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Production Implementation of Multiple Machine, High Speed Fiber Placement for Large Structures

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ABSTRACT

A two machine Automated Fiber Placement (AFP) cell capable of laying ½” and ¼”tow at rates up to 1800”/min (45.7m/min), including feeds and cuts, has been implemented for the manufacture of large primary aircraft structures.

The control architecture of the cell is such that part programs are machine independent and can run on either machine or simultaneously on both machines at the same time. A Central Cell Controller pushes part programs to each AFP machine and coordinates the cell.

Volumetric accuracy of the two machines is under 0.008” (0.2mm) radial error in the entire compensated envelop, which is approximately 64’ x 21’ x 14’ (19.5m x 6.4m x 4.3m) for each machine. This is accomplished through optimization of volumetric kinematic compensation parameters using a linear numerical solver. The machines reference a common coordinate system which allows great flexibility in part programming.

A detachable head design was implemented which allows each machine to swap between ¼” and ½” tow widths in 120 seconds. The creel is contained on the head which provides very short tow paths and isolates the AFP process to the detachable tool. This allows creel re-fills, AFP head maintenance, repair, and upgrade of AFP head to be performed off line without interrupting production.

INTRODUCTION

Electroimpact produced a cell built around a control architecture that permitted the use of two machines running simultaneously or independently using common programs which can be run on either machine, Figure 1. Additionally, the machines are independent in that the failure of one machine (e.g. dropped tow) does not interrupt the second machine laying tow. Furthermore, the use of detachable, modular AFP heads offered offline load, cleaning and maintenance for increased cell uptime, and provides a way to rapidly change tow widths during production.

Existing technology - Some knowledge of traditional AFP machine technology is helpful in understanding the unusual features of this machine. Typically, large AFP machines feature a “creel house” removed from the head which stores multiple spools of tow in an air conditioned environment and feeds them out to the head via a series of idle rollers along a 20’-30’ (6.1m-9.1m) tow path. The most notable down side of this design is the very long tow path increases the chance of tows becoming twisted and makes threading tow difficult and time consuming. Changing tow widths is an involved process and most AFP path maintenance requires down time on the machine. The complex tow path may also preclude true bidirectional tow laydown in all tow directions, as the tow path must be twisted as the end effector rotates. In contrast, the Electroimpact AFP machines use a discrete AFP head that places all of the AFP elements - including the “creel house” - on the detachable head. The heads are interchangeable via a tool changer, allowing 120 second change-outs to a fresh head or a head of a different tow size.

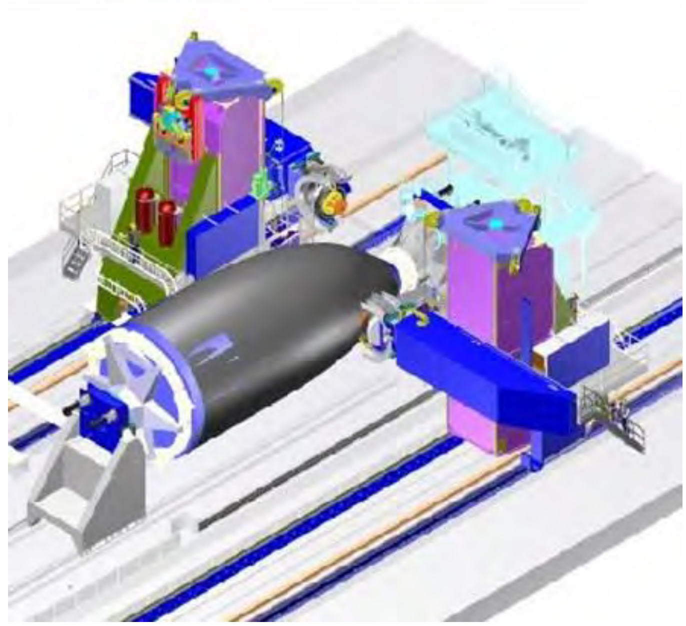

Figure 1 – Machine Cell

Some multiple machine systems have a single CNC machine controlling the rotator and machines. If using two machines in such a cell it is very desirable to be able to quickly switch to a single machine or move work to an alternate machine. With a single CNC machine system, programmer intervention or multiple part programs are required to switch the number of running machines.

