OPTIMIZATION TOOL FOR WELDING OF THERMOPLASTIC COMPOSITES

Darko Stavrov*, Giovanni F. Nino*, Harald E.N. Bersee*, Adriaan Beukers**
* Design and Production of Composite Structures, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS, Delft, The Netherlands,
**Fellow Doshisha University, Kyoto, Japan

Keywords: *process optimization, welding, thermoplastic composites*

Abstract

An optimization tool for determining the optimal process parameters for resistance welding of thermoplastic composites is presented in this paper. The optimization algorithm was developed on the basis of a transient thermal finite element model of the welding process. The thermal model assumes a homogeneous orthotropic thermal behavior of the composite material. Computed transient temperature profiles were used as an input for the optimization algorithm. The optimization algorithm was employed for automatic determination of the design space (optimal processing window). Processing windows for different welding configurations (different thickness of the heating element) were determined. Afterwards, an optimal power level was determined for all welding configurations considered and compared with data from an experimental study for validation. The results showed very good agreement, within 5% of the experimental data.

1 Introduction

Joining has proved to be a critical step in the process of manufacturing thermoplastic composite products [1] because it can initiate a number of irregularities in the structure that can result in weakening of its properties. Fusion bonding, also known as welding, is considered to be an ideal technique for joining thermoplastic composites [2]. It is a joining technique that uses their main characteristic, the possibility to be subsequently melted and cooled while retaining their properties, to form the joint. The welding process can be simply described as joining of two parts by fusing their contact interfaces, followed by cooling (consolidating) under pressure, which enables the bond to be made [3].

From the large amount of available welding techniques, resistance welding is considered to be one of the most promising [4]. The heat to the interface is provided by electrically resistant heating element that remains trapped in the joint after the welding. The main advantages of the resistance welding are very simple, low cost tooling [5] and little or no surface treatment [6]. The fact that the heating element remains in the weld offers the possibility of reprocessing if inspection shows flaws or incomplete bonding [6, 7].

Modeling the process of resistance welding is of essential importance for the rapid development and optimization of the process. Modeling becomes an indispensable step in determining the optimal values of the process parameters, improving by that the efficiency of the process and reducing the high costs of experimental testing procedures [4]. Modeling the heat transfer is the first step in modeling the resistance welding process. Heat transfer models predict the temperature profiles in the welding stack, providing by that the input for further modeling of the consolidation, crystallization and the quality of the weld. Several heat transfer models were developed by various groups of researchers [8-12]. Although most of these models results were used for further modeling of the welding process, no study on optimization has been performed so far.

This paper presents an optimization tool for determining the optimal process parameters of the resistance welding process. The optimization procedure was developed on the basis of a transient thermal model of the welding process. The thermal model assumes a homogeneous orthotropic thermal behavior of the composite material. Computed transient temperature profiles were used as an input for the optimization algorithm. The optimization procedure started with an automatic determination of the design space, the optimal processing window. Processing windows for different welding configurations (thickness of the heating element) were determined. Afterwards, an optimal power level was determined for all welding configurations. The results of the optimization procedure were compared with the results from an experimental study and showed very good agreement, within 5% of the experimental data.

2 The Optimization Tool

2.1 The Optimization algorithm

The optimization algorithm was developed on the base of the 2D thermal model [13]. Schematic view of the optimization procedure is shown in Fig. 1. The procedure starts with the input of a desired geometry and the material properties to be used. This information is used to define the welding parameters and welding geometry (e.g. welding width, heating element material and dimensions, power input) that are used as input parameters for the thermal model. Standard lap shear geometry with heating elements with different thickness was used in this study.

The material properties and the assembly strategy are also used for extracting the physical constraints used for the processing window and the optimization calculations. These constraints are polymer melting temperature, polymer degradation temperature, maximum available power for welding and maximum processing time allowed. It is also possible to introduce some safety factor values for the time and the temperatures. The output of the FEM simulations is used to identify the welding processing window as well as for further process optimization. In this study, processing windows for glass reinforced polyetherimide (GF/PEI). The determined processing window was used as a design

