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Computational Analysis of the Bonding Process and Structure of the Bond Point During Through Air Bonding

M. Hossain, M. Acar, and W. Malalasekera
Department of Mechanical and Manufacturing Engineering
Loughborourough University
Leicestershire, LE11 3TU, UK

Email: M.Acar@lboro.ac.uk
Phone: 0044 1509 227533
Fax: 0044 1509 227648

ABSTRACT

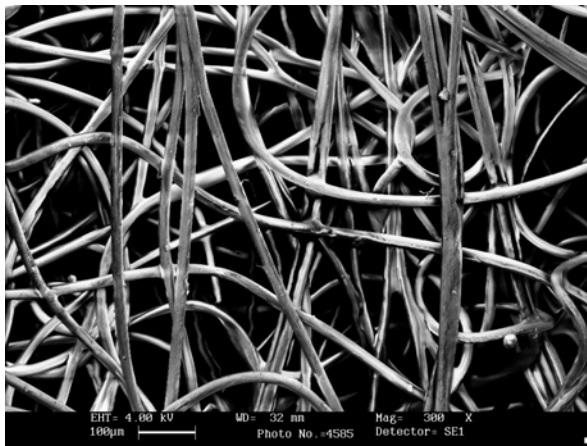
Through-air bonding is one of the methods of bonding fibres in nonwoven webs. A computational study of the formation of bond point between two bicomponent fibres during the through-air bonding is reported in this paper. The computational method involves solving the Navier-Stokes equations for two-phase flows of air and molten polymer in a three-dimensional configuration. The heating, melting and bonding of fibres are modelled by the Volume of Fluid (VOF) model together with a melting model. The simulated results show the formation of the bond between two fibres in contact and the change of shape of the bond with time at different bonding temperatures. The computation shows that the rate of bonding increases slightly at higher temperature.

INTRODUCTION

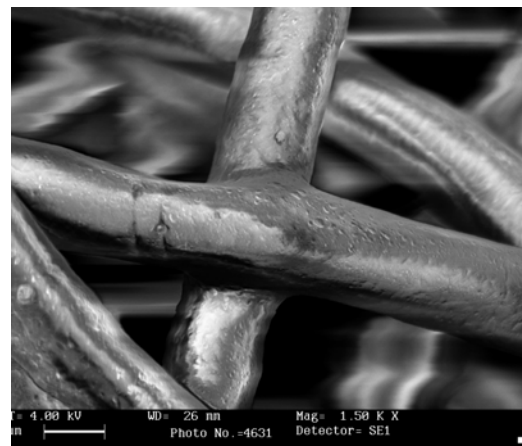
Bicomponent fibres consisting of core and sheath polymers of two different melting points are widely used in the through-air bonding process to produce bonded nonwoven webs. The mechanical properties such as tensile strength, tear strength and bending properties of nonwoven webs largely depend on the degree of bonding. The bonding process is therefore the most important factor for controlling the mechanical properties of the nonwoven webs. A better understanding of the formation of bond is essential for the improvement of the existing products and processes, cost savings and the development of new products. The through-air bonding process involves passing hot air through an unbonded nonwoven web, usually wrapped around a perforated rotating drum and heating the fibres above melting temperature of sheath fibre, which melts and flows towards the crossover point of the two adjacent fibres in contact to form a bond. However, it is recognised that the optimum heating and bonding conditions for the through-air bonding is difficult to establish. The nonwoven fabrics will be weak if there is insufficient bonding, on the other hand, the fibres will melt and deform if excessive heat is applied. One way to establish the optimum bonding condition is by experimentation under different conditions in a production line. This process is, however, time consuming, expensive and often not profitable. Mukhopadhyay et al. [1] proposed a single-fibre test method that can provide a better insight into

the thermal bonding behaviour than measuring the nonwoven fabrics from full-scale production lines. Kim et al [2] reported an experimental investigation of thermal-bonding behaviour of two bicomponent fibres in point contact under different bonding temperatures and fibre diameters. Subsequently, Kim et al [3] reported a numerical investigation for the same experimental set up and represented the 3D fibre configuration by two cases of 2D flow, first case representing the flow along the fibre axis and the second case representing the flow perpendicular to the fibre axis. Although their simulation showed that general trend of the bonding point, it failed to represent the 3D nature of the shape of the bond point.