MAIN SECTION

This section is divided into three sub-sections

- Cell Description
- Accuracy and Compensation
- Control Architecture

CELL DESCRIPTION

The cell consists of two machines, a rotator, a maintenance area and a control station. The cell is specifically designed for lay-up of forward section wide body composite fuselage, including the cockpit region, Figure 2. Additionally, three ½" heads, two ¼" heads, and one probe head were delivered with the cell. The heads attach to the machine using a robotic tool changer. The maintenance area contains four head transfer stands and head transfer carts.

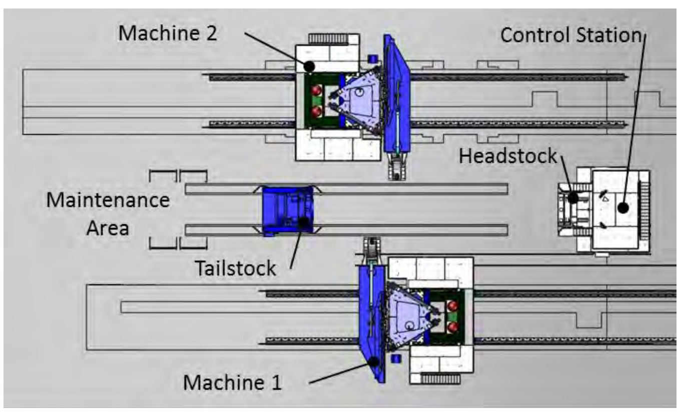

Figure 2 – Cell Layout

Major Machine - Two moving column floor mill or "post" style machines were implemented on either side of the part, Figure 3 and Figure 4. The very large part diameter and customer specifications drove the machine envelope of 22.2' (6.77m) of Y axis travel and 14.2' (4.35m) of Z axis travel, along with X travel to address the 48' (14.6m) longer proposed derivatives. 135 degrees of "A" rotation at 2700 degrees/minute, 90 degrees of "B" rotation at 1800 degrees/minute and an infinite "C" axis at 12000 degrees/minute permit maintaining normality to the part at any position in the work envelope. Linear axes move at 2000"/minute (50.8m/min) with accelerations of 0.18g. High acceleration is critical to machine performance where many short courses exist, which turns out to be the case even for parts as large as this fuselage.

Rotators - A large and accurate rotator was required for rotational (U axis) positioning of the mandrel assemblies. The rotator consists of an independently driven headstock and tailstock, Figure 2. The tailstock X axis travel allows it to accommodate a variety of tools.

