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A Fuzzy Logic Control Model for the Curing Process of Heat-Activated Coupling of FRP Composites to Alloy Pipes

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ABSTRACT

A fuzzy control (FLC) approach has been developed to control the curing process of a polymeric laminate used as the bonding material for the heat-activated coupling (HAC) of a fiberglass composite to Cu-Ni alloy pipe. Controlling the temperature of the curing environment is required in order to achieve uniform cure within the bonding prepreg. Without temperature control, the alloy side of the coupling is essentially a heat sink. Therefore, a controlled heat source on the alloy pipe is needed to compensate for the heat sink effect that tends to decrease curing temperatures within the laminate. The simulation results obtained show that the curing process of HAC of a composite-to-alloy pipe is significantly improved with required uniform cure characteristics being obtained through the thickness of the laminate.

INTRODUCTION

Fiber reinforced plastics (FRP) are materials that have gained increasing usage in engineering applications in the past decade. The curing process of these materials to convert them into structural parts for engineering systems involves heating. The prescribed heating process cures the uncured FRP normally referred to as pre-impregnated (prepreg) laminate. Controlling the temperature of the curing environment is desirable in order to achieve uniform cure within the prepreg laminate with optimum mechanical properties.

For such type of systems a fuzzy logic control approach can be employed. Since the experience of the experts directs the control structure, the control system does not need analytical model. Fuzzy logic models, called fuzzy inference systems, consist of a number of conditional "if-then" rules. For the designer who understands the system, these rules are easy to write, and as many rules as necessary can be applied to describe the system adequately (although typically only a moderate number of rules are needed).

In fuzzy logic, unlike standard conditional logic, the truth of any statement is a matter of degree; e.g. “how cold is it,” “how high should we set the heat?” Fuzzy inference systems rely on membership functions to send input data to the computer so that a correct value between 0 and 1 can be calculated. The degree to which any fuzzy statement is true is denoted by a value between 0 and 1.

Not only do the rule-based approach and flexible membership function scheme make fuzzy systems straightforward to create, but they also simplify the design of systems and ensure that the system can easily be updated and maintained over time. [1]

Fuzzy logic may also be considered as an assortment of decision-making techniques. In many applications like process control, the algorithm’s outcome is ruled by a number of key decisions, which are made in the algorithm. Defining the best decision requires extensive knowledge of the system. When experience or understanding of the problem is not available, optimizing the algorithm becomes very difficult. This is the reason why fuzzy logic is useful [2].

Furthermore, fuzzy logic starts with and builds on a set of user-supplied human language rules. Then, the fuzzy systems convert these rules to their mathematical equivalents. This simplifies the job of the system designer and the computer, and results in much more accurate representations of the way systems behave in the real world.

Additional benefits of fuzzy logic include its simplicity and its flexibility. Fuzzy logic can handle problems with imprecise and incomplete data, and it can model nonlinear functions of arbitrary complexity. "If you don't have a good plant model, or if the system is changing, then fuzzy will produce a better solution than conventional control techniques," Bob Varley [1].

Ever since Mamdani applied fuzzy set theory to control a steam engine and boiler combination by a set of rules, there have been several fuzzy inferencing systems proposed by various researchers reported in literature [3]. In Mamdani type fuzzy inference system, the resultant control action of two rules is shown in Figure. 2. In this case, the resulting action is based on *min max* composition. The final crisp value is obtained by calculating the centroid of area. This process of defuzzification is known as center of area (COA) defuzzification method.

Fukuhara, Ishii and Agusa studied on an internal welding robot system to promote pipeline-joining efficiency in inside/outside simultaneous welding. They used fuzzy control system to stabilize the welding arc. The system consists of six major units: a welding head, a hydraulically-operated line-up clamp, a self-drive mechanism, an imager controller, a system controller and a welding power supply unit. The welding head has a welding torch, a weaving mechanism, charge couple device cameras and a laser beam projector, and welding operation can be remotely controlled with an arc monitoring system. An image sensor/processor system is used to locate the center of the weld seam and the power supply unit is characterized by a fuzzy control system that stabilizes the welding arc [4].

