**Northrop-Grumman**	**12**
Automated Dynamics	4	Raytheon	5
Bailey Corporation	2	SGL Carbon Composites Inc.	4
Bell	1	Textron Inc.	5
Boeing	5	Vision Composites Inc.	1
CASA	2	Vought	1
Fuji Heavy Industries	1	Switzerland - companies, universities	1
Corporate Research and Engineering	1	Australia - companies, universities	1
Dassault	1	Taiwan - companies, universities	1
EADS	**8**	Korea - companies, universities	1
Eurocopter	1	USA - companies, universities	1

Figure 1 – Partial list of the installed fiber placement machines

The cost benefits of automated fiber placement has led to it implementation on the F/A-18, T-45, V-22, C-17 and many other military aircraft and now is the main manufacturing process used on commercial aircraft such as the Boeing 7E7 aircraft.

Automated Fiber placement

The fiber placement process, consists of towpreg kreel and take-up reels, which guide the prepreg down to the placement head, at the placement head a towpreg guide with cut-clamp capability is integrated along with a, compaction wheel, heat source, preheating [optional], temperature monitoring, and inspection equipment. See Figure 2. The primary limitation of geometries that can be fiber placed is determined by the profile of the placement head equipment. The fiber placement uses multiple narrow towpregs, such that the fiber buckling associated with tape placement, is minimized during fiber steering on a complex shape is eliminated [1]. It also allows for cut and adds of tows for material savings.

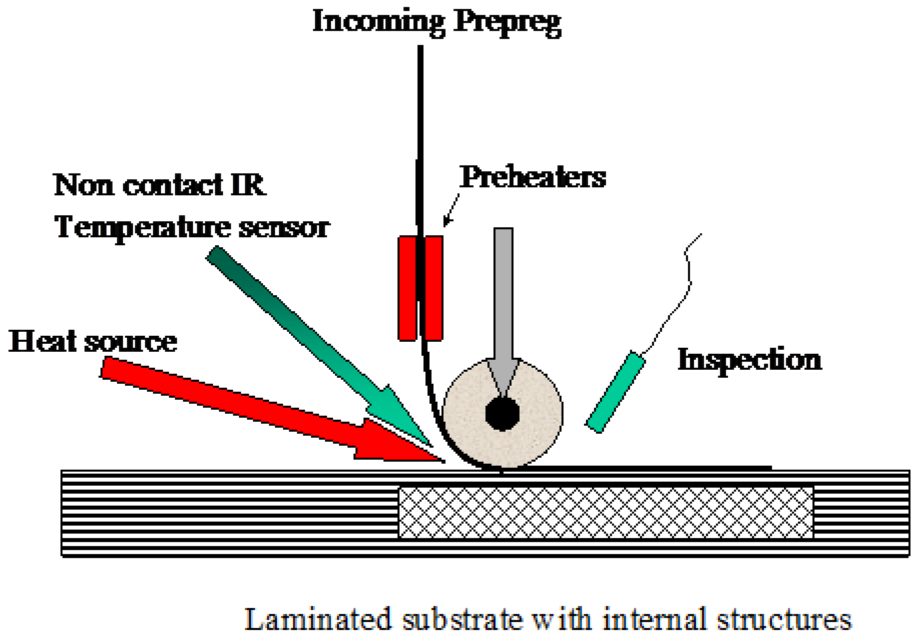


Figure 2 – Block diagram of nit-point area for fiber placement

Epoxy Fiber Placement Process

Epoxy Fiber placement typically involves the application of epoxy prepreg that is spooled out of an environmentally controlled [refrigerated] kreel housing. The prepreg tows are transported to the placement head where a nit-point heater warms the materials [50 C (120F) – 65C (150 F)] to create tack. Where upon the compaction wheel compacts it to substrate. The heat transfer from a hot gas heat source moving over a substrate is a major factor in the final part quality and is difficult to control [3]. This is due to the heating mechanism, which is due convective heat transfer, which means a long dynamic response time. Therefore, hot gas based fiber placement does not have the ability to apply and control the heat into the nit-point during machine accelerations and changes in the part substrate and geometry. This ultimately leads to poor placement quality.