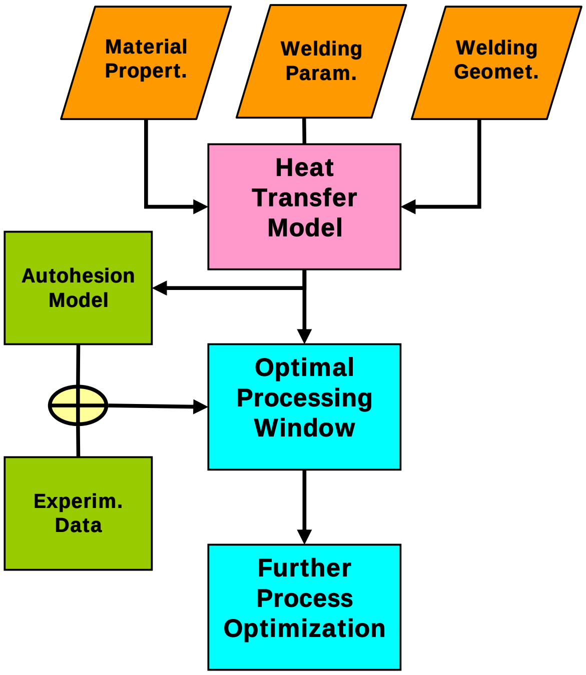

Fig.1. Flow diagram of the optimization procedure

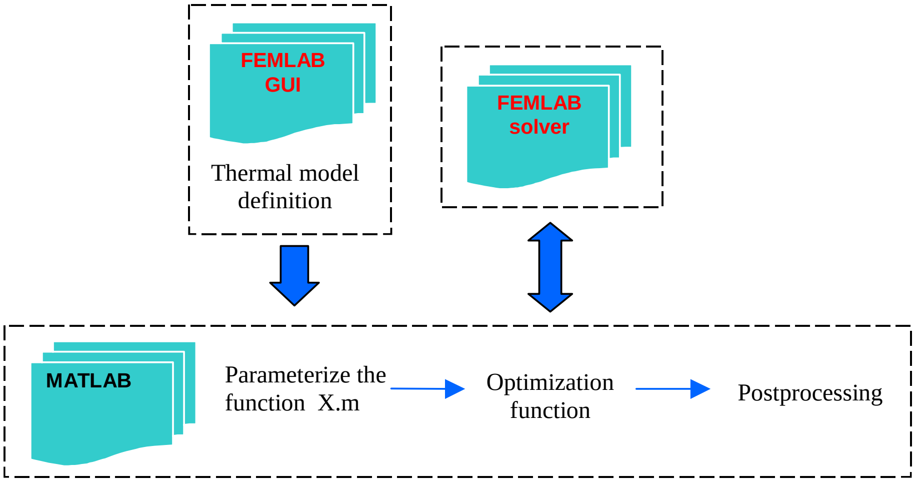

Fig. 2. COMSOL/MATLAB interaction process

space for further optimization of the welding process using heating elements with different mesh thickness and a number of empirical design constrains (processing temperature, dwell time, maximal reached temperature). The goal of the optimization step was to determine the power input for different mesh thickness for a given dwell time (above process temperature of 320°C) and to check for the maximum temperature reached in the weld.

The possibility for integration between COMSOL Multiphysics and MATLAB software packages was fully utilized for the computational simulations. The geometry of the 2D thermal model created in COMSOL was parameterized in MATLAB, which optimization toolbox was used to feed back the Multiphysics FEM models. The process is schematically shown in Fig. 2.

2.2 The Thermal Model

A two-dimensional finite element heat transfer model was used to perform the optimization of the welding process [13]. The finite element model was generated, solved and post-processed using COMSOL Multiphysics, version 3.3. Standard built-in meshing routine used for meshing the geometry gave results with satisfactory accuracy. The geometry of the model was based on the standard lap shear specimen welding configuration that was also used for obtaining the experimental data, schematically shown in Fig.3. Thermal symmetry was used to minimize the computational time, which resulted in the model geometry representing one fourth of the global one. The heating element was modeled as a homogeneous and isotropic stainless-steel stripe, and the heating was assumed uniform.