Even though FLC has been applied widely in various classical as well as complicated engineering problems not much work has been done in the application of FLC to curing processes of FRP composite. In this study an attempt has been made to apply the FLC to solve the critical problem of nonlinear heat diffusion with chemical kinetics in the curing of FRP composite systems. This approach is required in order to control temperature associated with the curing process.

NOMENCLATURE

K: Thermal diffusivity, m^2/sec
k: Thermal conductivity, W/m K
Cp: The specific heat capacity, J/Kg K
h: Convective heat transfer coefficient, W/m^2 K
r: Radial dimension, m
z: Axial dimension, m
i: Radial grid dimension
j: Axial grid dimension
t: Time, sec
N: Iteration number
T: Temperature, °C
$\dot{g}$: Thermal energy generation term, W/m^3
E: Error
Err: Error change
T_o: Observed temperature, °C
T_{at}: Target temperature, °C
ΔT_c: Control temperature, °C
N: Negative
NB: Negative Big
NVB: Negative Very Big
Z: Zero
P: Positive
PB: Positive big
PVB: Positive very big
c^r: Center of gravity value for rule r
x_i: The crisp value for input i to the fuzzy logic controller
ρ: Density, Kg/m^3
α: Degree of curing
β: Thermal conductivity constant
η: Specific heat constant
μ: Membership value

PLANT MODEL

Figure 1 shows a schematic representation of HAC pipes. The pre-impregnated fiber and organic matrix material is selected to have the same properties as the FRP composite pipe being joined after it has cured. It is assumed that both the pipe and joint section have uniform, isotropic and temperature dependent thermo-physical properties. Therefore, under these assumptions the differential equation that governs the transport of thermal energy through the composite system wall with internal heating is the heat diffusion equation in two dimensions with energy generation is nonlinear and nonhomogenous as in [5]:

$$\rho\, C_p(T)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(k(T)\, r\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right) + \dot{g}(T) \tag{1}$$

The thermal properties C_p(T) and k(T) are linear function of temperature as follows [6]:

$$c_p = c_p + c_{po}\eta T \tag{2}$$

$$k = k + k_{po}\beta T \tag{3}$$

Thermal energy generation due to chemical kinetics of the curing prepreg was accounted for using an autocatalytic kinetic model as follows [6]

$$\dot{g} = \rho H_r Z e^{-E/RT}\alpha^m (1-\alpha)^n \tag{4}$$

Initial conditions

The pipes and the prepreg are initially at room temperature.

$$(T_1 = T_2 = T_3)_{t=0} = T_0 \quad (5)$$

Temperature Boundary Conditions

The boundary conditions used in this study is derived from manufacturers cure cycle required for the prepreg material:

Prepreg Boundary:

$$T = \begin{cases} At & 0 \le t \le t_1 \\ At_1 & t1 \le t \le t_2 \\ -\dfrac{At_1}{t_3 - t_2}(t_3 - t) & t_2 \le t \le t_3 \end{cases} \quad (6)$$

Radial Outer Boundaries (-a < z < a):

$$-k_1 \frac{\partial T_i}{\partial t} + hT_i = hT_\infty \quad (7)$$

where T_0 is the initial temperature of the joint. T_1, T_2, T_3, h, k_1, k_2, and k_3 are temperature, convective heat transfer coefficient, and thermal conductivity in the prepreg, fiberglass composite pipe, and the alloy pipe, respectively. T_∞ is the environmental temperature.

Interfacial condition

$$\begin{aligned} &(k_1 \frac{\partial T_1}{\partial r})_{r=R_1} = (k_2 \frac{\partial T_2}{\partial r})_{r=R_1} && (0 < z < a) \\ &(T_1)_{r=R_1} = (T_2)_{r=R_1} && (0 < z < a) \\ &(T_2)_{r=R_0} = (T_3)_{r=R_0} && (0 < z < b) \\ &(k_2 \frac{\partial T_2}{\partial r})_{r=R_0} = (k_3 \frac{\partial T_3}{\partial r})_{r=R_0} && (0 < z < b) \end{aligned} \quad (8)$$

