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Effect of the developed temperature field on the molecular interdiffusion at the interface in infrared welding of polycarbonate composites

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A B S T R A C T

In this study, the effects of the welding temperature field developed during the infrared assembly process on the joining properties of glass fiber reinforced polycarbonate/unreinforced polycarbonate with carbon black were investigated. The temperature field and the contact time govern together the quality of the adhesion at the welding interface. The effect of the semi-transparent glass fiber reinforced polycarbonate composite/unreinforced polycarbonate composite with carbon black interface was quantified in term of quadratic distance of diffusion or diffusion depth through the welding interface. First, an experimental setup for the temperature measurement was performed using infrared camera, during infrared welding of materials joints. Then, numerical simulations using commercial FEM software COMSOL Multiphysics® allows simulating the temperature field by implementing a developed 3D heat source, in order to determine the generated heat source at the welding interface and the variation of the temperature field during the infrared welding process. The microstructural characterizations were investigated in order to inspect the welding zones quality and to observe their failure modes. The diffusion theory has then been applied to calculate the variation of the quadratic distance of diffusion versus time at different locations. The complete self-diffusion is supposed occurring only at temperature above the polycarbonate glass transition temperature (140 °C) and with a quadratic distance of diffusion superior to the mean square end-to-end distance. At the welding interface, the calculation of the quadratic distance of diffusion showed that a complete self-diffusion has not yet been reached. A perfect cohesion was not established.

1. Introduction

Our previous studies [1–3] investigated a global analytical model (refraction and absorption phenomena) for modeling of transmission laser/infrared welding process in thermoplastic composites. This model allows describing the attenuation of laser beam, the prediction of heat source in laser welding process thermal simulation in the case of UD thermoplastic composite as well as the evolution of the three dimensional temperature field during the welding process.

The part performances in the case of the association of two or more materials depend not only of the own properties of each material but also on their interface and/or interphase properties directed by the assembly process (thermal or chemical assembly). In the case of melted assembly of miscible thermoplastics (thermal welding or co-molding processes), the polymer adhesion will be considered depending of the contact time, the surface wettability and chain diffusions [4,5].

More than one mechanism contributes to the adhesion of polymers. The mechanical adhesion, the electrical theory, the

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Nomenclature

D	Self-diffusion (m^2/s)
ρ_v	Density (kg/m^3),
x,y,z	Space variables
T	Temperature (°C)
I_o	Laser power (W)
r_{spot}	Initial laser beam radius (m)
σ_o	Spatial shape parameter of the initial laser beam (m)
σ_x	Scattering standard deviation (m)
A	Optical scattering coefficient of the semi-transparent composite (m^{-1})
K	Absorption coefficient (m^{-1})
α_a	Absorption factor of the absorbent composite
ρ_a	Reflection coefficient of the absorbent material
ρ_t	Reflection coefficient of the semi-transparent material
I(x,y)	Surface laser beam power at the interface (W/m^2)
Q(x,y,z)	Heat source (W/m^3)
ρ_λ	Reflectivity coefficient
$\underline{\underline{k}}$	Orthotropic thermal conductivity tensor (W/m.K)
ρ_v	Density (kg/m^3),
h_c	Convection heat transfer coefficient (W/m^2 K)
h_r	Radiative heat transfer coefficient (W/m^2 K)
T_0	Ambient temperature
ε	Material emissivity
σ_b	Black body emission coefficient (5.67×10^{-8} W/m^2 K^4)
R	Virtual gas constant (g/mol.K)
M_e	Molecular weight of entanglement (g/mol)
M_c	Critical molecular weight (g/mol)
M_w	Molecular weight (g/mol)
η_0	Newtonian viscosity (Pa.s)
η_{0,M_c}	Viscosity at the critical molecular (Pa.s)
R_g	Mean square end to end distance of the chain (m)
G_N^0	Plateau modulus (Pa)
l^2	Quadratic distance of diffusion (m^2)
T_g	Glass transition temperature (°C)
PC	Polycarbonate
CB	Carbon black
t	Time (s)
d_t	Semi-transparent part thickness (m)

wettability model, the diffusion or inter-diffusion model, the chemical link theory are generally used to explain the polymer adhesion, each of them being applicable in a specific domain depending of the nature of the welded polymers and the assembly conditions [5,6].

In the case of the adhesion of two miscible polymers, the total melting of the whole surface is necessary for the development of the diffusion mechanism [7,8]. The adhesion is then characterized by molecular chain entanglement. The molecular aspect at the interface during the diffusion can be described by the reptation model developed by De Genne [9,10] or by the simplified model of the minor chain [11,12] (Fig. 1).

At the origin ($t = 0$) the molecular contact is achieved at the interface, the reptation of the chain end segments can start ($t = 1$), at $t = 2$ only the minor chains contribute to the interdiffusion, finally when the time is close to the reptation time or relaxation time, the chain entanglements are achieved.

Finally the adhesion by interdiffusion or self-diffusion is based on two fundamental criteria: the thermodynamic criterion, in other words the polymer miscibility and the kinetic criterion directed by the molecule mobility depending on the temperature, the contact time, the pressure, the nature and molecular mass of the polymers [7,13,14]. This concept of interdiffusion widely described in the case of co-extrusion process, can also be considered as the illustration of thermoplastic welding at molecular level [15–17]. The weld strength develops as the polymer chains diffuse across the interface and lasts up to the reptation or relaxation time according to the schematic representation illustrated in Fig. 2 [11].

The theory of healing has been extensively studied by Wool and

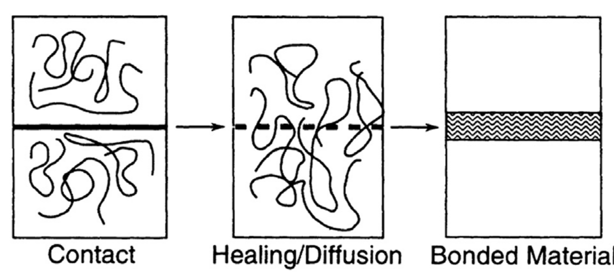

Fig. 2. Steps involved in fusion bonding of thermoplastic surfaces [11].

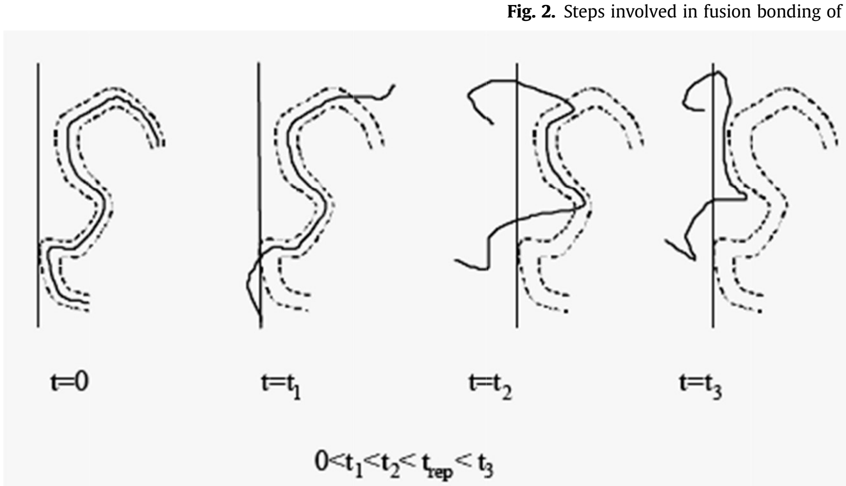

Fig. 1. Diffusion of polymer chains across the interface (reptation theory) [9,10].