In an earlier study, Hossain et al [4] investigated the airflow and heat transfer through a nonwoven web treating the web as a porous media in macroscale. The calculation investigated the time of heating of the web under different operating conditions. In the present study, the airflow and heat transfer, melting and bonding of fibres are analysed in microscale by the CFD technique. The modelling technique involves modelling of melting of fibres and two-phase flow modelling of air and molten polymer using the volume of fluid (VOF) method. Figure 1 (a) shows a scanning electron micrograph (SEM) of a through-air bonded nonwoven web. Because of the statistical nature of fibre distribution in a web, it is impossible to generate a realistic computational model for a complete web. However, the analysis of the formation of a single bond point will provide an insight into the bonding behaviour. Therefore, a single bond modelling strategy is adapted to investigate the formation of a bond between two fibres laying perpendicular to each other similar to the one shown in Figure 1(b).



(a)



(b)

Figure 1: Scanning electron micrograph of (a) a through-air bonded nonwoven web, (b) a bond point between two fibres laying perpendicularly.

3. MODELLING APPROACH

Nomenclature

c	specific heat
d_f	diameter of fibre
E_a	activation energy
h, H	enthalpy
k_{eff}	effective thermal conductivity
P	pressure
R	universal gas constant
S	source term
t	time
T	temperature
u	velocity

greek

α	volume fraction
β	fraction of melt of sheath fibre
Δh	heat of melting
μ	viscosity
ρ	density
σ	surface tension force

3.1 Mathematical formulation

The two-phase Volume of Fluid (VOF) method is used for the modelling of the air and molten polymer fibre flows. In the VOF method, a single set of momentum equations is shared by phases (here, air and polymer) and volume fraction of each phase is tracked through the computational domain. The solidification/melting model is also utilised to model the melting of fibres. The surface tension force plays the most important role in the bond forming process and therefore is included in the computational model. The governing equations for the VOF model is given below:

Continuity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{u}) = 0 \quad (1)$$

Momentum:

$$\frac{\partial (\rho \bar{u})}{\partial t} + \nabla \cdot (\rho \bar{u} \bar{u}) = -\nabla P + \nabla \cdot \mu (\nabla \bar{u} + \nabla \bar{u}^T) + S + F \quad (2)$$

Initially, the fibres are in solid state and obviously the velocity is zero. When the fibres are melted by heat transfer from the flowing hot air, the molten polymer starts to flow. The term S in the above works as a momentum sink to ensure that the fibre velocities in the initial cold state and then in the molten hot state are correctly represented. The surface tension force in equation (2) is represented by F . The force at the surface is expressed as a volume force and is added to the momentum equation as a source term.

Energy equation:

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \bar{u} H) = \nabla \cdot (k_{eff} \nabla T) + S_h \quad (3)$$

where S_h is a source term in the energy equation. This term represent the thermal energy needed to melt fibres.

Volume fraction equation:

To track the interface between phases a volume fraction continuity equation for the secondary phase (fibre) is solved along with the above equations:

$$\frac{\partial \alpha_q}{\partial t} + \bar{u} \cdot \nabla \alpha_q = 0 \quad (4)$$

where subscript q represents each phase component. Air volume fraction is obtained from the relation $\sum_{q=1}^2 \alpha_q = 1$. The properties appearing in the transport equations are determined by the presence of the component phases in each control volume. For example, the density is considered to be:

$$\rho = \sum_{q=1}^2 \alpha_q \rho_q$$

3.2 Parameters for computation

The fibre used for the computation study is a polyethylene (PE) sheath and polypropylene (PP) core bicomponent fibre. The sheath diameter is 15.15 μm and the core diameter is 10.86 μm . The bonding is investigated at temperature of 130 $^{\circ}\text{C}$, 140 $^{\circ}\text{C}$ and 150 $^{\circ}\text{C}$. The viscosity of the sheath polymer at 140 $^{\circ}\text{C}$ is experimentally measured to be 600 Pa.s [3]. The viscosity at 130 $^{\circ}\text{C}$ and 150 $^{\circ}\text{C}$ was calculated to be 745 Pa.s and 488 Pa.s respectively, from the Arrhenius equation

$$\frac{\mu}{\mu_o} = \exp\left(\frac{E_a}{R} \left(\frac{1}{T} - \frac{1}{T_o}\right)\right)$$

where, E_a is the activation energy of 30 kJ/mol, R is the universal gas constant.

The surface tension is calculated using the equation,

$$\sigma = \sigma_c (1 - T/T_c)^{11/9}$$

where σ and σ_c are the surface tension at a temperatures T and the critical temperature T_c , respectively. With the critical temperature of 1000 K and the surface tension of 26.6 mN/m at 150°C [3], the values of surface tension at 140°C and 130°C were calculated to be 27.1 and 27.7 mN/m. The density of the polyethylene (PE) is taken as 900 kg/m³ and that of polypropylene (PP) as 950 kg/m³. The values of specific heat are set at 1800 and 1600 J/kgK for polyethylene and polypropylene respectively. The thermal conductivities of polyethylene and polypropylene are 0.35 and 0.2 W/mK respectively. The values of density, specific heat and thermal conductivity are supplied by fibre manufacturer KoSa.