Symmetrical condition

$$\begin{aligned} &(\frac{\partial T_1}{\partial z})_{z=0} = (\frac{\partial T_2}{\partial z})_{z=0} = (\frac{\partial T_3}{\partial z})_{z=0} = 0 \\ &(\frac{\partial T_3}{\partial r})_{r=0} = 0 \end{aligned} \quad (9)$$

FUZZY LOGIC CONTROL SYSTEM

In this section a fuzzy logic model is constructed for a proper curing process as explained in the introduction of this study. A FLC is composed of three main parts, namely fuzzyfication, inference engine and defuzzyfication [9]. In the fuzzyfication part, inputs are fuzzyfied according to the fuzzyfication method chosen. In this study singleton fuzzyfier is used. Labels and their corresponding domains are defined based on expert knowledge.

In the inference engine part, rules that will be used to calculate the fuzzyfied control value are embedded into the F.L.C. model. These rules are determined based on the expert knowledge. In this study minimum inference engine is used.

In the defuzzyfication part, the fuzzyfied output obtained from the inference engine is converted to the crisp value according to the defuzzyfication method. In this study the center of gravity defuzzyfier method is used.

The block diagrams of the system are shown in Figures 3 and 4.

Rules:

Error is defined as:

$$E = T_t - T_o \quad (10)$$

Error change is defined as:

$$Er(n+1) = \Delta E(n+1) = E(n+1) - E(n) \quad (11)$$

Rule-1: IF error is N AND error change is N
THEN control temperature should be NVB
Rule-2: IF error is N AND error change is Z
THEN control temperature should be NB
Rule-3: IF error is N AND error change is P
THEN control temperature should be N
Rule-4, 5, and 6: IF error is Z
THEN control temperature should be Z
Rule-7: IF error is P AND error change is N
THEN control temperature should be P
Rule-8: IF error is P AND error change is Z
THEN control temperature should be PB
Rule-9: IF error is P AND error change is P
THEN control temperature should be PVB

Using singleton fuzzyfier, minimum inference engine and center of gravity defuzzyfier, the defuzzyfier output [10] will be:

$$\Delta T_c = \frac{\sum_{r=1}^{9} c^r \min_{i=1}^{2} \mu_{A_i^r}(x_i)}{\sum_{r=1}^{9} \min_{i=1}^{2} \mu_{A_i^r}(x_i)} \quad (12)$$

where

c^r: Center of gravity value for rule r.

x_i: Inputs to the fuzzy logic controller, E and Er.

$\mu_{A_i^r}(x_i)$: Membership value of x_j for A^k label.

ALGORITHM

A finite difference program based on Alternating Direct Implicit (ADI) methods was developed in a parallel study [7] to solve for the temperature distribution and degree of cure within the laminate. After discretization is applied to all points of the grid, the system matrix model will be

$$[A]*(T)=(d) \qquad (13)$$

where

$$A=\begin{bmatrix} c_{1,0} & u_{1,0} & & & & & \\ & \cdots & & & & & \\ & & \cdots & & & & \\ & & & \cdots & & & \\ & & l_{i,j} & c_{i,j} & u_{i,j} & & \\ & & & & \cdots & & \\ & & & & & \cdots & \\ & & & & & & \cdots \\ & & & & & l_{r,z} & c_{r,z} \end{bmatrix} \quad T=\begin{pmatrix} T_{1,0} \\ \cdots \\ T_{i,j} \\ \cdots \\ T_{r,z} \end{pmatrix} \quad d=\begin{pmatrix} d_{1,0} \\ \cdots \\ d_{i,j} \\ \cdots \\ d_{r,z} \end{pmatrix}$$

where r and z are the last points in vertical and horizontal direction respectively.