An often-overlooked issue is ancillary heating of machine components. The hot gas jet plume envelops the machine, which requires additional measures to cool the fiber placement head to reduce the issue associated with prepreg material sticking to the guides, and reels inside the fiber placement head. Machine maintenance and up time is swiftly becoming a major issue for the automated fiber placement industry.

Despite the tremendous success of hot-gas based fiber placement systems, current manufacturing rates are well below machine capabilities that exist today. Improving the nit point heating through advanced, precise and controllable heating systems would enable maximum machine speed to be reached rapidly and in a controllable manner.

Thermoplastic – Ultimate Cost Savings

For the thermoplastic composites, the ability to perform in-situ consolidation may have the potential to further increase production quality and lower production costs. Like epoxy based systems, thermoplastic composites manufacturing processes involves the process where the resin impregnated tow prepregs are continuously oriented, heated and laid down, but unlike epoxy the thermoplastic composite is consolidated, and cured onto the tool surface in a single step. Once the tool has been covered and the thickness has been achieved, the part is finished. Secondary processing steps required by epoxy impregnated composite parts, such as autoclave or hot-press consolidations are eliminated. This process is inherently suitable for manufacturing parts with large surfaces and moderate curvatures, such as fuselage structures and deep submersibles [4,5].

Because the towpreg is fully consolidated and locked in the vicinity of the nit-point of the melting point as it is placed onto the structure, conceptually there is no limitation on producing parts with thick cross-sections and large surface areas. Furthermore, complex, non-geodesic, and even concave winding paths are also achievable, thus allowing design flexibility. Thick-section thermoplastic composites experience a build-up of residual stresses caused by the large volumetric changes during melting and solidification in post consolidation. The effects of residual stresses on the mechanical properties of composite structures have received considerable attention. It has been demonstrated that the high level of residual stresses may lead to dimensional instability and premature failure. However, due to localized heating and solidification, the on-line fiber placement process has the potential to prevent the build-up of residual stresses and, in turn, to produce better quality composite structures. [4]

Localized Melting

For thermoplastic impregnated towpreg to be fully consolidated melting has to occur. This limits the region of the melt only to the nit point where the incoming prepreg and consolidated substrate meet. A representative thermal plastic resin material such a PEEK (Polyetheretherketone) typically has a glass transition temperature of 289°F (143°C) and a melting temperature of 649°F (343°C). This high temperature presents a major obstacle to high-speed fiber placement. Presently, the required lay up rates to make thermoplastic cost effective is so high that a single hot gas based nit point heaters are unable to quickly achieve the melting temperature. Typically pre-heating system are used to elevate the temperature of incoming prepreg. Since the prepreg must be heated to well above melting temperature in seconds, highly focused heaters must be used to guarantee melting of the mating surfaces. However, excessive heating or improper heating may lead to resin degradation by polymer chain scission and oxidation, and consequently may affect the crystallization, adhesion of the fiber/matrix interface, and matrix properties [6]. Therefore, appropriate selection and arrangement of the heating sources are the most important factors for a successful on-line consolidation system.

Many heat sources, including hot-gas, focused infrared; laser, ultrasonic, microwave, induction, and conductive energy can be used for diffusion bonding of thermoplastic composites. Among these, the highly focused heat sources, such as hot-gas and laser energy, have been demonstrated for nit point heating and the infrared heaters are mostly found in the pre-heating stage [4].

Heating Alternatives for Fiber Placement

In order to allow high-speed production at high temperature, a efficient heating source has to be incorporated. Furthermore, the response time of the heaters needs to be as quick as possible with a stable performance. Weight, size, flexibility, and price are also important considerations for heating tool selection. Heating tools for flexible composite manufacturing are compared qualitatively in Table 1.

