AUTOMATED FABRICATION OF HIGH PERFORMANCE COMPOSITES: AN OVERVIEW OF RESEARCH AT THE LANGLEY RESEARCH CENTER

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ABSTRACT

Automated heated placement of consolidated fiber reinforced polymer ribbon/tape is a rapid, cost effective technique for net shape fabrication of high performance composites. Several research efforts in the United States are developing the heated head robotic hardware and associated software needed to bring this technology into widespread use for building aircraft parts. These efforts emphasize the use of pre-consolidated thermoplastic ribbon or tape which is thermally welded on-the-fly. The approach provides in-situ consolidation and obviates the need for autoclave processing and massive debulking, thereby reducing costs.

Addressed in this paper are some key issues being pursued at NASA Langley related to this technology. These include (a) preparation of high quality intermediate materials forms such as thermoplastic powders, powder-coated towpreg and consolidated ribbon/tape and (b) achievement of precise control of the following: robot head positioning on the tool; material placement; heat delivery to the lay-down zone; and cut/add, start/stop capabilty. Heated head development has dealt with the use of hot gases alone and in combination with focused infrared radiation as heat sources.

1.0 INTRODUCTION

To be economically viable in competition with metals for high performance applications, fiber reinforced polymer composite fabrication must utilize high quality material forms and fully exploit automated processing technology. Automated processes employed in the composites industry include pultrusion, filament winding, automated tow/tape placement (ATP) and the textile processes of weaving and braiding in combination with resin transfer molding or resin infusion molding.

The automated placement of composite tow/tape is one of the most promising fabrication methods for rapid, cost effective, net shape composite part manufacture.[1] To apply this technique in various aerospace research programs, NASA Langley Research Center is emphasizing an approach where preconsolidated high temperature, thermoplastic, graphite fiber reinforced ribbon or tape is thermally welded on-the-fly. This approach provides for in-situ consolidation of the part and eliminates the need for laborous debulking and autoclave post-placement processing. As ATP research and development efforts proceed, important issues that require resolution have been identified. Examples include open section residual stresses, autohesion requirements, prepreg material quality and post annealing of semi-crystalline polymers.

2.0 PRECONSOLIDATED COMPOSITE RIBBON AND TAPE

Most basic of these issues is the requirement for high quality, fully consolidated, thermoplastic ribbon and tape having close dimensional tolerances. The old axiom, "garbage in, garbage out," cannot be overemphasized in ATP practice. An important part of the NASA program has dealt with developing ways to fabricate the required product forms. The necessary and important restrictions on the processes were as follows. (a) Utilize no solvents, therefore no solvents would have to be removed in subsequent fabrication steps. (b) Avoid melt impregnation; it is almost an impossible task with the high melt viscosities of high performance polymers such as polyimides and polyarylene ethers. The scheme finally developed at Langley utilized impregnation of finely ground polymer powder onto a spread unsized carbon fiber tow bundle followed by thermoplastic forming of the towpreg into consolidated ribbon and tape.

2.1 Powder Impregnation. Processes for making towpreg have been developed from both slurry and dry powder techniques.[2] An optimized process, called "powder curtain" was found at Langley to be the most efficient way of distributing solid polymer particles throughout continuous filament tows (see Figure 1). The resulting towpreg yarn was flexible, bulky and abrasive. Composites made with this material by frame-winding followed by press molding gave mechanical properties quite favorable to those made from solution prepregging (Table 1).[3]

2.2 Consolidated Ribbon/Tape. Robotic placement heated heads are generally designed to utilize stiff, preconsolidated ribbons or tapes having consistent cross-section. A number of debulking techniques were studied to convert powder-coated towpreg yarns into fully preconsolidated ribbon and tape.[4] Issues included towpreg material quality, transverse squeeze-flow, appropriate timing for heating and pressure application and tool contact/release. Several processing methods were designed, built and experimentally evaluated. Four powder-coated towpreg yarns, Aurum™-500/IM-8, PIXA-M™/IM-7, LARC™-IA/IM-7 and APC-2™ (PEEK/AS-4) were used in this evaluation. Reactive plasticizers and solvents were excluded. The work concentrated on the fabrication of 0.63 cm wide ribbon from two 12K IM-7 powder coated tows and 7.6 cm wide tape from twenty-five powder-coated tows.[4,5]

By utilizing desirable attributes of several of the designs, a novel processing technique was developed. The equipment was comprised of two primary components (Figure 2).