The algorithm of the implementation is given below:

- Initialize the system
- Construct rule and database engine

While iteration number < defined iteration number

- Start vertical trace
    - o Construct F matrix to calculate $F_{i,j}$
    - o Construct A matrix and d vector to calculate
        - Corners, $c_{i,j}$
        - Uppers, $u_{i,j}$
        - Lowers, $l_{i,j}$
    - o Calculate temperatures, $T_{i,j}$.
- Start fuzzy control
    - o Calculate error and error change.
    - o Fuzzyfy error and error change.
    - o Apply rules using look-up table.
    - o Calculate the axial value of the center of gravity.
    - o Calculate defuzzified crisp output called control increment value.
    - o Calculate new control value using control increment value. This new control value is applied on the alloy as an additional source temperature as follows:

$$T(N)=T_\infty+f(E,Er)$$

in the region $-(b+3a)/4 < z < -a$; $r = R_1$

- Start horizontal trace
  Repeat same steps used in vertical trace
- Start fuzzy control
  Repeat same steps above for fuzzy logic control.

The flowchart of the algorithm and simulator screens is shown in Figures 7 and 8 respectively. The time complexity of the algorithm is O(n * Ng) where n and Ng are the number of iterations and the number of grid points, respectively. The space complexity of the algorithm is O(Nr * Nz) where Nr and Nz are the size of vertical and horizontal dimensions, respectively.

RESULTS AND DISCUSSION

In Figures 9 and 10 radial temperature histories of prepreg curing process and radial degree of cure of prepreg on alloy and composite pipe respectively are shown. These figures reflect the results for middle points on axial joint, (i = 10, j=35) and (i = 10, j=45), and for middle layer, (i = 12, j=35) and (i = 12, j=45), and for the layer just before the outer layer, (i = 13, j=35) and (i = 13, j=45); see Figure 15 for the grid coordinates. In Figure 9, at the interface layer of the prepreg-pipe joint, i = 10, the temperature distribution is almost the same, around initial value of 21 ºC. The temperature distribution increases while approaching the boundary source temperature of 155.4 ºC. Also because of the thermal conductivity difference between alloy and composite pipes, at the same layer the temperature distribution differs, especially near to the interface layer. As shown from these figures, without control the curing process temperatures predicted on the alloy side of the prepreg are lower compared to symmetrical locations on the composite side. Figure 10, shows that without control the goal of 100% uniform cure on both alloy and composite side cannot be met. On the alloy side it is barely 10% cured while on the composite side it reaches about 67% cured. This effect is due to the lower temperature results from the heat sink effect of the allow side.

In Figures 11 and 12, it is shown that there is a very good improvement after applying the fuzzy logic control. Figure 11 shows that the temperature distribution is much more desirable when the mass points are selected as second half of the joint interface points. Also in the same figure, it is shown that the control process results in a good curing for a larger size joining. (Dimensions in meters: Length of the pipe = 4.40436, length of the prepreg joint = 0.25908, radius of the pipe = 0.08636, thickness of the pipe = 0.010795, thickness of the prepreg joint = 0.008636)

Radial degree of cure of prepreg and radial temperature history of prepreg at the interface and successive layers are shown in Figures 13 and 14. These results also validate the results shown in Figures 11 and 12.

SUMMARY AND CONCLUSION

In conclusion, a fuzzy logic control (FLC) model has been developed to control nonlinear 2-D heat diffusion process in the curing of a polymeric prepreg laminate used the bonding material in joining an FRP composite pipe to a Cu-Ni alloy pipe. Since the alloy is a much better conductor and loses heat rapidly, it causes the bonding prepreg to cure much more slowly on the alloy side. In order to reduce cost in detailed experimental investigation and analysis of the curing process, a computer simulation program with heat loss controller algorithm was developed.

It is shown that FLC caused very good curing through the joint. When the mass points are selected as the second half of the joint interface points to calculate the fuzzy inputs, the control process gives improved results compared to when end points are selected as the mass point.

FUTURE STUDY

For the optimum control parameters, advanced fuzzy logic control method, such as adaptive F.L.C., can be used. Moreover, the computation of required thermal energy to map the output of the controller i.e. the necessary boundary conditions of alloy side are to be evaluated for the smooth running of the proposed fuzzy control system. This aspect is currently under investigation.

