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THE EFFECTS OF WELD GEOMETRY AND GLASS-FIBER ORIENTATION ON THE MECHANICAL PERFORMANCE OF JOINTS – *PART II: KINETICS OF GLASS-FIBER ORIENTATION AND MECHANICAL PERFORMANCE*

Abstract

The mechanical performance of injection molded short glass-fiber reinforced thermoplastic components is anisotropic and is highly dependent on the fiber orientation and distribution. Similarly, the bulk and short and long-term mechanical performance at the weld is influenced by these fibers and the specific welding technology used as related to melt-pool formation.

The purpose of this analysis is to show:

1. the short-fiber orientation (analytical and simulation data) and distribution at the pre-welded bead, ribs and wall areas;
2. advantages of SigmaSoft injection molding simulation software, which utilizes full three dimensional fiber representation of any molded part;
3. the mechanical performance of welds with optimized geometry (US Patent 6,447,866).

Findings on the mechanical performance of butt-joints with different designs and localized geometry will help designers and technicians with plastic part design optimization. In a previous ANTEC paper (Part I)[1], we related these findings to the kinetics of welds and part design issues for straight and T-type butt-joints.

Introduction

This paper is a part of our continuous effort toward improvement and optimization of the mechanical performance of injection molded and welded plastic parts. In our previous investigations, we analyzed and reported to ANTEC (1996-2002) on the efficiency of various welding technologies for un-filled and reinforced thermoplastics [1-2, 4-5]. The phenomenon of short glass-fiber re-orientation at the weld inter-phase is partially responsible for optimal weld performance and was described in [2-3].

Later we presented at ANTEC '99 and 2000 our findings about the influence of "memory effects of nylon" on the performance of vibration and hot-plate welds [4-5]. These findings helped us to develop special methods and specimens for evaluating the mechanical performance of welded butt-joints [6]. In a presentation at ANTEC 2002 [1], we discussed the role of butt-joint design (straight and T-type) on the mechanical performance of welds as influenced by geometry such as the thickness of welds and the presence of ribs and walls.

The next step in our investigation focuses on the development of localized weld geometry, which may provide improved mechanical performance due to optimized glass-fiber orientation at the weld [7]. To reinforce our discussion of glass-fiber orientation [1-2, 4, 7], we have utilized results from optical and scanning electron microscopy and injection molding process simulation for short glass-fiber filled plastics. Both methods (analytical and simulation) have their own advantages and disadvantages related to the accuracy of the information presented herein. Analytical investigation is time-consuming and not fully automatic [8].

Currently there are several software packages that can simulate 3-D flow analysis, but until very recently, none have had the ability to predict glass-fiber orientation as well. Because fiber orientation significantly affects the mechanical performance and quality of the molded part, its accurate prediction is critical to effective weld and part design. This can only be accomplished with a true 3-D representation of the part geometry and a simulation code based on a mathematical model using this representation.

Advantages and Limitations of Flow Patterns and Short Glass-Fiber Simulation Methods

The work presented in this paper involves the use of Moldflow® and SigmaSoft® software. Moldflow

[1] The Effects of Weld Geometry and Glass-fiber Orientation on the Mechanical Performance of Joints Part I: Kinetics of Glass-fiber Orientation and Performance at Bulk and Weld Areas" [1].

was originally developed to use (and still uses) a finite element mesh model, comprised of two-dimensional nodes and triangular shell elements located in a three-dimensional (3-D) ***x, y, z*** space. The classical equations used for producing the molding simulation are applied to this so-called 2.5-dimensional (2.5-D) geometric representation of the injection molded parts.

The ability to predict complex, non-linear flow patterns is very useful when trying to optimize part design before committing to a final product shape or mold design. In general, the predictions for short glass-fiber orientation and dispersion are limited by the assumptions that the software makes in predicting the more basic parameters such as pressure, temperature and flow dynamics. It can also be influenced by the use of the 2.5-D model because the thickness is prescribed numerically and is not always accurately represented by the finite element mesh.