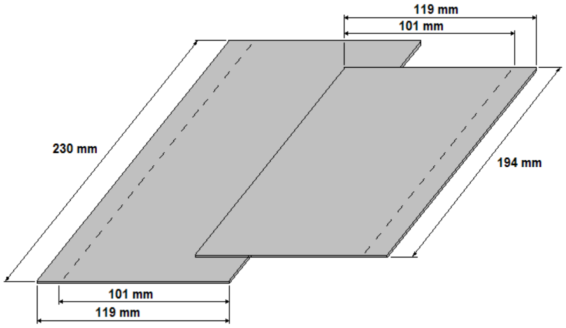

Fig. 3. Geometry of the welded specimen

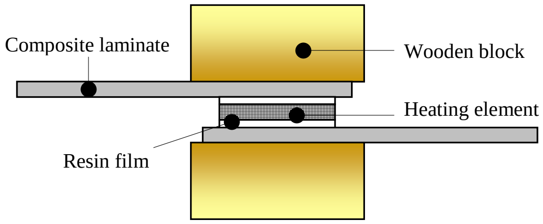

Fig. 4. 2D geometry of the welding stack

The Joule heating within the heating element was simulated as a volumetric heat generation correspondent to the applied input power level. The neat resin film (0.1 mm thick) used for impregnating the heating element was modeled as a separate layer of isotropic material. The composite laminates were assumed homogeneous and orthotropic. The longitudinal and transversal heat transfer coefficients

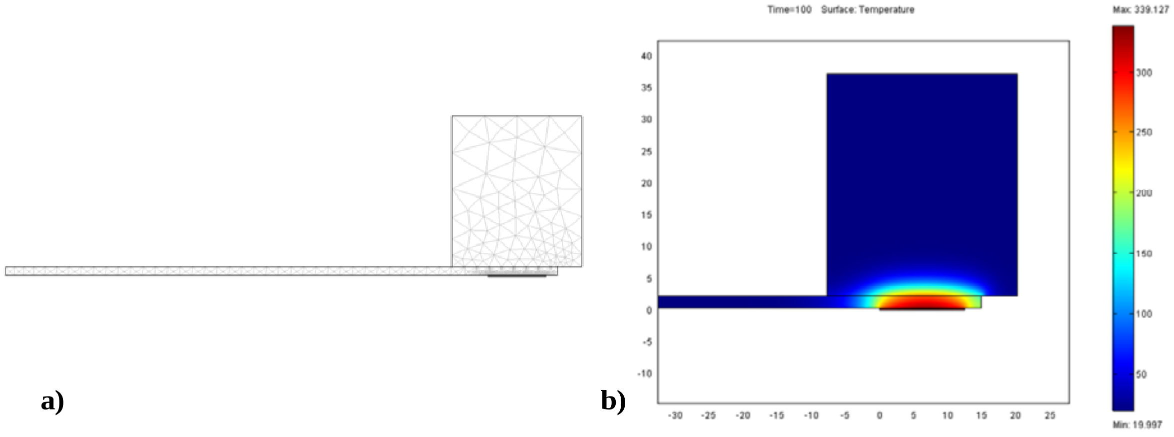

Fig. 5. a) FEM discretization mesh for the thermal model; b) 2D thermal model of GF/PEI specimen

were computed using the rule of mixtures.

From a heat transfer point of view, the resistance welding process is a typical heat conduction process. The convection and radiation heat transfer modes are present only on the boundaries. At the planes of symmetry a thermal insulation (zero heat flux) condition was applied. Convective losses were assigned to the areas of the welding stack and the heating element that were exposed to the environment. The convective losses to the environment were modeled as free convection to the ambient air, with a convective heat transfer coefficient of 5 W/m^{2}K and constant ambient temperature of 21°C. The constant volume heat generation was applied at time zero with a smoothening term in the first two seconds in order to simulate the start of the process more realistically.

The geometry of the modeled welding stack is depicted in Fig. 4. Figure 5 a) shows the FE discretization mesh for the 2D thermal model that consisted of 1980 triangular elements. In order to reduce the computational time further, fine mesh was used only in the vicinity of the heating element and the heat affected zone of the laminate. A computational iteration for a GF/PEI specimen with a heating mesh thickness of 0.4 mm, welded at P=66 KW/m^2 for 100 seconds, is shown in Fig. 5 b).

3 Process Optimization

The optimization procedure was performed in two steps: in the first step the theoretical optimal processing window (design space) was determined, and in the second step optimal process parameters (power input) for heating elements with different thickness were determined using the above described optimization algorithm.