	Hot Gas Torch	Infrared Lamps	Laser Traditional [CO2 and Nd:YAG	Diode Laser [Direct and Fiber coupled
Heating Efficiency	--	=	+	++
Response Time	--	=	+	++
Size	++	=	--	++
Weight	++	+	--	+
Price	=	+	--	-

Note: ++ Very Good , + Good , = Nuetral, - Bad, - - Very Bad

Table 1 – Comparison of nit-point heat sources

Laser Heating

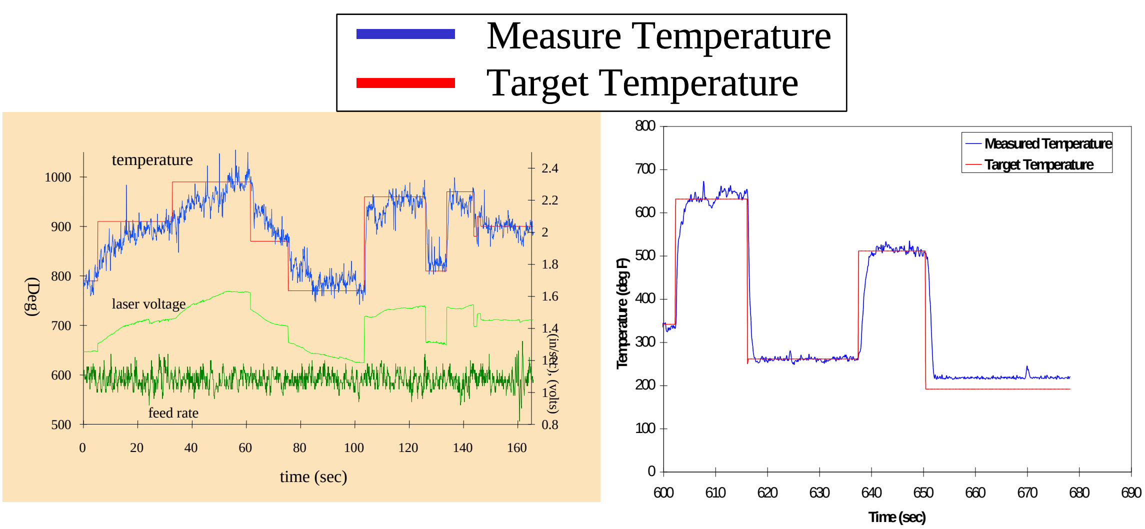
Laser beam radiative heating is an excellent heating technique for energy-efficiency and fast response time. Laser beam radiation, which can be focused into only the nit point, will instantaneously heat the incoming prepreg and the substrate material. Since the coupling into the material is close to 100% with carbon composite materials the heat efficiency is at its highest without an ancillary heating of machine components.

Utilizing a laser, as the heat source was first introduced by Beyeler and Güçeri [7]. An 80 watt CO2 laser was used to partially melt the incoming tape and substrate. Mazumdar and Hoa implemented a laser-assisted processing technique using A 65 watt CO_2 laser [8]. For mass production purposes, McDonnell Douglas Aerospace (MDA) had developed a laser-assisted fiber placement machine that originally utilized a CO_2 laser, which was changed to a Nd:YAG laser then eventually to a diode laser. This machine was capable of producing thermoplastic parts up to 52 inches in diameter and up to ten feet in length. See Figure 3. The fiber placement facility included a winding machine and a gantry, which housed optics to control the size of the heating zone, a compliant compaction shoe for pressure application, and a band-cut-and-add head for handling the towpregs. [9]

Figure 3 – McDonnell Douglas Aircraft CO_2 laser assisted fiber placement machine circa-1995.

Controllability of Laser Sources

A Comparison of the degree of temperature control between a CO_2 laser heater and diode laser heater where made and MDA. A complex neural controller was employed to control the CO_2 laser a much simpler control mechanism was implement with the solid sate diode laser. Show in Figure 5 is a comparison of the control achieved with the CO2 and diode laser. The difference in the controllability of the laser heat sources is inherent in their design. The CO_2 laser has coherence across it beam and is a gas cavity with RF excitation and diode is in coherent combination of many solid-state diode lasers. The coherence leads to constructive and destructive interference on the part, which lead to hot, and cold spots. The diode laser produces a very uniform incoherent beam that yields a uniform temperature profile. Since the diode is solid state it is effectively a digital heat source. Therefore, when using a diode laser the limitation in controlling the temperature has moved from the laser heat source to the temperature measuring devices.