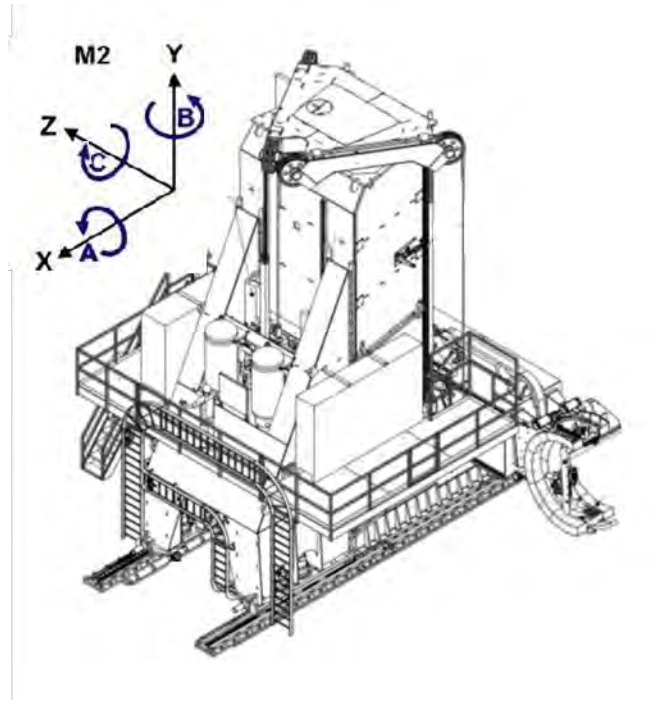

Figure 3 – Major Machine

Figure 4 – Major Machine

Modular AFP Heads - The machines are equipped with both ¼" and ½" tow widths. The ability to lay multiple tow widths is accomplished by implementing quick change AFP heads. The AFP process is completely contained on each head. Each head contains 16 spools of tow, an infrared heater for highly controllable and responsive heating and air for cooling, Figure 5. A high speed local PLC provides head control with minimal delays for the AFP process (e.g. cutters, feed rollers, heater, etc.). All AFP process elements are designed for the very rapid response required by the design laydown speed of 2000 inches/minute.

Modular AFP Head Advantages - The removable modular head offers several advantages specific to this design.

The head offers 360 degree positioning about the C axis and therefore true bidirectional layups. Because the fiber placement system is independent of the machine, the head does not “care” which way it is oriented and the tow path is not influenced by head orientation considerations.

The removable head offers a multiplicity of tow widths with a 120 second change. Each head uses exactly one tow size, with 16 spools. To date, 1/8”, ¼” and ½” heads have been implemented (the 1/8” on other machine cells). Other tow widths and other materials are possible with the removable head concept.

The very short tow path (approximately 3’ (1m) long) offers significant advantages whenever threading new tow is required. All the fiber placement elements are located within arm’s reach of the operator and any operations – tow stringing, cleaning, diagnosis, cutter replacement, etc. are greatly simplified.

The rapid head change means that nearly all fiber placement maintenance tasks (loading new tow, cleaning, cutter replacement, etc.) can take place offline while another head is attached to the machine and laying tow.

Future developments in head design are easier to implement. A new generation of head has already been developed. Such improved heads may be brought online and used alongside the existing heads, as desired.

Other special use heads are possible. Currently a probe head is used for locating the mold and for machine compensation purposes. The possibilities exist for other heads, such as an NDI head or an ultrasonic profiler.

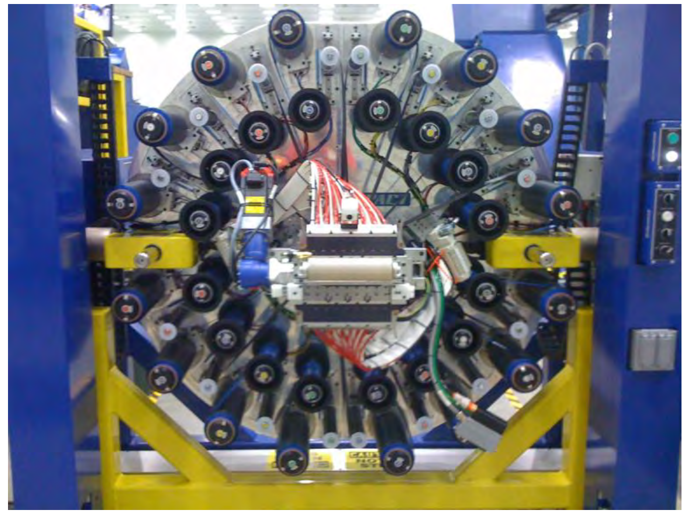

Figure 5 – AFP Head

Transfer Stands - Transfer stands allow for the rapid change-out of a head. They are positioned at the maintenance area for ease of access to head maintenance tools and spools of tow. The transfer stands provide fully automated safe and secure head swap and provide a staging position for newly ready heads. Additionally, the transfer stands provide power and air to the heads for full off-machine functionality. Figure 5 shows a head in a transfer stand in the lowered position.

Figure 6 – Head on Transfer Cart

Head Transfer Carts - Head transfer carts are provided for loading and unloading the heads in the transfer stands, Figure 6 and Figure 7. The head transfer carts allow the heads to be swapped between machines or to be taken offline for maintenance. They are designed to allow rotation of the heads for ease of maintenance and provide full functionality to the head through umbilical cords which provide power and air.