In more complex injection molded parts, such as those with many welds, walls, ribs, thick and thin transitions or diverging flow, only a true 3-D model can accurately capture all relevant thermal and dynamic nuances. The accuracy of the short glass-fiber orientation predictions is, however, only as good as the ability of the software to accurately predict the flow and kinetics of the reinforced plastic within the mold during the injection stage.

In predicting the kinetics of short glass-fiber interactions and ultimately the fiber orientation, Moldflow software attempts to apply known models to the aforementioned 2.5-D representation and can predict the average distribution and direction of fibers within the injection molded part. Moldflow utilizes short glass-fiber predictions based on the relationships developed by C. L. Tucker and F.P. Folgar [9]. To investigate flow patterns, temperature profiles and other basic molding parameters, this software is quite useful and has been an effective tool for parts of this study. Its basic non-fiber 3-D flow results can sometimes be used (in more simple geometries) to help make informed guesses about fiber orientation.

SigmaSoft is a relatively new molding simulation software package that utilizes a full 3-D representation of any molded part. In addition, SigmaSoft has recently included the ability to predict fiber orientation, thereby allowing users to make discrete evaluations of fiber alignment and dispersion anywhere in a molded part. This software is unique because it utilizes technology derived from the metal casting industry, which by necessity requires the use of thicker and large, 3-D models. Unlike Moldflow, SigmaSoft takes account of the transient heat transfer within the mold and its components, including ejector pins, runners and other small bits that affect the molding process. Because of its ability to predict 3-D fiber orientation and its more thorough heat transfer analysis, SigmaSoft may be a more appropriate tool for optimizing fiber–filled part design.

Analytical Mathematical Models

Short glass-fiber reinforced thermoplastic materials may be considered as particles or fibers suspended within a viscous medium. There may be mechanical and/or hydrodynamic interactions between these reinforcements (short glass-fibers). The suspension may be dilute, semi-concentrated or concentrated, as follows:

1. dilute—the fibers are never close to one another and do not interact;
2. semi-concentrated—no mechanical contact between the fibers, but the hydrodynamic interactions become significant;
3. concentrated—the fiber orientation behavior becomes very complex, since both mechanical and hydrodynamic fiber interactions apply.

A model describing the motion of a single fiber immersed in a large body of incompressible Newtonian fluid was first established by G. B. Jeffery [10]. His model applies only to suspensions that are dilute to the extent that any inter-fiber interactions (even hydrodynamic interactions) are negligible. An important measure for assessing suspension concentration is the average distance between the fibers. Consider fibers of diameter (***d***) and length (***L***), with an aspect ratio (***L/d***), a fiber concentration by volume (***c***) (or volume fraction V_f) and having a uniform length distribution. Most reinforced plastics contain 6-60% fibers by weight and thus can be regarded as concentrated suspensions.

For concentrated suspensions, a term called the interaction coefficient (C_I), has been incorporated in the model for fiber orientation [11]:

1. interactions among fibers tend to randomize the orientation;
2. the term takes the same form as a diffusion term and since interactions only occur when the suspension is deforming, the effective diffusivity is proportional to the strain rate;
3. the dimensionless C_I term determines the strength of the diffusion term.

The addition of the diffusion term to account for the fiber interactions tends to improve the orientation predictions, as Jeffery's equation by itself does not give precise predictions for fiber orientation. To date, Tucker-Folgar's model has been the best available description for short-fiber orientation representation in concentrated suspensions. The model is given in this form by Advani and Tucker [12]:

$$\frac{\partial a_{ij}}{\partial_t} + v_k \frac{\partial a_{ij}}{\partial x_k} = -\frac{1}{2}\left(\omega_{ik} a_{kj} - a_{ik}\omega_{kj}\right) + \frac{1}{2}\lambda\left(\dot{\gamma}_{ik} - 2\gamma_{kl} a_{ijkl}\right) + 2C_I \dot{\gamma}\left(\delta_{ij} - \alpha a_{ij}\right)$$

where:

α equals 3 for 3-D and 2 for planar (2-D) orientation,

v_k is the velocity component;

ω_{ij} and γ_{ij} are the vorticity and deformation tensors;

λ is a constant that depends on the geometry of the particle;

δ_{ij} is a unit tensor, and

C_I is the interaction coefficient.