CO_2 Diode

Figure 4 – Temperature Comparison of CO_2 and Diode laser heater

Optical Properties of Prepreg

The optical properties of materials now becomes the main parameter that determines heating efficiency when using laser heat sources. The emissivity [absorption] of the composite prepreg materials is shown in Figure 5. What was shown through the MDA development was that the emissivity of the resin is highly dependent on wavelength of light. At the CO2 [10600 nm] wavelength the resin is highly absorptive and at the Nd:YAG [1064 nm] and Diode [808 nm] the resin is transparent. Therefore, when using the CO_2 laser as a heat source there is a greater risk of burning and oxidizing the resin surface of the prepreg therefore affecting the adhesion of the fiber/matrix interface. At the Nd:YAG and diode wavelengths the heating is primarily due to the absorption of the laser light by the carbon fibers. Since the carbon fibers are very thermally conductive along their length, this achieves a more uniform and controllable heating of the prepreg.

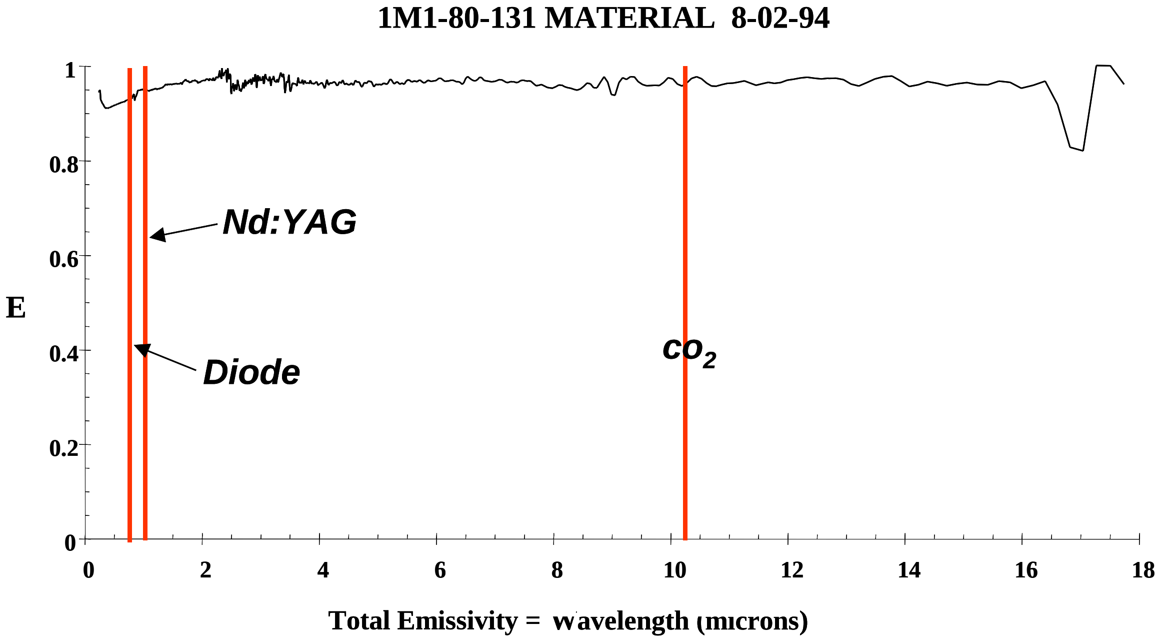


Figure 5 – Emissivity of IMI-80-131 Carbon/Epoxy Prepreg material

High Power Diode Laser Heater

Advanced high power diode lasers employed as a automated fiber placement nit-point heater can meets all the requirements for a advance heat source for both epoxy and thermoplastic high-speed fiber placement. These small, highly efficient, highly controllable, low-maintenance, highly reliable, both direct and fiber coupled diode lasers, are currently used in various other industrial fabrication processes. This compact solid-state laser can provide multi- kilowatts of near infrared (IR) radiation that can be modulated at rates up to 20 kHz. As compared to tradition technology, such a hot gas, the diode laser rapidly heats only the nit point and can have response times of microseconds. Since, the heating mechanism is by radiation and not by convection the temperature response is proportional to the diode response time. Therefore, a digitally controlled diode laser provides two orders of magnitude faster temperature control at very high lay-up rates when compared to conventional hot-gas torch systems

