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RESEARCH REGARDING MODELING OF THE PROCESS PARAMETERS FOR MICRO-INJECTION MOULDING OF POLYMERIC MICRO-COMPOSITES

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Abstract: *Miniaturization represents a significant and remarkable trend in the worldwide progress of manufacturing technology. Polymeric micro-composites offer a wide range of properties that can be chosen according to the functional necessities. Polymeric micro-composites represent composites with polymeric matrix and submicron fibers with high aspect ratios or fine hollow spheres as reinforcing element. The successful development of such new micro-composites devices is highly dependent on manufacturing systems that can reliably and economically produce large quantities of micro-components. In polymer micro-manufacturing technology, software simulation tools provide useful assistance for the optimization of moulding tools, mould inserts, micro-component design, and process parameters. Research aims the simulation and optimization of injection moulding process parameters of polymeric micro-composites using advanced software tools. This paper analyze phenomena that occurring during the injection process: temperature field, injection pressure, cooling and injection cycle time. Using these results are obtained reduced part cost, increased part accuracy, improved cycle times and opportunity to achieve isotropic products made from polymeric micro-composites.*
Keywords: *polymeric micro-composites, micro-injection moulding, miniaturization, process parameters.*

1. INTRODUCTION

The development of thermoplastics composites reinforced with short fibers has enlarged the applications of polymeric materials, especially in devices that need high performance and good surface appearance. Micro-composites represent composites employing submicron fibers with high aspect ratios, or fine hollow spheres or fibers for reinforcement. During the last few years, polymer micro-composites have attracted significant interest, due to market demands. They represent a new class of composite materials containing dispersion of micrometric size particles in a polymer matrix. The micro-injection moulding of polymeric micro-composites (MIM-PMMCs) is a well established technique for production of automotive and aerospace components. During injection, fiber orientation remains mostly unchanged, which allows for a good control of the mechanical properties of the part. The relativity low viscosity of thermosets allows for a low injection pressure and a good wetting of the reinforcement. The resin and the mold can be heated before injection in order to accelerate mold filling by optimizing the viscosity of the resin. It is a method which offers good repetability combined with low costs and the ability to produce complex components which would otherwise be impractical. The development of new micro devices is dependent on manufacturing systems that can produce reliable and economic, micro-components in large quantities. An example of polymeric micro-composite (PMMCs) is presented in figure 1.

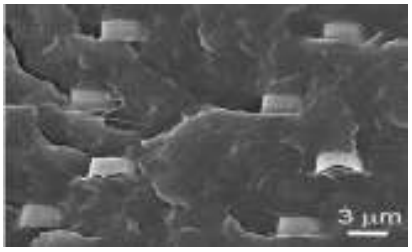

Figure 1: Polymeric micro-composite [7]

2. REINFORCEMENTS CHARACTERIZATION OF POLYMERIC MICRO-COMPOSITES

2.1. Hallow glass spheres

Hallow microscopic spheres of chemically stable soda lime borosilicate glass are increasingly used in plastics compounds, for reinforcement and weight reduction of both thermosets and thermoplastics. They have a density of about one-fifth that of most thermosetting resins. For an equal weight, hallow spheres occupy about five times the volume of resin, so reducing the cost and weight of a compound. They can also produce/improve other useful properties, such as resistance to impact and thermal shock, and the finishing characteristics. They can be used in formulation for spray-up and casting, and in moulding compounds. A typical range runs from very low density (0.125 g/cm^3) with moderate pressure strength (17 bar) to moderate density (0.60 g/cm^3) with high pressure strength (690 bar). Other grades include 8 µm diameter boro-silicate spheres, which are white in colour and can be used at injection moulding pressures. The density of a typical range is 1.1 g/cm^3. On an equal weight addition would be (1.1/2.5)x100 or 44% by weight. [4]

Table 1: Compressive strength of hallow spheres [4]

Grade	True particle density (g/cm^3)	Median particle diameter (µm)	Isostatic compressive strength (bar)
K 1	0.125	65	17
K 15	0.15	60	21
K 20	0.20	65	34
K 22	0.22	35	28
K 25	0.25	55	52
K 32	0.32	40	140
K 37	0.37	40	210
K 38	0.38	40	280
K 46	0.46	40	420
S60/10,0000.125	0.60	30	690

2.2. Glass spheres-Solid spheres

Microscopic solid glass spheres added to a reinforced plastic compound give smoothness, hardness and excellent chemical resistance, with low oil absorption. The spheres lower the viscosity of most resin mix systems, acting as miniature ball bearings to improve flow. They can be used in combination with fibers and other particle shapes, reducing product defects. Precision geometry allows even dispersion, close packing and easy wetting out in the compound, four high filler loadings. High loadings add significantly to the dimensional stability of finished products, by reducing shrinkage and improving part flatness. High loadings can increase flexural modulus, abrasion resistance and surface hardness, and also improve stress distribution. [4]