Experimental

Welding, Material and Mechanical Tests

All specimens and prepared samples were welded using a small, laboratory-scale universal linear vibration welding machine (Mini-Welder-II type[2]). The linear vibration frequency was equal to 240 Hz (nominal). In this study, we used previously optimized and fixed processing settings [2, 4-5]. The material analyzed in this investigation was heat stabilized 33 wt.% short glass-fiber reinforced nylon 6 - Capron® 8233G HS[3]. This grade is widely used for various welded structural components in automotive under-the-hood applications and power tools such as chainsaws, leaf blowers, etc. All tensile test results were used for performance optimization. Samples with high tensile strength were selected for morphology analysis at the weld zone (inter-phase).

Results and Discussions

Full 3-D models were created in a standard CAD system for use with Sigma software. A common 33% short glass fiber-filled nylon 6 was used with melt and mold temperatures set at 280°C and 80°C, respectively. The filling time was prescribed at 1 second. Figures 1 - 4 show the predicted ***Z***-directional fiber orientation of four models[4] each with different features in the center of the model. Blue[5] (dark) regions indicate high levels of orientation and yellow regions (light) designate orientation in either the ***X*** or ***Y*** directions. Numerical values indicate the relative weight of the directional distribution, i.e., the most oriented have a value of one (1) and the least oriented a value of zero (0). As expected, the percentage of ***Z***-direction fibers is quite low throughout the majority of each model; because the gate was chosen to be aligned in the ***X***-direction. Interestingly, in each case, the highest percentage of ***Z***-oriented fibers is seen in the middle feature. This phenomenon is produced as the flow diverges from the primary (injection) direction into a secondary flow direction at the middle feature. The successful re-orientation of fibers is clearly a function of the central feature geometry. In each case, the re-orientation of the fibers into the ***Z***-direction may provide for stronger welds by promoting additional fiber engagement across the weld.

Moreover, the placement of the gate will have a strong influence on the plastic flow direction and must be carefully chosen to work with the chosen model design feature. Basic principles regarding the influence of local geometry on plastic flow formation are shown in Figure 5. Under conditions of optimized design, it is possible to control this process in 3-D space (Figure 5c – smooth groove with the waves). Mechanical performance for various design versions is shown in Table 1. With optimized design conditions (for local, specific geometry) it is possible to increase mechanical performance (tensile strength) of a joint up to 10%.

The results of a localized analytical investigation on fiber orientation are shown in Figures 6 and are in satisfactory correlation with glass-fiber simulation data (Figure 1-4). Presently, it is not clear how efficient this 3-D simulation is for very small, discrete geometries, since the resolution of this technique has not been established. As mentioned previously, electronic-microscopy is very efficient for investigating the details of glass fiber-orientation in localized regions, such as those with sizes of approximately 300-500 μm and less. These are typical dimensions for the thickness of a weld inter-phase.

The orientation of any single fiber may be calculated from its elliptical profile (see Figure 6). Families of the equations that predict mechanical performance (tensile strength and Young's modulus) of plastic were presented in [13]. Predicted performance is extremely sensitive to matrix density (ρ_m). The density of

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[2] Mini II Vibration Welder is welding machine from Branson Corporation (Danbury, CT).

[3] Capron® - is a registered trademark for BASF Corporation nylon plastic products. We evaluated the mechanical performance of welded nylon 66-based plastics also.

[4] Simulations prepared by Sigma Engineering, GmbH (Aachen, Germany).

[5] Simulation results are typically produced in color. When reproduced in black and white they only appear as light and dark shades of gray.

matrix (ρ_m) may be different from the density of base resin ρ_r for a number of reasons, such as nucleating effects of the glass-fibers, kinetic of polymer chains at an interface, influence of sizing, etc. These factors may influence the accuracy of the estimated values of tensile strength and Young's modulus.

Conclusions

Previously established empirical data related to part thickness and fiber orientation can augment software analysis such as SigmaSoft and Moldflow, in the effort to optimize weld and part design. SigmaSoft is a relatively new molding simulation software package that utilizes a full 3-D representation of an injection molded component. SigmaSoft has recently included the ability to predict fiber orientation, thereby allowing designers and material developers to make efficient evaluations of fiber orientation and distribution.