Another benefit that the diode lasers has emission wavelengths of 805, 940, and 980 nm. This light transmits through the resin and is primarily absorbed by the carbon fibers. The carbon fibers are very conductive along their length, which transfers the heat into the nit very efficiently. Unlike CO_2 laser, the diode laser only heat the carbon fibers thereby eliminating the problem of charring or destroying the resin materials.

The diode laser is the most compact laser source available, close to $10W/cm^3$, but also can be fiber coupled. This allows for implementation of diode laser heaters on any fiber placement machine. The small size is such that multiple diode heaters either direct or fiber coupled, can be placed on the fiber placement head thus giving the uses even more flexibility if controlling the temperature across the knit point of any spatial extent.[10] This spatial control allows for prepreg tow adds and drop capability and enhanced fiber steering.

In addition to allowing faster machine speeds, the narrowly directed laser radiation heats only the composite material. Hot-gas torches heat the material and the placement head, producing temperature rises that cause the material to jam in the head, resulting in lost maintenance time

The laser control software, would utilizes a feed forward-feedback control algorithm, which assures that laser maintains the required material temperature even during rapid changes in the material feed rate. The feed forward component provides laser power based only on the instantaneous placement rate, while the feedback component modulates the power to correct for deviations from the desired temperature, as determined by an optical pyrometer monitoring the compaction-region.

HPDL Demonstration

A commercially available 4 kW direct diode laser from Nuvonyx, Inc. was mounted on a production Boeing fiber placement machine. See Figure 6. The diode heater was been demonstrated on AS4/3501-6 and IM7/977-3 carbon/epoxy and IM7/5250-4 carbon/bismaleimide materials. One-meter long flat panels in a variety of cross-ply configurations were placed with a production prototyping automated fiber placement machine at the maximum machine acceleration rates up to 1200 inches per minute head speed.

In Figure 7 an IR image of the heat generated by the diode laser across the nit point area. The profile is very small and there is total illumination of the nit-point. Due to the high absorption efficiency of the carbon composite there is virtually no ancillary heating. These directly translate into less machine maintenance and more machine up time.

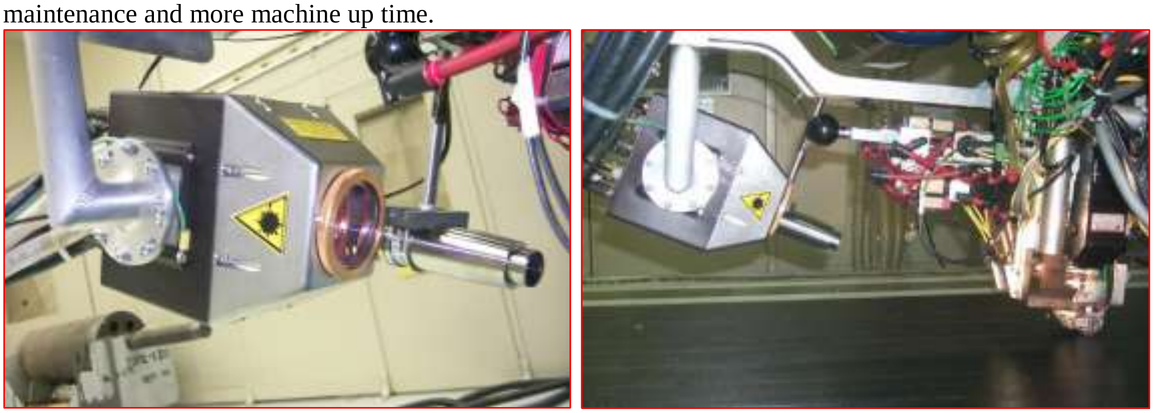


Figure 6 – Commercially available 4 kW Direct diode laser and IR pyrometer mounted on a fiber placement head.