The ceramic hot bar fixture facilitated transverse melt squeeze flow while the cool nip-roller assembly solidified the ribbon/tape into preconsolidated ribbon/tape with consistent cross-section. The heat transfer and pulling force were modeled from fundamental principles to develop a basic understanding of the process for application to a variety of polymer materials.

3.0 AUTOMATED FIBER PLACEMENT

3.1 ATP Process. During automated placement, preconsolidated composite ribbon and tape are fed from spools through a delivery system located on the placement head. A band of collimated ribbons or the tape is placed with heat and pressure to laminate it onto the work surface.

Fiber placement differs from filament winding in that it requires the tow placement tool tip to contact the surface of the part rather than floating off the part. This allows for placement in non-natural paths which may be required for complex parts.[1] Contrasted to filament winding which is limited to continuous placement on closed part geometry, ATP with its cut/add capability can place on open as well as closed parts.

Specific work cell configurations for fiber placement depend upon the geometry of the parts to be fabricated. However, the following elements are common to all fiber placement machines:

- Placement Head
- Automated Machine Platform
- Electronic Controls and Software
- Placement Tool

The placement head is a stand alone end effector that feeds, cuts, places and laminates the ribbons or tape.[6] The platform is usually a commercially available gantry or an articulated arm unit to which additional degrees of freedom may be added.[1]

3.2 NASA ATP Facility. Acquisition and utilization of an automated thermoplastic fiber placement machine for materials and processing evaluation was an important part of the NASA program.[7] The machine, shown in Figure 3, was manufactured by Automated Dynamics Corporation (ADC) and is comprised of an Asea Brown Boveri robotic arm with an ADC thermoplastic fiber delivery head (Figure 4) and placement tools. The latter are comprised of both flat and cylindrical steel tooling. The computer control system and software for the work cell were jointly developed by ADC and Composite Machine Company (CMC). ADC performed the total system integration.

3.3 Machine Development. Materials and processing evaluation activities carried out with the ATP machine at Langley were an intergal part of several NASA aereospace research programs involving even larger and more sophisticated proprietary machines being developed at several corporate research laboratories. These NASA/industry research programs continue to address ATP requirements such as precise control of robot head positioning, material placement rates, heat delivery to the lay-down zone and cut/add, start/stop capability. Machine development for thermoplastics has dealt with the use of hot gases, lasers, focused infrared radiation and combinations of these as heat sources. Current work also is directed toward start-on-the part, turning radius limitations, autoadhesion requirements and development of sensors that give on-line part quality information that could be used for on-line placement defect repair. The latter would yield a remarkable cost-savings for fabrication of commercial aerospace composite structure.

3.4 Modeling. Consolidation models have been developed to relate ATP machine design, operating parameters and sensor readings to the processing conditions necessary for making good quality composite parts. In-situ bonding models have served to establish a processing window bounded by the upper and lower limiting values of the processing conditions within which acceptable parts can be made. The models attempt to describe the mechanisms involved in the ATP process. These include heat transfer, tow thermal deformation and degradation, intimate contact, bonding and void consolidation.[8] Finite element analysis, neural networks and fuzzy logic techniques have been used in these computer-based models.[9]

One of the primary purposes for developing models has been to aid on-line control. The computer execution time is therefore critical. Unfortunately, even in their most simplified form, most models take too long for predictive use on-line. As a result, the models are run off-line for various parameters in the processing window and a computer look-up table constructed that can be used as a guide to on-line control.[9]

3.5 Composite Fabrication/Testing. During the past year, in-situ consolidated laminates have been prepared from high temperature polyimides such as AURUM™ PIXA/IM7, AURUM™ PIXA-M/IM7 and LARC™ PETI-5/IM7 and polyarylene ethers and sulfides such as APC-2™ (PEEK)/AS4), APC-2™ (PEEK)/IM6, PEKK/AS4 and PPS/AS4. It should be noted that thermosetting materials such as the LARC™ PETI-5/IM7 require a high temperature postcure to optimize their performance. Some properties of PEEK and PIXA panels made by ATP on large industrial equipment are given in Table 2 and compared with properties obtained from panels made by hand lay-up/autoclave procedures. The ATP panels exhibited from 85 to 93 percent of the properties of composites made by hand lay-up/autoclave. These results indicate that heated head ATP technology can be used to effectively fabricate quality high performance composite materials. The ATP goal of the period ahead is to achieve 100 percent of hand lay-up/autoclave results.