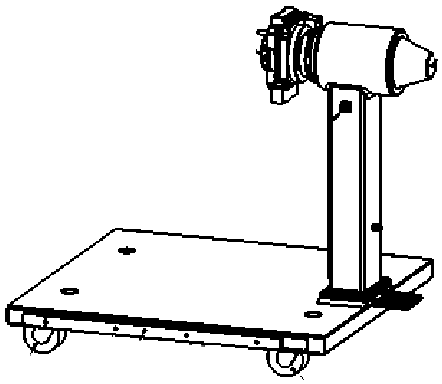

Figure 7 – Head Transfer Cart

Probe Head - A probe head was also provided. It attaches to the machine using the same quick change method as the AFP heads. The probe head is used for probing the part with a Renishaw probe and nests 1.5” Spherically Mounted Retroreflectors (SMR’s) for compensating the machine. Further details of the probe head are covered in the machine compensation section.

Cell Operation - Each machine runs independently of the other machines in the cell. The result is a system that can scale machine participation up or down in between any courses without interrupting other machines.

There are two modes of operation:

1) Static mode
2) Dynamic mode

The cell is controlled by a Cell Control which orchestrates the machines. The Cell Control pushes part programs to each AFP machine. For a given ply, the mandrel is positioned, programs pushed to both machines, and executed until completion. The Cell Control then automatically advances to the next position and pushes the next set of programs to the machines. If a machine goes down at any point, the remaining machine can pick up where the down machine left off and continue production. One machine is capable of completing all part programs.

Cell Performance - The cell was production qualified to Boeing AFP specifications from a minimum of 1600 inches/minute (40.6m/min) and up to 1800 inches/minute (45.7m/min). This qualification includes static and dynamic modes of operation for both ¼” and ½” heads. Both adds and cuts of material are qualified at these speeds.

Machine performance exceeds the qualified speed, so process related improvements will enable the machine to qualify at higher AFP speeds.

COMPENSATION AND ACCURACY

Machine compensation is traditionally done via single axis compensation, this cell instead used a volumetric compensation system to achieve greater accuracy and reduce the time to compensate the machine. The measuring was done solely with a FARO laser tracker collecting data directly in the Machine Reference System (MRS). During Acceptance Testing one machine needed mechanical adjustment and required re-compensation. The compensation was complete and verified to meet accuracy specification in less than two one shift work days.

Common Coordinate System - The machines in the cell reference a common coordinate system, the MRS, Figure 8. Referencing a common MRS is easily accomplished for multiple machines by employing volumetric compensation. It requires no additional work over using two separate coordinate systems. The system is actually simplified as only one MRS must be maintained.

However, the greatest benefit of the machines referencing a common coordinate system is that any program can be executed on any machine with no unique offsets. The same part transform can be used for all machines. This flexibility is maintained over the life of the machine even after it is re-compensated multiple times, as it is always compensated to the same coordinate system.