ACKNOWLEDGMENTS

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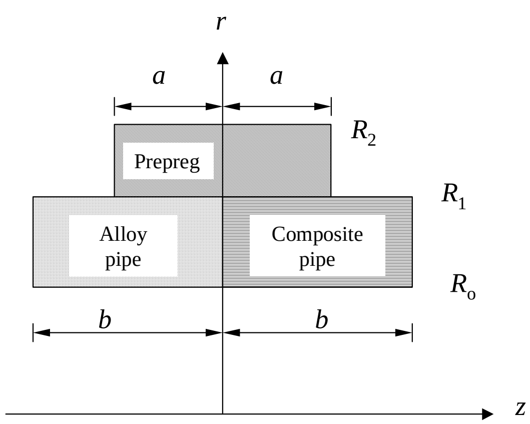


Figure 1 The Pipe Structure

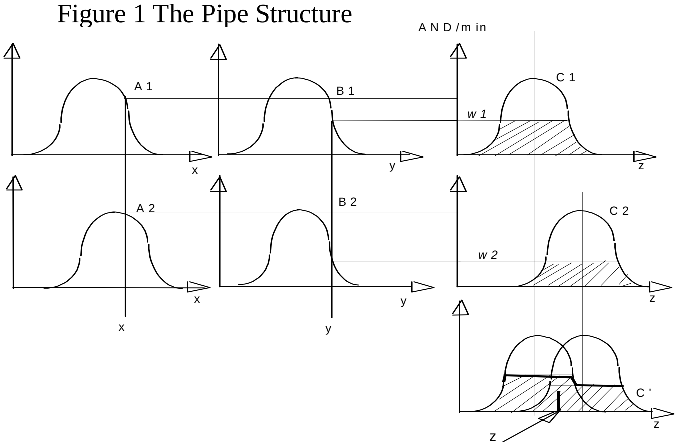


Figure 2 Fuzzy Inferencing; Mamdani Type

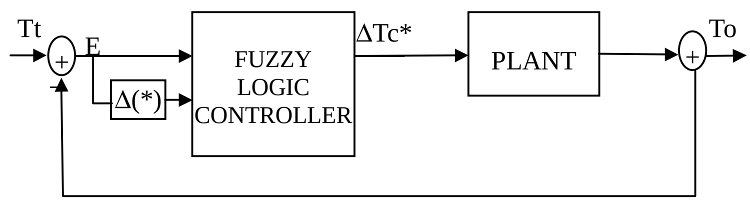


Figure 3 System Block Diagram

Table 1 Look Up Table

		ERROR CHANGE		
		N	Z	P
ERROR	N	ΔTc: NVB RULE-1	ΔTc: NB RULE-2	ΔTc: N RULE-3
	Z	ΔTc: Z RULE-4	ΔTc: Z RULE-5	ΔTc: Z RULE-6
	P	ΔTc: P RULE-7	ΔTc: PB RULE-8	ΔTc: PVB RULE-9