3.1 Determining the processing window

The theoretical processing window was determined by running the finite element simulation for a range of power levels and filtering the computed data according to manufacturing and material constrains. The results from a full run of the finite element simulation for the welding configuration are shown in Fig. 6. The red line denotes the points in time when the melting temperature of the PEI matrix was reached for each power level, while the green line denotes the points of 10 sec of residence time above the melting temperature. This was the manufacturing constrain used as a left boundary of the processing window. The right boundary was set at the maximum allowed process temperature for the material, in this case the degradation temperature of the PEI matrix (440°C). The upper and lower boundaries were set by the limits of the power equipment and the reasonably acceptable welding time (120 seconds) respectively. The final processing window for the welding configuration is shown in Fig. 7. Processing windows for GF/PEI configurations with different heating element thickness were determined. The results were used as an input for the second step of the optimization procedure.

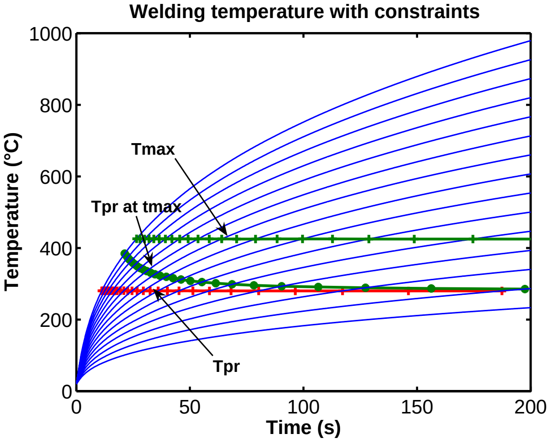

Fig. 6. Temperature profiles for CF/PPS

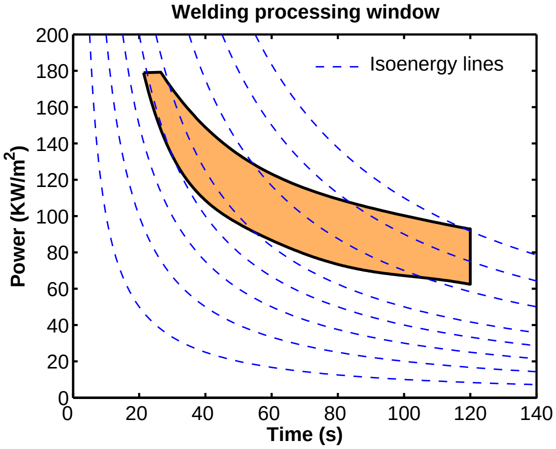

Fig. 7. Optimal processing window for the modeled welding configuration

3.1 Determining the optimal processing parameters

In the second step of the optimization procedure, the goal was to optimize the process parameters for heating elements with different thickness using their processing windows

Table 1. Comparison of the experimental data and the results from the optimization

Mesh thickness [mm]	*Experimental data*			*Optimization results*		
	Dwell time [sec]	*Max. temp. [°C]*	*Power [KW/m^2]*	*Dwell time [sec]*	*Max. temp. [°C]*	*Power [KW/m^2]*
0.70	10	330	70	10	333	67
0.40	20	335	65	20	346	66
0.28	9	330	60	10	333	62
0.06	18	340	58	19	346	60

determined in the first phase of the optimization procedure as a design space. Experimental data from a previous study [14] were used for validation of the results. For that reason, the choice of the heating elements thickness and design constraints in the optimization algorithm was made according to those used in the experimental study.

Four different heating elements were modeled, with thickness that ranged between 0.06 and 0.7 mm. Main design constraint was the so-called dwell time (the period the temperature at the weld interface was above processing temperature of 320°C), that was varied between 10 and 20 seconds, according to the experimental data. The optimal power level for each of the heating elements was determined using the optimizing algorithm. Additionally, maximal temperature in the weld was checked and compared to the maximal temperature reported in the study. The maximal temperature limit was set at the maximum allowed process temperature for the PEI matrix, 440°C.

The results of the process optimization for all different heating elements, compared with the experimental data are shown in Fig. 8. Complete results, including the comparison of the maximal temperatures in the weld are given in Table 1.

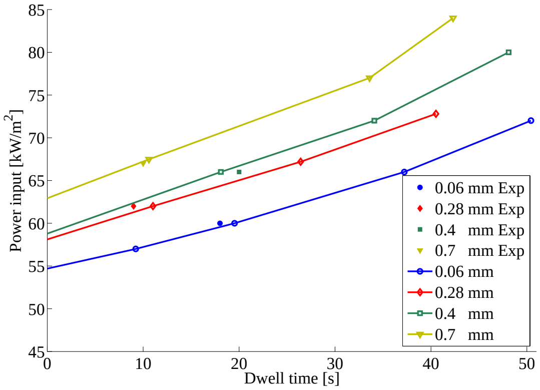

Fig. 8. Optimal power levels, compared to experimental data

The results showed very good agreement with the experimental data. Optimal power levels determined using the optimization algorithm were within 5% of the experimentally determined power levels. The same applies for the maximal temperature in the weld.