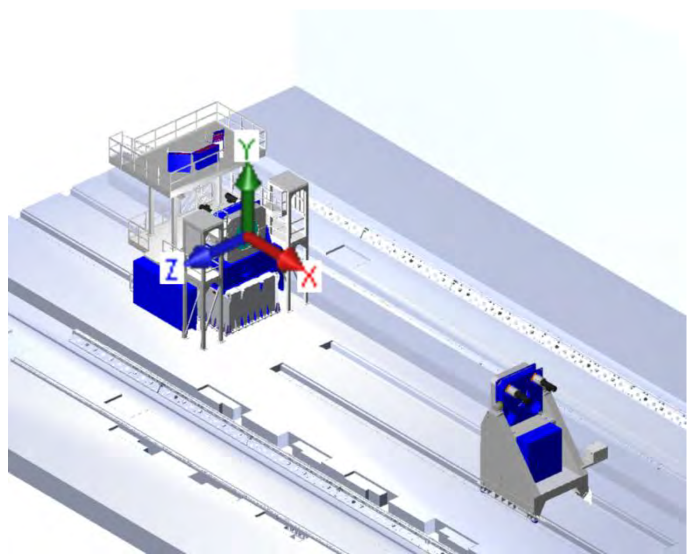

Figure 8 – Common Machine Coordinate System

Defining the Machine Reference System - This MRS is referenced through an array of points on the floor, Figure 9. Numerous 1.5” SMR nests, optical tooling points (OTP), are permanently mounted flush in the floor to allow access to the MRS from any location in the cell. All nominal values for the points are with respect to the MRS, so once the tracker measures floor points and best fits them to the nominal point values, subsequent measurments are in the MRS. This “absolute” MRS allows the machine to easily be compensated to the same coordinate system over years of use. This consistency allows any program that references the MRS to continue to function after re-compensating the machine and allows programs to run on future machines added to the cell.

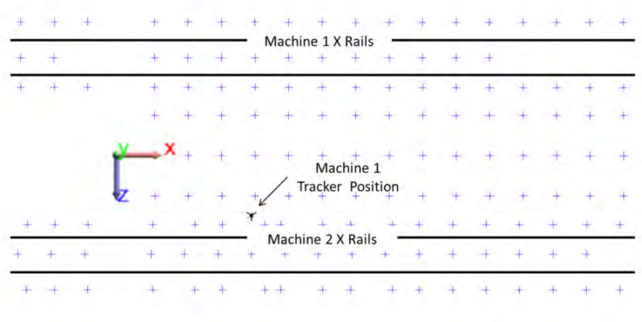

Figure 9 – Example of Floor MRS Locations

Measure points w/ tracker from single location - The data collected to compensate the machine consists of individual axis movements and 6-axis Random data. Nearly 900 data points are taken throughout this process using both a 1.5” SMR and an API Active Target, Figure 10. An active target is a self-aligning substitute for an SMR.

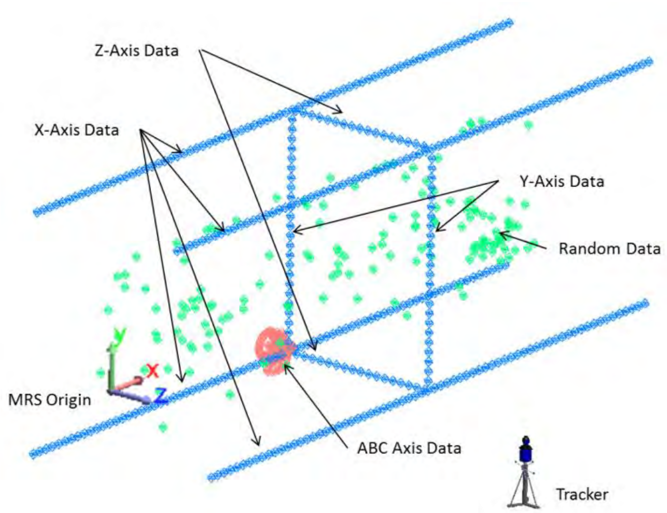

Figure 10 – X, Y, Z, A, B, C and Random Compensation Data

Data is taken at both the toolpoint and other fixed locations on the probe head to provide orientation definition. For the individual axis data, each respective axis is moved systematically through its range of travel in predetermined increments, such as 10” (250mm) for a linear axis or 10deg for a rotational axis. For rotational measurements, 3 points are measured at each axis position to fully define position and orientation. The Probe Head, Figure 11, has multiple nests. Typically the toolpoint and two other SMR nest locations are measured to fully define orientation, as shown in Figure 11.