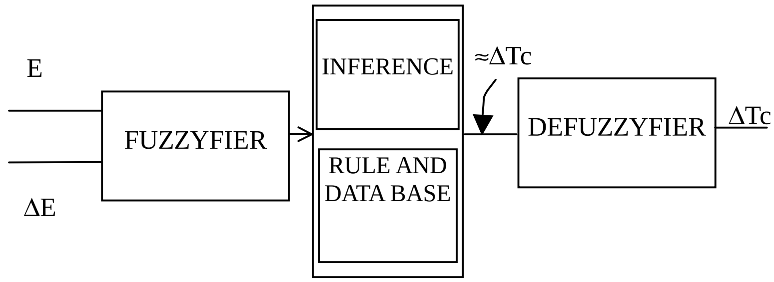


Figure 4 F.L.C. Block Diagram

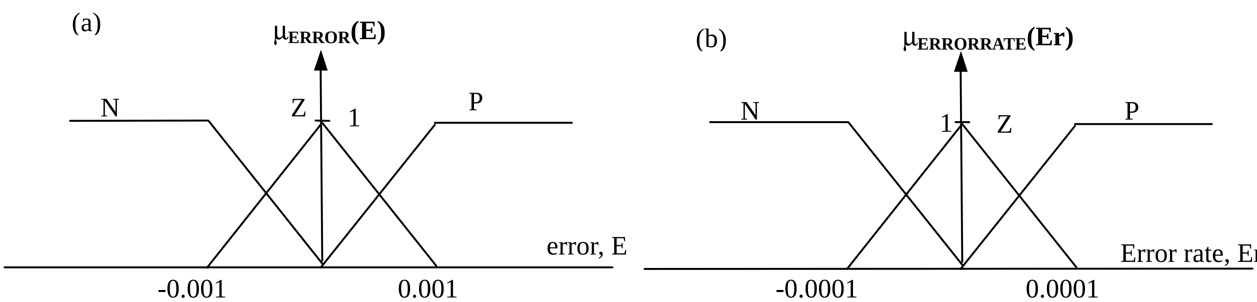


Figure 5 Input Membership Function: a) Error b) Error change

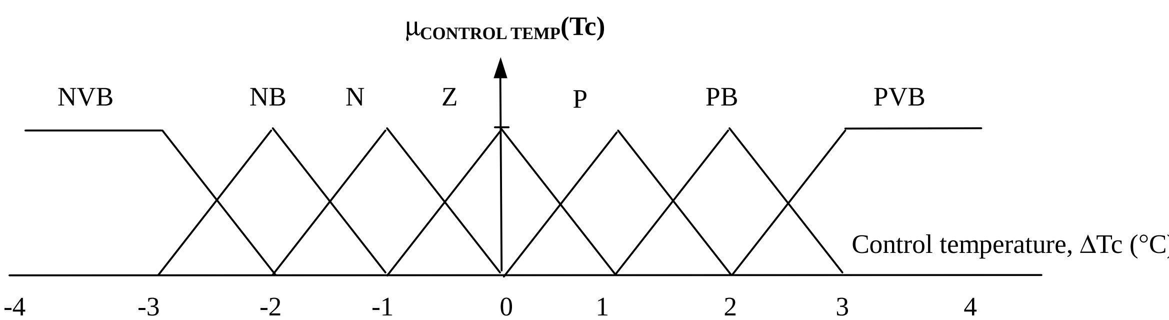


Figure 6 Output Membership Function (normalized by 4/0.0047)