4. RESULTS AND DISCUSSION

Heating

In the though-air bonding process, the fibres are heated, softened and melted by flowing hot air. The simulated results of heating to melting of fibres are shown in Figure 2. Hot air at a temperature of 413 K (140°C) and at a velocity of 1.5 m/s is passed over the fibres. The heat is convected from the air to the fibre surface and then conducted through the fibre. When the fibre temperature exceeds the melting temperature of 128°C, the polyethylene sheath starts to melt. The melt fraction of fibres are shown in Figure 3. It took approximately 6.5 ms to heat the fibres to melting temperature and 2 ms from the beginning to the end of melting of the whole of sheath fibres. The heating and melting times are influenced by the air temperature. At air temperature of 130°C the computed heating time is 15 ms and melting time is 6 ms; at 150°C, the heating time is 4 ms and melting time is 1 ms.

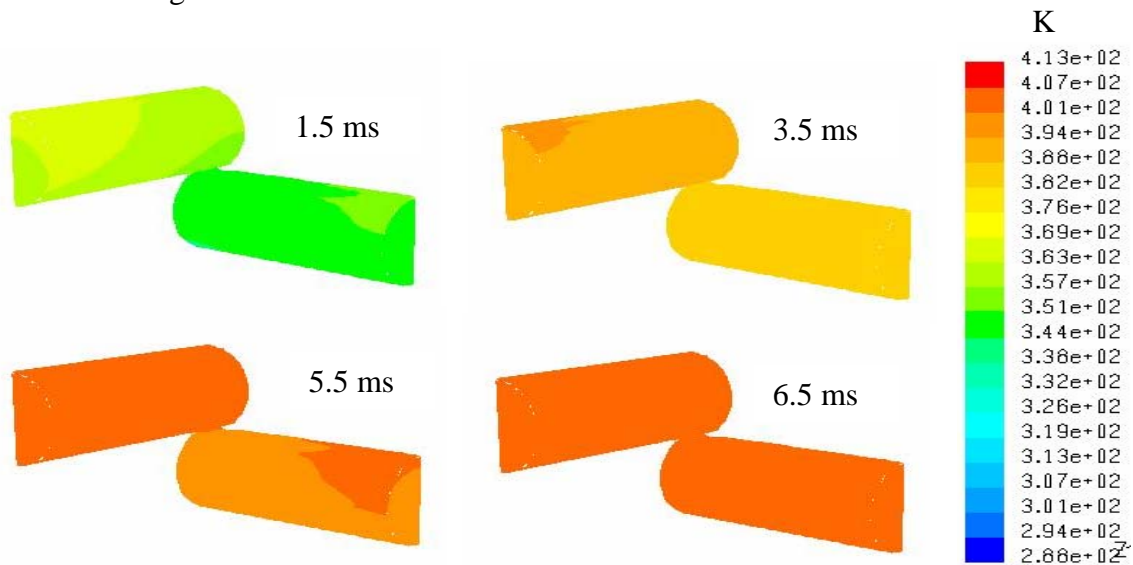


Figure 2: Temperature of fibres at different time steps for bonding temperature of 140°C.