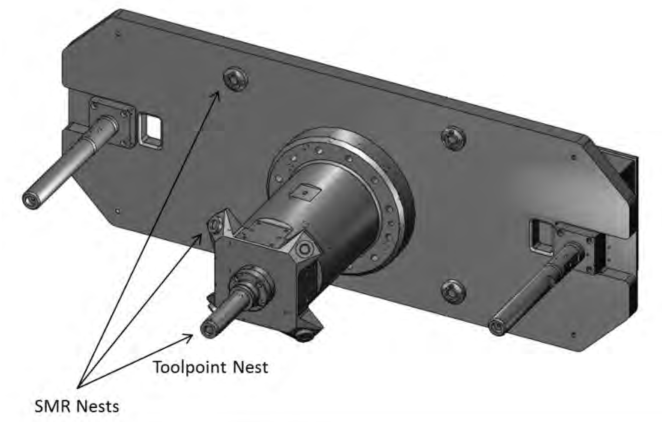

Figure 11 – Probe Head Nests

Solve with third Party linear numerical solver - The compensation data collected and the commanded toolpoint position is then sent to a third party linear numerical solver. The solver calculates the optimal kinematic parameters to maximize the accuracy of the machine throughout the entire envelop of data provided. The compensated accuracy of the machine is then predicted which has demonstrated to be a reliable indicator of machine accuracy verification, Figure 12. The predicted accuracy readily reveals if the compensation is valid, further reducing compensation time by preventing unnecessarily checking an inaccurate machine. Bear in mind that the data shown in Figure 12 is quantifying the positional accuracy of 6-axis moves over the entire envelope, not individual axes or relative accuracy. This includes all positional error for rotation axes.

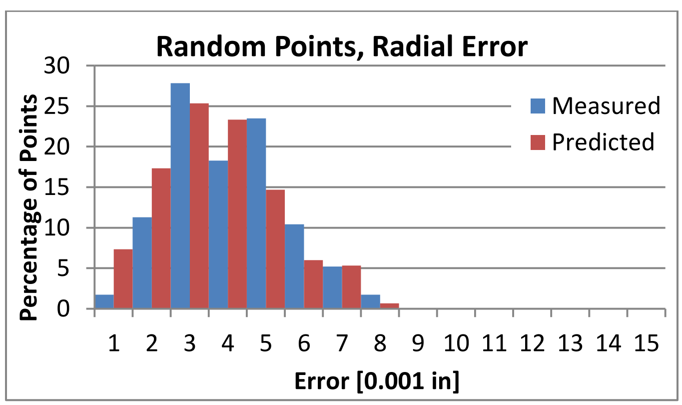

Figure 12 –Error Distribution

Load Data onto Machine - The compensation tables are then loaded directly onto the CNC, a process which takes merely seconds. It should be emphasized at this point that no manual entering of numbers has taken place, greatly reducing the likelihood of errors. The machine position data is collected with a tracker, the kinematic parameters for compensation are solved numerically and the compensation table automatically populated, and this table is automatically transferred to the CNC.

CONTROL ARCHITECTURE

Configuration - Each of the two machines and the rotator has its own FANUC CNC. The system is implemented with the aid of FANUC's customer board. The control architecture features the ability to include individual tow commands into the CNC executive's main interpolation loop. Resolution of this interpolation is 20us or sub .001" at 2000"/min feedrates. Additionally, part program execution for dynamic mode allows the machine to track the independently moving part and predict and intercept the part at a precise location in space and time so that a path executed in dynamic mode or static mode are indistinguishable. Since the dynamic mode programs are executed on independent machines (slaved to the moving part by a single Mcode) the machines can exit and enter the work zone without affecting the moving part or another machine in the cell. The architecture also permits federate overrides on the fly for increased flexibility. No re-posting or other programming is required to support federate overrides for maximum operational flexibility.

Cell Objective - As stated earlier, the Electroimpact cell utilizes a unique control architecture that enables efficient simultaneous use of multiple machines in the cell. The multi-machine cell had many goals and some important ones for this discussion are:

1) Any program can run on any machine-AFP head combination. Even if the machines are on opposite sides of the part.
2) It must be easy to switch a program designated to run on one machine to another in cases where the designated machine is unavailable.
3) A machine that becomes unavailable will not prevent the cell from producing AFP layups.
4) The mandrel's position only needs to be such that the envelope of the part program is within the working envelope of the machine. The machines in the cell will transform the programs on-the-fly as necessary to locate the AFP layup where necessary and within tolerance.