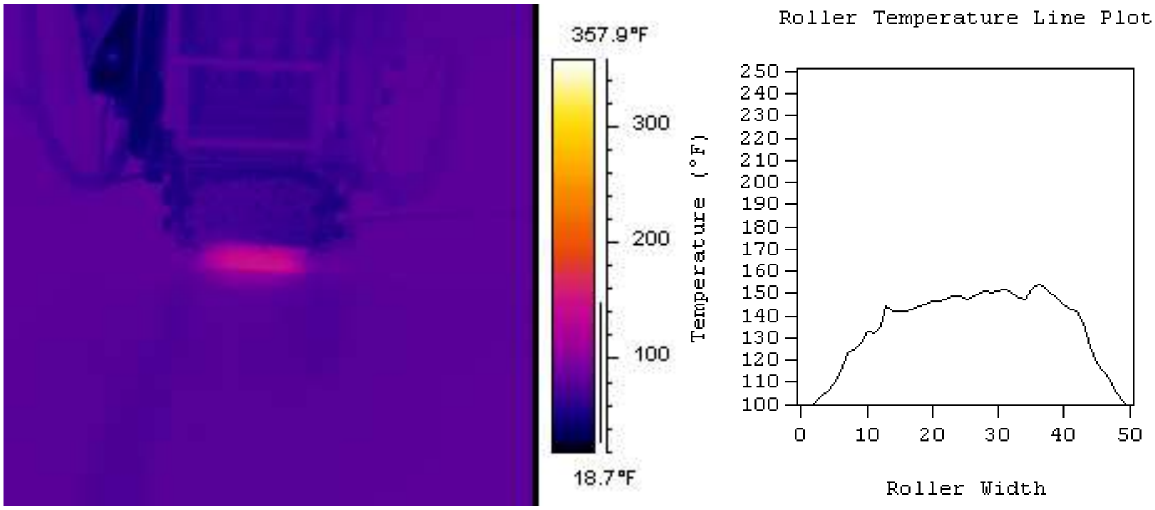


Figure 7. IR image of the resulting heat from a diode laser illumination of nit-point between substrate and incoming tow prepreg.

As an aircraft production demonstration, the laser technology was used to place a C-17 pod fairing, See Figure 8, at GKN's St. Louis facility. Figure 9 shows the 4 kW Nuvonyx laser and pyrometer mounted to GKN's Ingersoll fiber placement head. The figure also shows a false color image of the compaction region as a ply was being placed, with the relative intensity of the IR radiation on a red-to-yellow scale. Although this coloration makes the material look very hot, the desired 120ºF processing temperature was maintained during the entire lay-up cycle. [11]