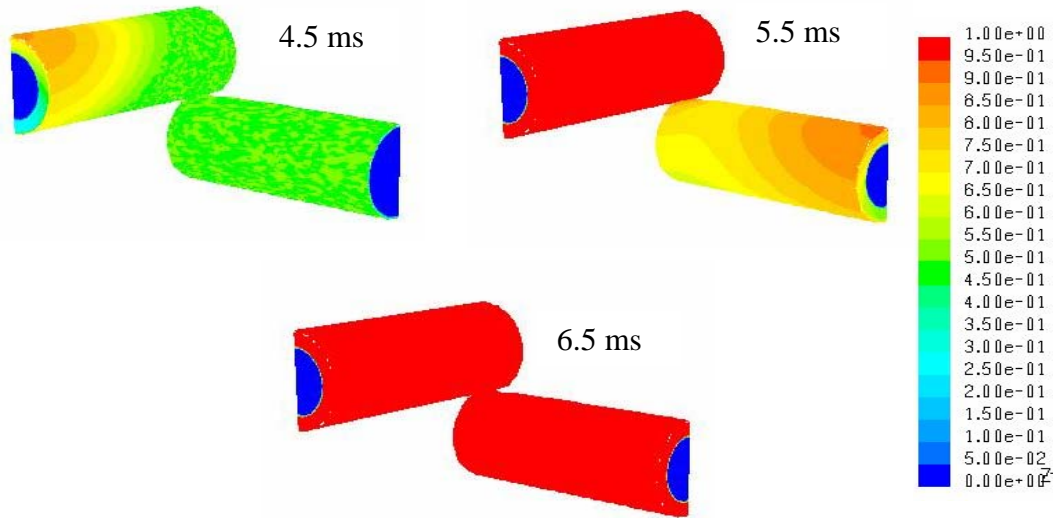


Figure 3: Progression of melting of fibres heated by hot air at 140°C.

Bonding

A typical bonding behaviour of the two polyethylene sheath/polypropylene core bicomponent fibres is shown in Figure 4. The bonding starts at the intersection of two fibres. The flow of molten polyethylene proceeds to form a bond at the intersection to minimize the surface energy, in that the polymer flows towards the contact point by surface tension force. In the initial stage of bonding, the sheath polymer polyethylene flows circumferentially to the contact point, then the polymer flows along the fibre axis towards the bond point. Accordingly, the thickness of the sheath polymer in the vicinity of the intersection begins to decrease. With the increase in the bonding time, the amount of sheath polymer at the intersection continues to increase and the fibre diameter in the vicinity of the intersection continues to decrease.

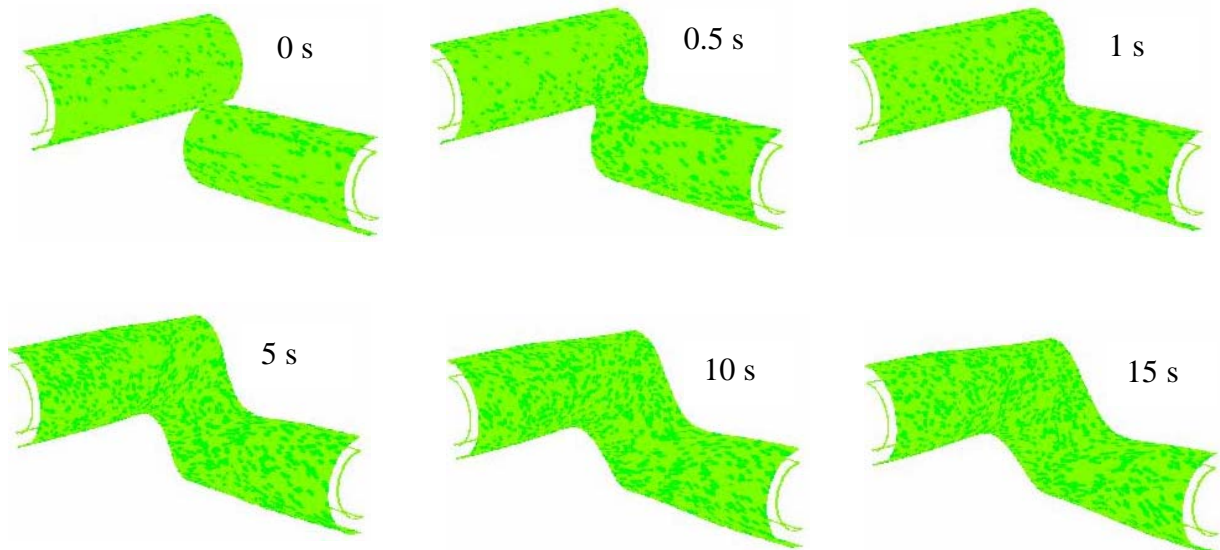


Figure 4: Formation of bond with increasing time calculated for the bonding temperature of 140°C.