4.0 CONCLUDING REMARKS

Significant progress has been made in developing automated heated head tow/tape placement technology for the fabrication of high performance composites. The key activities included development of methods for making good quality thermoplastic ribbons and tape, determination of machine design and operating requirements for in-situ placement and establishment of a base knowledge of the fundamental mechanisms involved in both ribbon/tape preparation and in-situ consolidation.

Studies during the period ahead will include the development of focused infrared/hot gas heating, on-line sensors and start-on-the part methods. Particulary important will be material qualification studies at NASA and the fabrication of large test specimens and component structures at several industrial laboratories.

5.0 REFERENCES

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Table 1. Mechanical properties of LARC™ IAX/IM7 polyimide composites made by solution and powder-coated prepreg*

Property	Test Temp., °C	Solution Coated	Powder Coated
SBS Str., ksi	RT	15.8	22.1
	177	7.9	8.9
O°Flex. Str., ksi	RT	213	314
	177	105	213
0°Flex Mod., msi	RT	18.6	19.8
	177	15.1	19.8
0°Compress. Str., ksi	RT	167	202
0°Compress. Mod., msi	RT	23.4	23.7

*Data normalized to 60/40 fiber/resin vol. %; Polyimides were formulated to 4% offset in favor of the diamine and endcapped with phthalic anhydride.

Table 2. Open hole compression strengths of quasi-isotropic thermoplastic composites

Process	APC-2™ (PEEK)/AS4	APC-2™ (PEEK)/IM6	AURUM™ PIXA/ IM7
Hand Lay-up/Autoclave	47 ksi	46 ksi	46 ksi
Adv. Tow Placement	40 ksi	43 ksi	39 ksi
% Retention	85	93	85