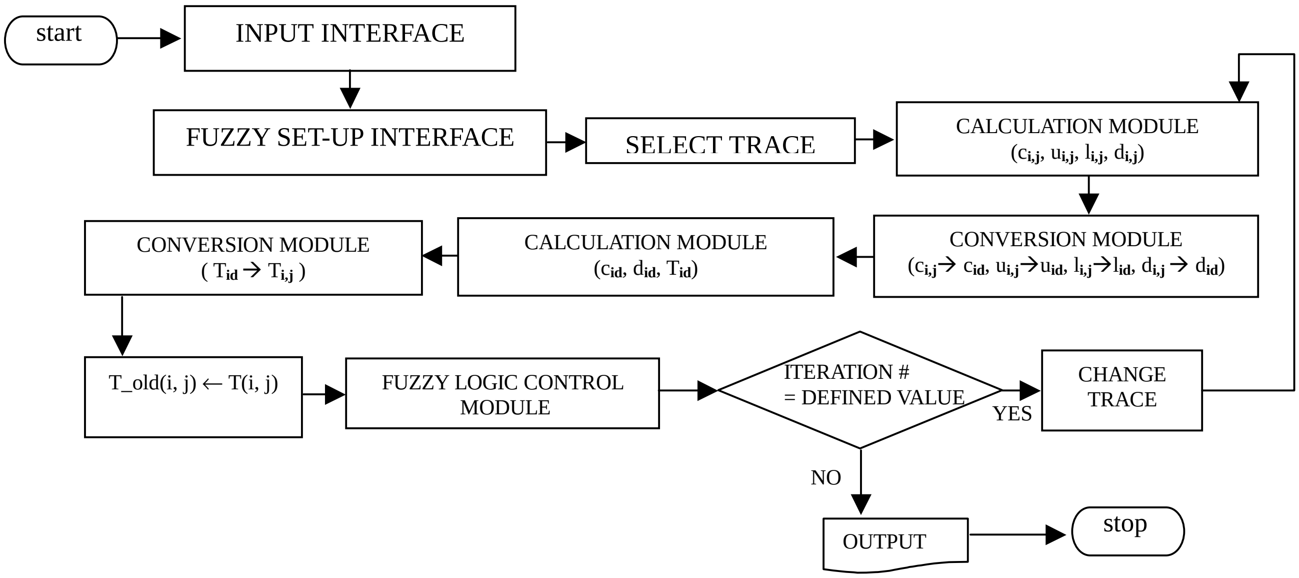
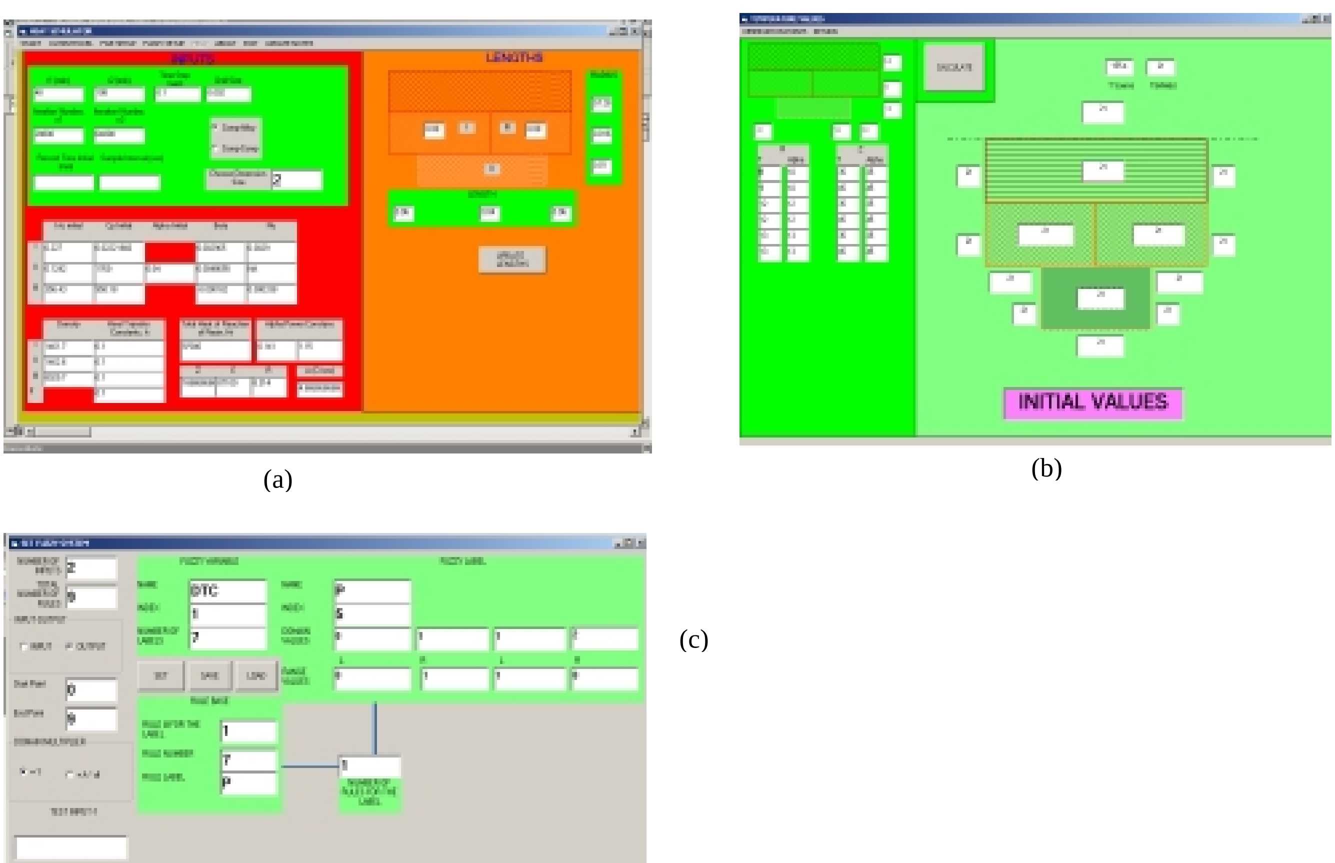


