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Numerical analysis of thermoplastic composites laser welding using ray tracing method

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ABSTRACT

Laser technology is a good alternative for continuous joining of thermoplastics composites structures. Presence of continuous fibers at a high fiber volume fraction (superior to 30%) does not allow using traditional development as for pure thermoplastic materials, due to the presence of fiber clusters or polymer rich areas. Those heterogeneities induce macroscopic light scattering through the structure, reducing the resulting energy level absorbed at the welding interface. The study proposed here takes into account the real microstructure of the composite in order to evaluate changes in local energy diffusion directly linked with local fiber arrangements. The objective of this work is to develop an affordable numerical simulation of the laser welding process modeled with adapted physics mechanism and taking into account the microstructure heterogeneity of the considered materials regarding optical and thermal properties. To model the optical path of the laser beam through the composite fibrous structure, a simulation tool based on geometrical optic is developed. Weldability is considered on composites with different thicknesses, showing the non linear relationship between welding energy and substrate thickness.

1. Introduction

Thermoplastic composites offer the possibility to use welding techniques for joining [1]. Laser welding applications are well spread among metallic industry and pure thermoplastic parts manufacturing. Due to recent developments of continuous fibers thermoplastic composites parts, investigation on the ability to weld is conducted here. Continuous fiber reinforced thermoplastic composites (CFTP) have been introduced as structural materials for high performance applications. Complex part shapes and/or weld seam geometry can be envisaged, and it overcomes the environmental difficulties related to existing gluing processes. In this study we propose to develop numerical tools in order to optimize [2] the laser welding process. Thermal composite properties depend on individual components properties they also depend on the relative constituent arrangement. As a result, the real fiber architecture of the composite should be taken into account at the microscopic (or fiber of ∅20 μm) level to evaluate macroscopic properties. This heterogeneous microstructure induces laser beam diffusion during transport through the semi-transparent substrate. The macroscopic diffusion observed is the result of the refraction occurring at the microscopic level at each fiber/matrix interface.

2. Thermal properties of composites parts during welding

Laser welding interacts at the local level on the structures, and the thermal aspects are to be considered at meso-scale [3]. Thermal properties of the materials forming the composite are different, a factor around 4 exits between resin and fibers conductivity for instance. Moreover, the final composite thermal properties also depend on the spatial organization of its constituents, resulting in anisotropic macroscopic effective properties. A numerical approach is conducted in order to evaluate local thermal properties and solve the thermal energy balance equation (Eq. (1)) for laser application [4,5].

$$\rho^c C_p^c \frac{dT}{dt} = \nabla \cdot (k^c \nabla T) - \nabla \cdot q_r \qquad (1)$$

ρ^c, C_p^c, k^c are respectively the composite density, heat capacity and thermal conductivity that depend on ρ^i, C_p^i, k^i; $i = m, f$ the corresponding thermal properties of the matrix (m) and of the fibers (f). This approach is derived from homogenization techniques on granular media for soil mechanic, by considering that transverse

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representation of a fibrous media in 2D can be represented by an assembly of circles. The corresponding 3D structure is obtained by extrusion of the generated 2D geometry. These granular random structures can also be periodized. Sab and Nedjar show that periodic homogenization converges more rapidly on the RVE size than homogenization of a random medium [6]. Using this result it is possible to use a periodic representation of a random microstructure (Fig. 1) while keeping the information brought by the structure randomness. In order to be able to do so, the considered cell size must be large enough. In the case of the microstructure represented in Fig. 1, if a single fiber is placed in the periodic cell, the resulting microstructure becomes in-plane orthotropic whereas the original organization is isotropic. Convergence in random media may only be reached on large RVE, this RVE possibly ending in a RVE bigger than one or more dimensions of the structure itself. As a result, random media homogenization techniques should not be applied at meso-scale. Moreover, numerical homogenization on large RVE (several thousands of fibers or considered geometries) requires large and consuming meshes of million elements. In the case of unidirectional fiber architecture, the reasonable assumption that all fibers are aligned will be taken during this work in order to reduce the generated structure to 2D space, thus extruded to have the 3D microscopic representation. A UD fibrous structure organization can be represented by a stationary random process and it can be periodized by using Voronoï [7] and Delaunay [8] developments. Other material properties can be derived directly from the fiber volume fraction determination. For laser modeling, the parameters of interest are the parameters influencing heat transfer in the part, which are the material density, the heat capacity and the heat conduction coefficient (Eq. (1)).