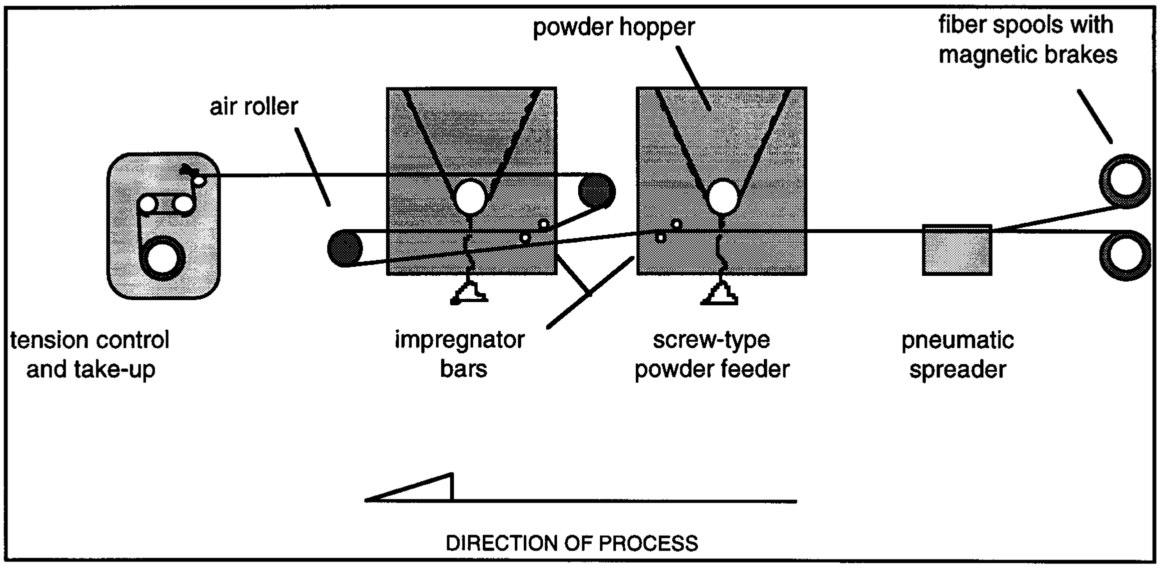

Figure 1. Schematic of the NASA Powder-Coating Line

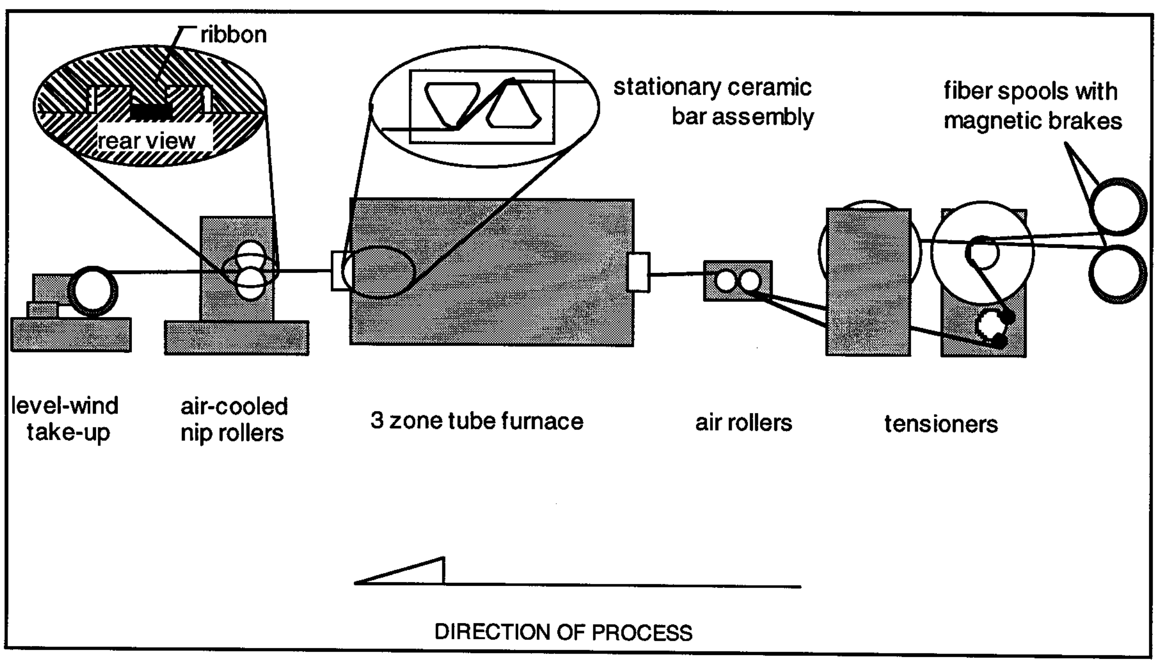

Figure 2. Schematic of NASA Ribbon/Tape Line