The problem was broken down into two modes:

Static: The mandrel is positioned at a specified index and the machine moves around the part to produce the AFP layup.

Dynamic: The mandrel is moving and the machines execute their part programs by dynamically referencing the mandrel's position and velocity.

Part Programs - A common theme among all Electroimpact equipment is part program compatibility. It is important in modern aircraft assembly that part programs once proven do not need to change for any of the following reasons:

1) inconsistent part loading
2) part is moving or positioned differently than expected by NC programming.
3) machine 1, machine 2 or machine N performing the work

Static Mode - Since the machine cell has a common reference system (defined earlier as the MRS) and since each machine is aware of its precise location in this system it is possible to utilize more than one machine-AFP head combination to run identical general case part programs in Static mode with only the addition of a small amount of functionality. Even though the mandrels or tool-units used in the subject AFP cell differ slightly from each other the part programs used across the tooling-units are identical. This is possible because the machines calculate the required position in the MRS on-the-fly via a common correction transform specific to the tool-unit. Additionally, there are several transformations applied to the part-program commanded positions on-the-fly. A series of simple six degree of freedom (6DOF) transforms accounting for the position of the mandrel, the specifics of the as-built tool-unit and the specifics of the loading of the tool-unit on the mandrel axis are utilized to transform the NC programming commanded tool position into the MRS. So the goal of running a single part program for all tool-units and all machine-AFP head combinations and for all barrel positions is achieved by the toolpoint control architecture utilized in all Electroimpact equipment. Since the machines can readily transform the part program positions into the MRS it is a simple matter to design a user interface to move a program from one machine to the other. With this functionality we have met our stated goals for static mode.

Dynamic mode - Dynamic mode is only an extension of static mode. Even in dynamic mode when more than one machine-AFP head combination is working, it is a separate general case program written to be run by a single machine. So when two machines are running in dynamic mode they are each running their own program, it is not a common program. Each machine performs the necessary transforms on-the-fly to execute this program correctly. In the part program there is no information about barrel speed or position. A unique mode of running was developed that allows the CNC to execute the part program at a rate synchronized to the moving mandrel by observing the mandrel's position, velocity and acceleration and transforming the position commands in the part program to meet the moving mandrel at the correct point in space at precisely the right instant. Since each machine is observing the mandrel position, information about mandrel speed need not be included in the part program. Likewise, information about the goings on of another machine in the cell is not required in the part program. The development of this control scheme ensured machine independence and general case programs. Because of this functionality, the utilization of multi-machine in dynamic mode is practical. For example, this machine independence allows a machine to pull off if there is a failed tow add without affecting the program execution of another machine. Furthermore, once corrective action is taken, the machine with the error can be seamlessly re-inserted into the active working cell...again not affecting the performance of another machine in the cell. Should for some reason a machine become unavailable for a period of time, the general case program planned to run on the unavailable machine can easily be transferred to and run by another machine.

CONCLUSION

Presently, the AFP machines are in production successfully running as designed. A variety of concepts and technologies were proven, such as multiple machines running common programs, true machine independence, rapid head changeout, multiple tow width use (½" and ¼") during part layup, offline spool load, cleaning and head maintenance, synchronization between multiple machines and rotators with multiple CNCs.

Volumetric compensation was successfully implemented and resulted in very good accuracy with a maximum 0.008" radial error throughout the cell. Additionally, it was demonstrated that the entire machine can be re-compensated from scratch in less than two one shift days.

The concept of a common MRS and general case part-program were used to successfully and practically coordinate more than one machine working on a part even when the part is moving. Additionally, it was shown that laying individual tows in the same course with different machines running the same program layed tow within our required tolerances.

CONTACT

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFP: Automated Fiber Placement

API Active Target: Laser Tracker target which actively points at the laser tracker to avoid breaking the beam.

Course: A single pass of 1-16 tows

DOF: Degrees of Freedom

MRS: Machine Reference System

OTP: Optical Tooling Points

SMR: Spherically Mounted Retroreflector