As a consequence of the lower absolute resistance of the coarser heating elements (with larger mesh thickness), the optimal power levels of the coarser heating elements were shifted towards higher energy levels. This effect was also clearly present in the results of the optimization procedure, due to the flexibility of the optimization algorithm that offers the possibility to vary the process parameters and the welding geometry simultaneously.

4 Conclusions

A novel tool for optimization of the process of resistance welding of thermoplastic composites was presented in this study. The optimization tool was based on a transient finite element thermal model that computed the temperature data used in the optimization procedure.

Optimization of the power input was performed for four heating elements with different mesh thickness. In the first optimization step, the optimization tool was used to automatically create theoretical processing windows for the different welding configurations. In the second step, optimization of the power input was performed for all heating elements, using the results from the first step as an input and experimentally determined design constraints.

The results showed very good agreement with the experimental data. Due to its flexibility, the optimization algorithm was able to describe the affect of the mesh thickness on the optimal power level.

References

[1] Don R.C., Bastien L., Jakobsen T.B. and Gillespie Jr. J.W. "Fusion bonding of thermoplastic composites by resistance heating". *SAMPE Journal*, Jan-Feb., pp 59-66, 1990.

[2] Eveno E.C. and Gillespie Jr. J.W. "Resistance welding of graphite polyetheretherketone composites: an experimental investigation". *Journal of Thermoplastic Composite Materials*, No.1, pp 322-38, 1988.

[3] Stavrov D. and Bersee H.E.N. "Resistance welding of thermoplastic composites-an Overwiev". *Composites Part A*, Vol. 35, pp 39-54, 2005.

[4] Ageorges C., Ye L. and Hou M. "Advances in fusion bonding techniques for joining thermoplastic matrix composites: a review". *Composites Part A*, Vol. 32, pp 839-57, 2001.

[5] Xiao X.R., Hoa, S.V. and Street K.N. "Repair of thermoplastic resin composites by fusion bonding. Composites Bonding". *ASTM STP*, 1227, pp 30-44, 1994.

[6] Lambing C.L.T., Don R.C., Andersen S.M., Holmes S.T., Leach B.S. and Gillespie Jr. J.W. "Design and manufacture of an automated resistance welder for thermoplastic composites". *Proceedings of ANTEC '91*, pp 2527-31, 1991.

[7] Ageorges C., Ye L. and Hou M. "Experimental investigation of the resistance welding for thermoplastic-matrix composites. Part I: heating element and heat transfer". *Composites Science and Technology*, Vol. 60, pp 1027-39, 2000.

[8] Maffezzoli A.M., Kenny J.M. and Nicolais L. "Welding of PEEK/Carbon Fiber Composite Laminates". *SAMPE Journal*, Vol. 25, Nr. 1, pp 35-39, 1989.

[9] Jakobsen T.B., Don R.C. and Gillespie Jr. J.W. "Two-dimensional Thermal Analysis of Resistance Welded Thermoplastic Composites". *Polymer Engineering and Science*, Vol. 29, No. 23, pp 1722-29, 1989.

[10] Xiao X.R., Hoa S.V. and Street K.N. "Processing and Modelling of Resistance Welding of APC-2 Composite". *Journal of Composite Materials*, Vol. 26(7), pp 1031-49, 1992.

[11] Holmes S.T. and Gillespie Jr. J.W. "Thermal Analysis for Resistance Welding of Large-scale Thermoplastic Composite Joints". *Journal of Reinforced Plastics and Composites*, Vol. 12, pp 723-36, 1993.

[12] Ageorges C., Ye L. and Hou M. "Characteristic of resistance welding of lap shear coupons. Part I: Heat transfer". *Composites Part A*, Vol. 29A, pp 899-909, 1998.

[13] Stavrov D. and Bersee H.E.N. "Thermal analysis of resistance welding of thermoplastic composites". *Proceedings of ICCM-15*, Durban, South Africa, 2005.

[14] Stavrov D. and Bersee H.E.N. "Resistance welding of thermoplastic composites-the influence of the metal mesh heating element". *Proceedings of SAMPE Europe*, Paris, 2007.