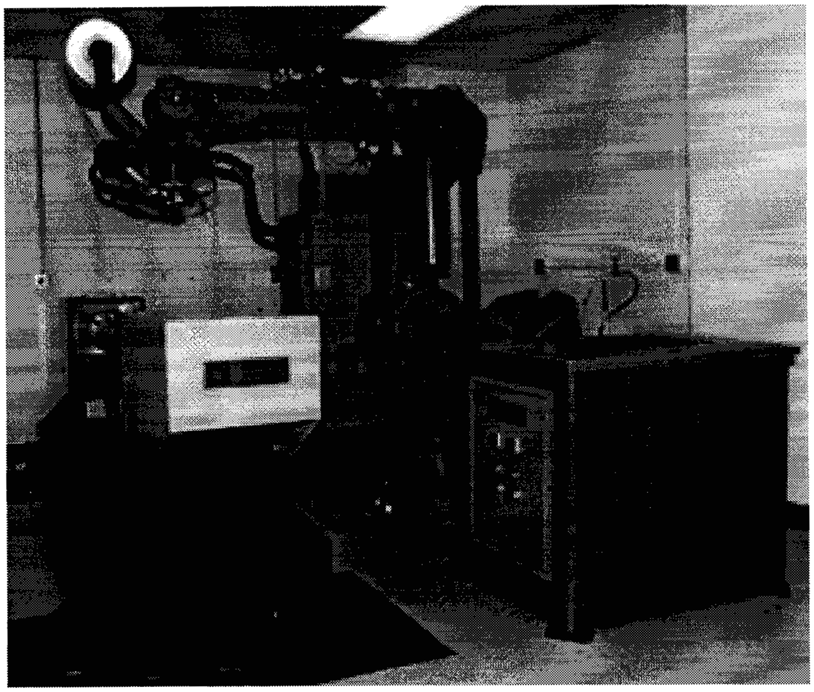

Figure 3. Photograph of the NASA Robot, Heated Head, and Heated Flat Tool

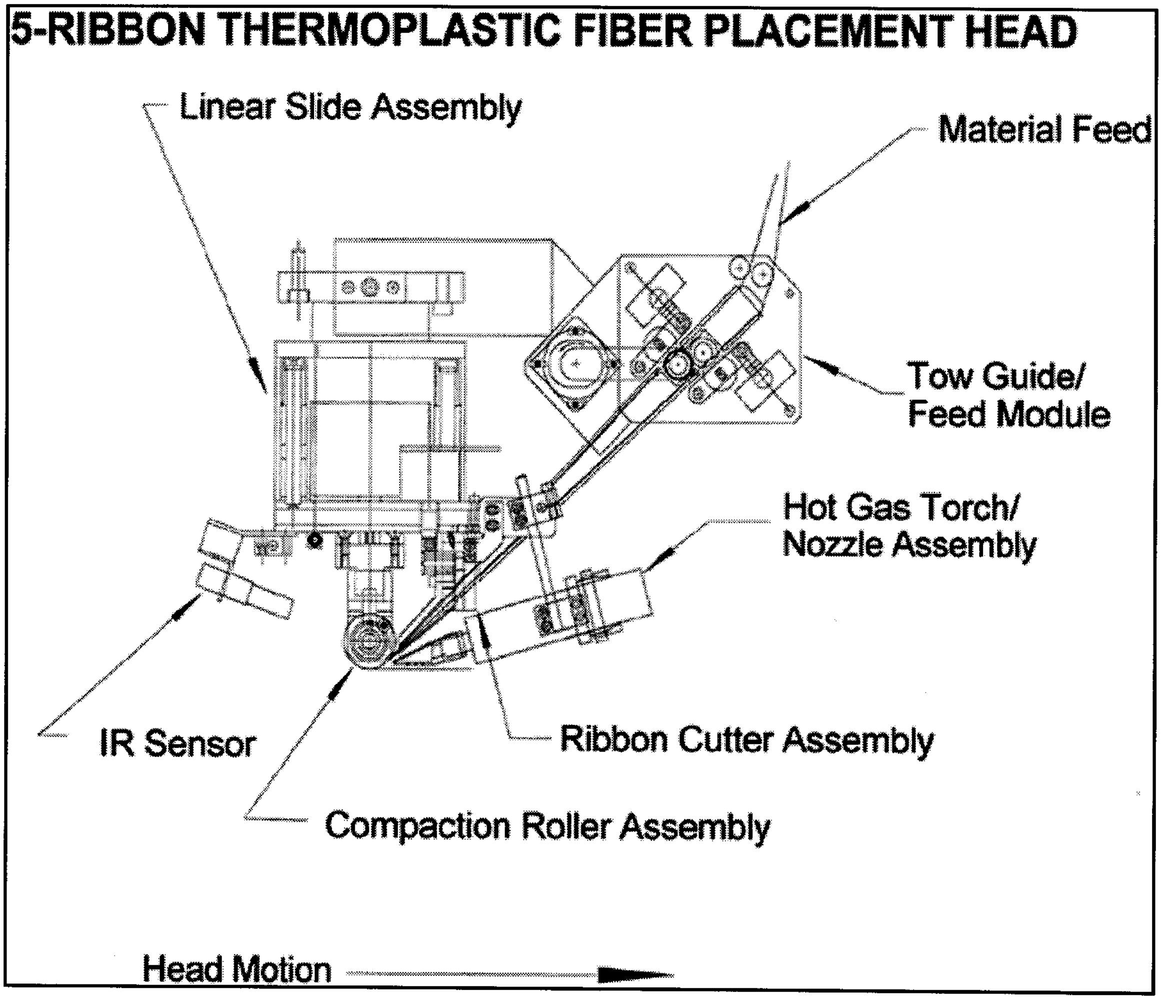

Figure 4. Schematic of the NASA Heated Head