Figure 7 Flowchart of the Algorithm



(a)

(b)

(c)

Figure 8 User Interface of The Heat Control Simulator: a and b) Input Screen c) Fuzzy System Set-up Screen

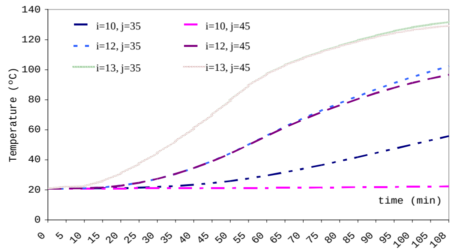


Figure 9 Radial Temperature History of Prepreg Curing Process without Control

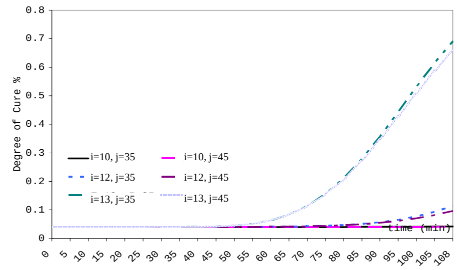


Figure 10 Radial Degree of Cure of Prepreg on Alloy and Composite Pipe without Control

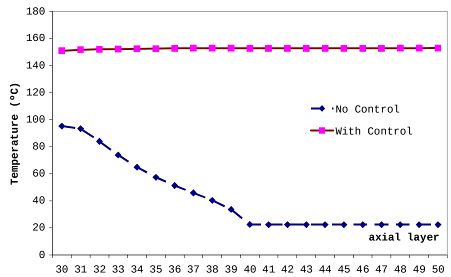


Figure 11 Comparison of Temperature Distribution at the Joint Interface with and without control

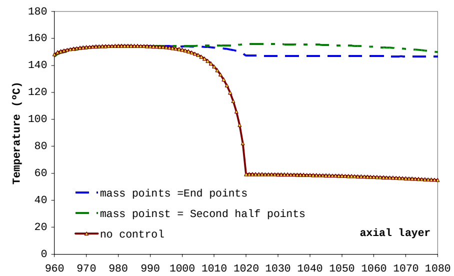


Figure 12 Comparison of Temperature Distribution at the Joint Interface with and without control for a Larger Size

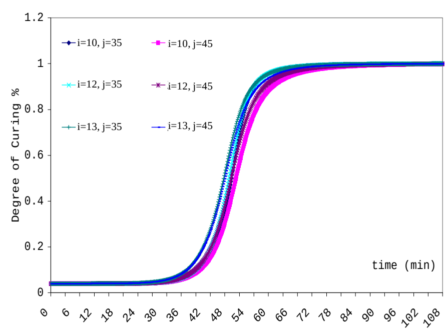


Figure 13 Radial Degree of Cure of Prepreg on Alloy and Composite Pipe For a Large Size Pipe with Control

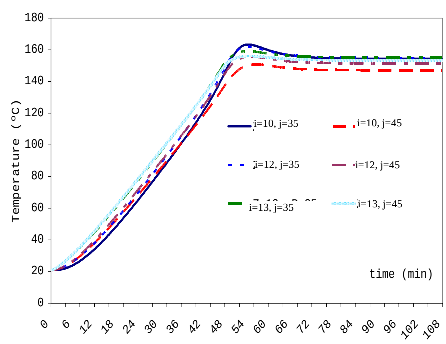


Figure 14 Radial Temperature History of Prepreg Curing Process For a Large Size Pipe with Control

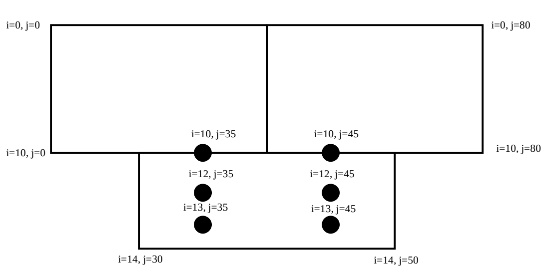


Figure 15 The Points for which the Temperature History and Degree of Curing Data are acquired