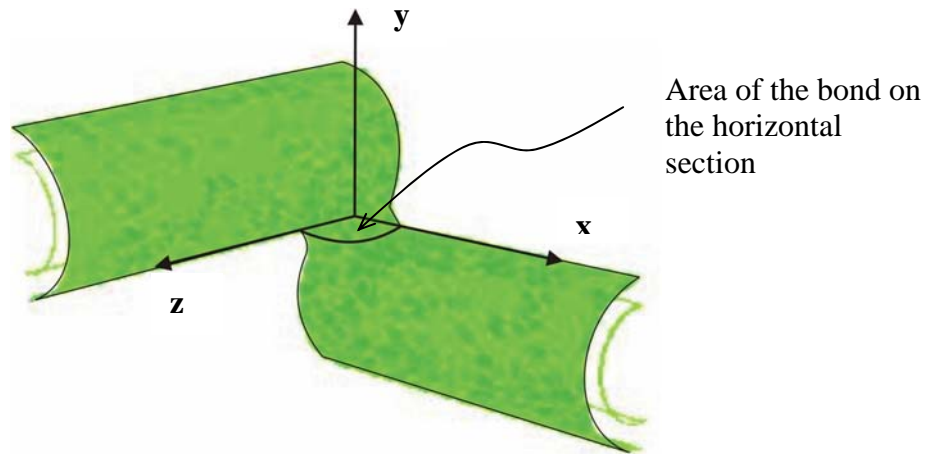


Figure 5: Characteristic bond area on the horizontal plane. The size of the bond is characterised by the diameter of this area.

In order to characterise the features of the bonding process, a characteristic bond size is defined as the diameter of the section of the bond on the horizontal plane as shown in Figure 5.

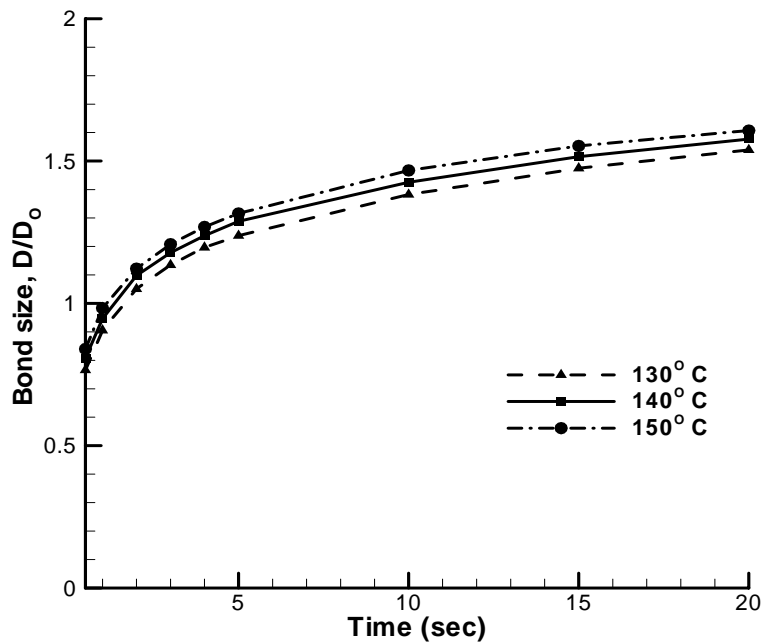


Figure 6: Change of bond size evaluated from the simulated results as a function of bonding time for three different bonding temperatures

Figure 6 shows the changes of the bonding size with bonding time under different bonding temperatures. A dimensionless bond size is defined by dividing the bond diameter by the initial fibre diameter D_0 . The bonding proceeds at a faster rate at the initial stages of bonding. The molten polymer flows rapidly to fill up the narrow gap at the contact point of two fibres. As the gap is filled up, the bonding proceeds at a slower rate (Figure 6) and the bond size curve becomes almost linear after 4-5 seconds, with a low gradient. The effect of temperature on the rate of bonding is also shown in the same figure. The bonding proceeds at a slightly faster rate at higher temperature. Surface tension and viscosity are the two most important parameters that control the flow of the molten polymer. When the bonding temperature changes from 130°C to 150°C the viscosity and surface tension decreases to about 65.5% and 96% respectively. At higher temperatures, the surface tension force, which is the driving force for the formation of the bond, decreases which leads to a slower rate of bonding. On the other hand, the reduction of the viscosity at the higher temperatures lead to a faster rate of bonding. Overall the reduction of the viscosity at higher temperatures more than compensate the reduction of the surface tension force and this leads to a small increase of the bonding rate at higher temperatures.

5. CONCLUSIONS

Through-air bonding of two fibres in a 3D configuration is numerically simulated by using a Volume of Fluid (VOF) model. The computation shows that heating time is greatly influenced by the air temperature; however, compared to the bonding time, it is two-three order of magnitude shorter. The bonding starts at a faster pace with the flowing of the sheath material to fill up the gap in the contact point of two fibres. Then the bonding process proceeds more slowly. The time required for the formation of bonding is investigated under different bonding temperatures. The bonding proceeds faster at higher temperatures mainly because of the reduction of the polymer viscosity. However, the effect of temperature on the formation of bond appears to be small.

ACKNOWLEDGEMENT

The research work is financially supported by Nonwovens Cooperative Research Center, Raleigh, NC, USA. We gratefully acknowledge their support. We also acknowledge the support of fibre manufacturer KoSa for providing fibre specifications.

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