Table 2: Typical size distribution of solid glass spheres [4]

	Mean	10%	50%	90%
A-glass(soda-lime)	219 µm	142	203	328
-ranging to:	11 µm	3	9	22
E-glass(boro-silicate)	26 µm	9	24	43
-ranging to:	18 µm	4	12	36

3. MATHEMATICAL MODEL OF POLYMERIC MICRO-COMPOSITES

The value of the results of numerical process simulation is highly dependent on the material models that are used. In the case of application of rapid curing resin systems, the exothermal chemical reaction and heat interaction between mould and part becomes important. Therefore new models to describe these phenomena were developed and are presented in this section, regarding: resin flow, kinetics of molded polymeric micro-composites, viscosity of molded polymeric micro-composites and heat transfer in the micromold.

3.1. Resin Flow

For microfiber impregnation Darcy's law [5], which describes the flow of a liquid through a porous medium is used:

$$v = -\frac{1}{\eta(T,\alpha)} K \cdot \Delta_p \quad (1)$$

The flow velocity vector v of the injected resin is depending on the viscosity η of the resin, which is highly dependent on the degree of cure α and the temperature T of the system. The second order tensor K depicts the permeability and p (atm) the pressure field. The permeability is heavily dependent on the porosity. Kozeny and Carman [4] found a relation between the fiber volume fraction v_F and the permeability:

$$K = \frac{R^2}{4c} \cdot \frac{(1-v_F)^3}{v_F^2} \quad (2)$$

where R is the fiber radius and c is the Kozeney-constant.

For the different zones of porosity the permeability can be determined by the relation of Kozeny-Carman in such a way that the effort for permeability measurements can be reduced. [5]

3.2. Kinetics of Molded Polymeric Micro-Composites

A new kinetic model is proposed for the numerical simulation of the curing reaction of rapid resin systems:

$$\frac{d\alpha}{dt}(T',\alpha) = A \cdot exp\left(\frac{-T_{kin}}{T'}\right) \cdot R(\alpha_{max}(T') - \alpha)^m \cdot \alpha^n \quad (3)$$

where T' is the temperature relative to the melting point T_m

$$T' = T - T_m \quad (4)$$

R is the ramp function

$$R(x) = \begin{cases} x, x > 0 \\ 0, x \leq 0 \end{cases} \quad (5)$$

$\alpha_{max}(T')$ is the maximum degree of cure, which is 0 at the melting point and converges to 1 with increasing process temperature, considering that the heat of reaction is not entirely during cross linking. The maximum degree of cure is expressed as:

$$\alpha_{max}(T') = 1 - exp\,(-\beta \cdot T') \quad (6)$$

The parameters A, T_{kin}, m, n and b have to be determined by a validation of the model by Differential scanning calorimetry (DSC) data. [5]

3.3. Viscosity of Molded Polymeric Micro-Composites

For a successful simulation –of the filling process in liquid composite molding, a viscosity model wich is dependent on degree of cure and temperature must be implemented. Under the assumption that the resin behaves like Newtonian fluid and is therefore independent of the share rate, the complex viscosity can be determined by the combination of the data from the isothermal DSC analysis and rheological measurements, without considering of share rate effects. Proposed new viscosity model (5):

$$\eta(T',\alpha) = \eta_\infty \cdot exp\left(\frac{T_{rheo}}{T'} + B \cdot \alpha\right) \quad (7)$$

where T' is the temperature difference to the melting point T_m (4). With the proposed modification the dependency of the model on temperature and degree of cure is much higher and fits therefore better to the data points of the experiments. The parameters η_∞, T_{rheo} and B have to be determined by a validation of the model by rheology and DSC data. [5]

3.4. Heat Transfer in the Micromold

Constant values for in plane and out plane thermal conductivity λ are used for heat transfer q.

$$q = \frac{\lambda}{t} \cdot \Delta T \quad \textbf{(8)}$$

where t is the wall thickness of the composite shell and ΔT is the temperature difference of the composite part to the mould. [5]

4. MICRO-MECHANICAL FINITE ELEMENT MODEL

4.1. Model set-up

The geometry, boundary conditions and loads applied on the "Finite Element" (FE) model used in the present work are shown in figure 1. The model represents a unit-cell of the micro-composite, with a layer of matrix sandwiched between two half-fibers. The choice of the present unit-cell has three important implications: (i) the initial misalignment of the fibers in the composite is uniformly distributed; (ii) the choice of the length L could affect the predictions; and (iii) up to initiation, the fibers deform in-phase. Regarding (i), the effect of various fiber distributions on kink-band formation has been studied by Kyriakides et al. and it was found that the distribution affects the value of the strength but does not change the formation process. The second (ii) implication results in a need to parametrically verify the influence of L, which is done below. For the third implication, it can be seen that the fibers at the kink-band tip, i.e. at initiation, deforms in-phase at a very small angle b to the y-axis. Below, it is verified that neglecting b does not change the predictions by comparing the results from the unit-cell model to a model containing 100 fibers. The periodic boundary conditions are applied on each side of the fiber as follows:

$$\forall x \in [0, L]: \begin{cases} u(x, y = d) = u(x, y = 0) \\ v(x, y = d) = v(x, y = 0) - U \end{cases} \quad \textbf{(9)}$$

where d and L are the height and length of the model. The constant U accounts for the transverse expansion caused by the compressive load. Shearing forces are applied at x = 0 and L. A compressive displacement is applied at x = L, while the displacements in the 1- direction are restricted at x = 0. For the compression step, the Riks algorithm is used such that potential snap-back or snap-through can be captured.

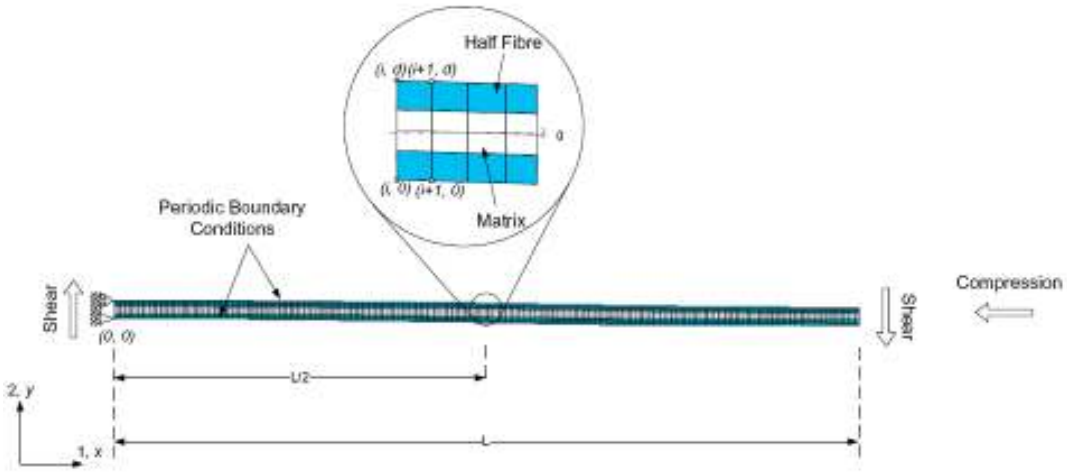

Figure 2: Micro-mechanical FE model: geometry, boundary conditions, and loading [7]

Plane stress (CPS4R) elements, with a 1 mm thickness, are used. The material properties for the baseline model correspond to those of the IM7-8552 system, which are reported in Table 3. The baseline model is used in the parametric study and unless stated otherwise. For this baseline model, a nonlinear elasto-plastic behavior is used for the matrix. The nonlinear shear curve for the matrix is back-calculated from the nonlinear shear curve of an IM7/8551-7 micro-composite. When the effect of the constitutive response of the matrix on the failure envelope is investigated, an elastic perfectly-plastic model is used with the properties shown in Table 3. A fracture energy-based damage model implemented in ABAQUS is used for the fibers, with only fiber tensile and compressive modes activated. The maximum stress criterion is used to predict failure onset and the toughness of

the fibers is taken as in . To define the failure envelopes, the longitudinal compressive strength is defined as the peak load reached during the compression step. [7]

Table 3: Input parameters used in the FE model [7]

	IM7-8552	T300-914	EXAS HIS-DX 6002
Fiber diameter	7	7	7
Fiber Young's modulus E_f (GPa)	276	231	276
Fiber Poisson's ration ν_f	0.3	0.3	0.3
Fiber compressive strength X_c^f (MPa)	3200	1330	2140
Fiber compressive toughness G_{1c}^{fc} (J/m^2)	7	7	7
Initial misalignment Φ_0	0°	0.5°/1.5°	4°
Matrix shear modulus G_m (GPa)	1.4	1.5	1.5
Matrix yield stress τ_y (MPa)	80/90/100	95/125	75

5. CONCLUSIONS

Hallow spheres occupy about five times the volume of resin, so reducing the cost and weight of a compound. They can also produce/improve other useful properties, such as resistance to impact and thermal shock, and the finishing characteristics.

The microscopic solid glass spheres added to a reinforced plastic compound give smoothness, hardness and excellent chemical resistance, with low oil absorption. The spheres lower the viscosity of most resin mix systems.

Many material parameters of resin like curing kinetics and viscosity data are important for a thermal simulation. The new kinetic and viscosity models, which were developed for rapid curing epoxy resin systems are the key of successful results.

The fibers at the kink-band tip, deforms in-phase at a very small angle β to the y-axis. Below, it is verified that neglecting β does not change the predictions by comparing the results from the unit-cell model to a model containing 100 fibers.

6. ACKNOWLEDGEMENT

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