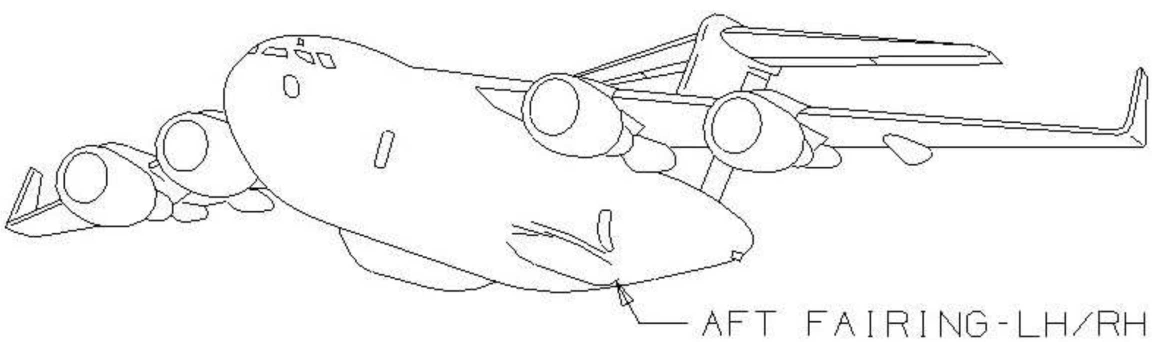


Figure 8 GKN Diode laser demonstration article - C-17 Skin, Fairing, Aft

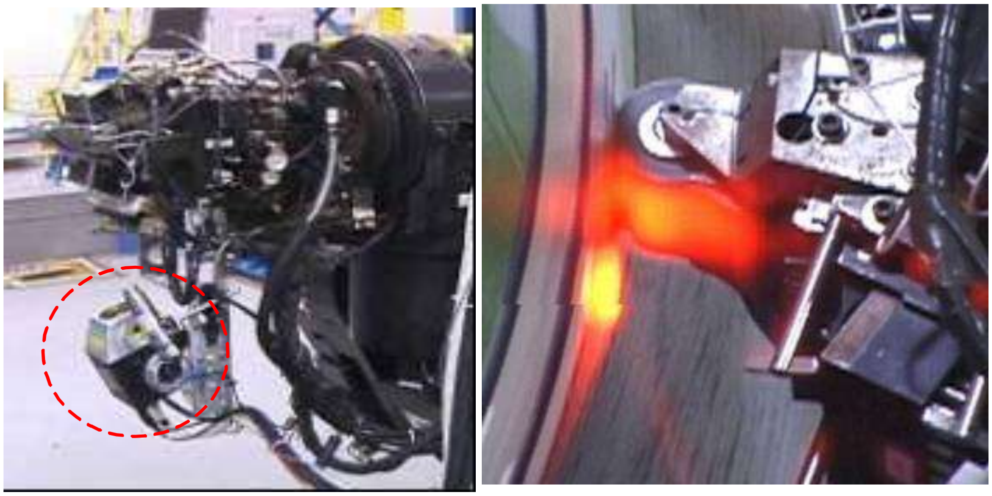


Figure 9: GKN's Ingersoll placement head and detail of compaction region during placement. The laser (black box) and pyrometer (cylinder) are circled in the first photo, and the resulting thermal image is shown in the second. [11]

The diode laser based fiber-placement heater achieved 100% of the maximum programmed machine speed at only 200 watts of optical power. This is compared to 50% usually achieved with the conventional gas torch. This high fabrication rate was achieved without affecting the quality of the part. A fabrication-time analysis including both production and increased up-times indicated that a 50% reduction in fabrication time could be realized with the diode laser system.

The commercial 4 kW direct diode laser shown is significantly larger physically than a laser that would provide the 200 W required for the pod fairing demonstration. While adequate for demonstrating the technology, the laser arrangement shown in Fig 9 is awkward for placing highly contoured structure. Currently there are multi-kilowatt fiber coupled diode lasers available. The diode laser energy can be transmitted from a remote diode laser source through hundreds of meters of flexible optical fiber up to the fiber placement head. The optical end effectors can be smaller than the profile of a hot gas torch and initial design indicates that this optic can be integrated into the tow guide.

To meet laser safety requirements, the high-power lasers required for fiber placement demonstration was used in an enclosed, limited-access area. In application, the laser radiation has not posed a problem for the machine operators. The laser power reflected from the compaction region during the GKN demonstration was measured to be lower than the power for which eye protection would have been required.

Conclusions

Commercially available high power diodes lasers have been demonstrated to meet the requirements for the next generation automated fiber placement nit-point heaters. The high power diode lasers both direct and fiber coupled meets all requirements for power, controllability, size, weight, and optical wavelength. We have demonstrated that the high power direct diode laser can be easily implemented on current fiber placement machines. The current bottleneck for high-speed fiber placement is the hot gas torch heaters. With the implementation of the high power diode lasers this bottleneck is moved from the heat source to the fiber placement machine and material handing equipment.

Acknowledgements

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