Material density is obtained from a simple and exact rule of mixture, as this property is only dependant on the component volume fraction and not about their space arrangements. On the other hand, heat conductivity is dependent on the arrangement of fibers. Meaning that for a same volume fraction but different fiber diameters, heat conductivity coefficient may vary. A numerical determination of the thermal conductivity coefficient is developed to determine the influence of the fibrous architecture, according to the following steps to create a periodized random microstructure:

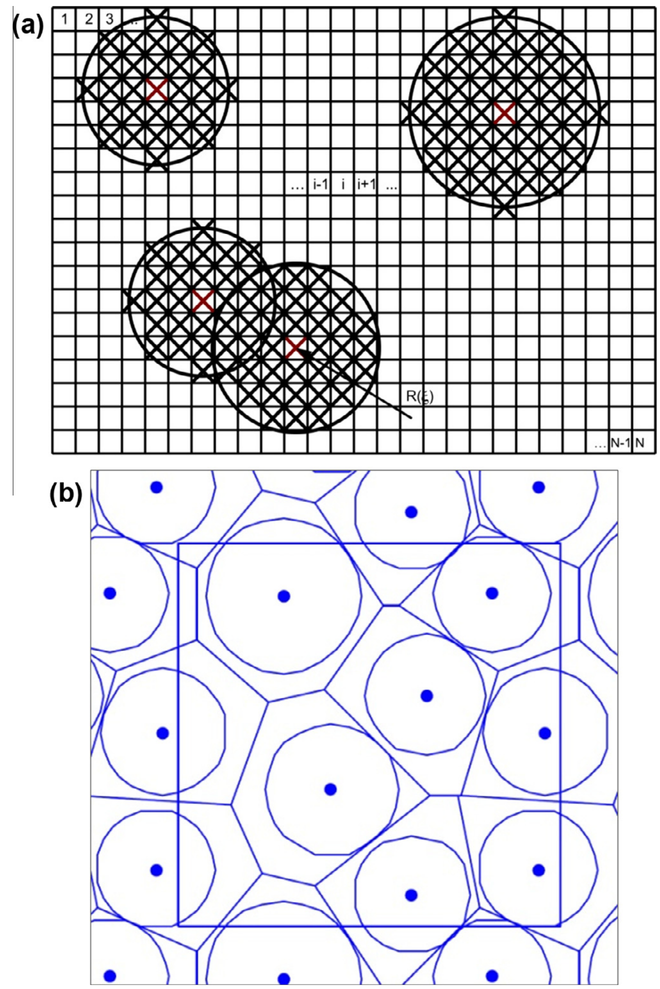

Fig. 2. (a) Grid used to define Voronoï cell centers and (b) Voronoï diagram representation (reduced representative periodic cell).

2.1. Creation of the reference grid

An original file with the maximum fiber count (up to 60%) is created. Microstructure is generated by choosing randomly each fiber center location and diameter. The 2D fiber cross section space is divided in pixels with the desired fineness. A convergence study shows that the grid fineness definition have little influence on calculation time for periodic cell definition. Likewise, the grid size is not coupled with FEM mesh size. Those pixels then represent a grid for possible fiber centers. The possible location coordinates are stored in a vector. A calculation loop chooses randomly one center coordinate and remove the neighboring centers from the location vector according to an influence sphere defined from the desired fiber aspect ratio, as illustrated in Fig. 2a. The aspect ratio is the fiber diameter over the representative cell length. Another center is chosen and so on until no more coordinate remains available. In order to generate a periodic cell, the described sequence is conducted on a 3×3 arrangement of identical grids. This way, when the influence sphere crosses over the grid border, it is then consider on the other side of the grid.

Fig. 1. UD composite microstructure, transversally to fiber direction. Average fiber diameter is 18 μm.

2.2. Creation of the reference cell

Using Delaunay triangulation to separate the representative cell in fiber domains, and Voronoï diagram to define the resulting fiber diameter, a periodic representative cell is drawn. Example of Voronoï diagram and resulting representative cells are given in Fig. 2b.

2.3. Temperature field modeling

The representative cell is then imported and discretized under COMSOL Multiphysics. A periodic heat flow is then imposed, setting the fiber material parameters in the fiber regions and the polymer material parameters in the space between the fibers. Periodic Dirichlet boundary conditions are then imposed to generate a temperature gradient. The homogenized representative cell material parameters are then deduced from calculating the heat flux to temperature gradient over the domain. For plane thermal properties determination, 3 equations with 3 unknown coefficients ($k_{11}, k_{22}, k_{12}k_{11}, k_{22}, k_{12}k_{11}, k_{22}, k_{12}$) have to be solved (Eq. (2)).