Electron-microscopy examination may be used to further validate the accuracy of software analysis data. Ultimately, we desire these techniques to lead us to a complete representation of the fiber orientation in any given region of our weld or part design, which will allow us to prescribe the optimal fiber orientation for maximum strength and performance.

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Design Version	Weld Geometry	Relative Strength[6]	
		PA 6	PA 66
Flat	Figure 1	1.00	1.00
Tooth	Similar to Figure 2	1.04	1.03-1.05
Bump	Figure 3	0.98-1.01	0.97-1.01
Smooth Groove	Figure 4	1.07-1.10	1.05-1.07
Waved Groove	Figure 5c	1.08-1.10	1.06-1.08

Table 1. Influence of weld design on mechanical performance of joint.

[6] Relative Strength = strength of weld (design) / strength of weld (flat design).

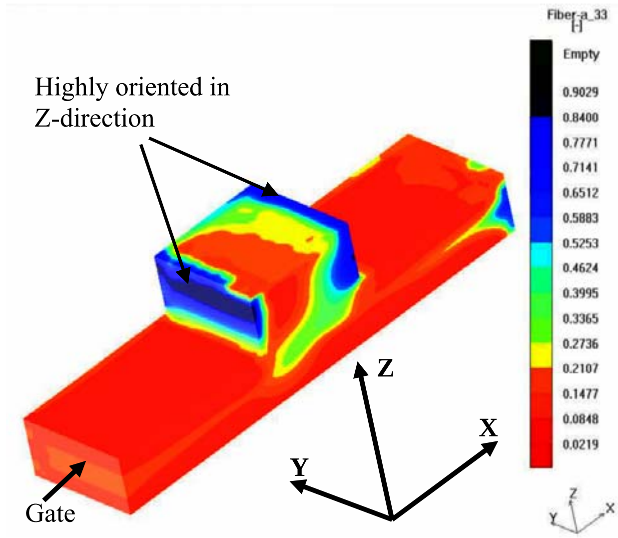


Figure 1. Predicted Z-direction fiber orientation: Flat Bump. Highest orientation seen at leading/trailing edges of center flat bump.

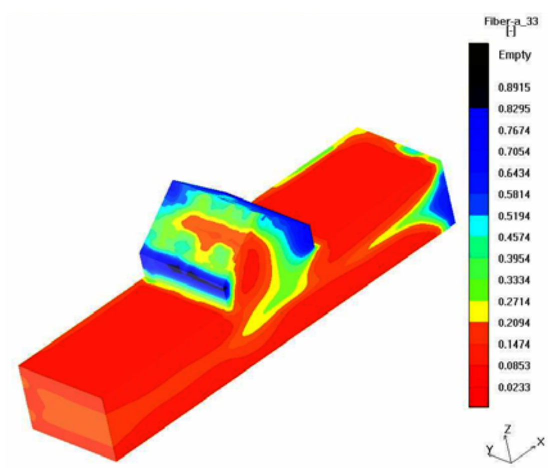


Figure 2. Predicted Z-direction fiber orientation: Tooth (similar to energy director). High orientation located at leading/trailing edges.

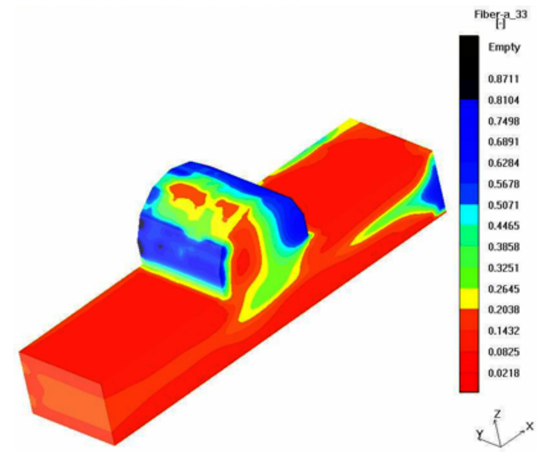


Figure 3. Predicted Z-direction fiber orientation: Round Bump.

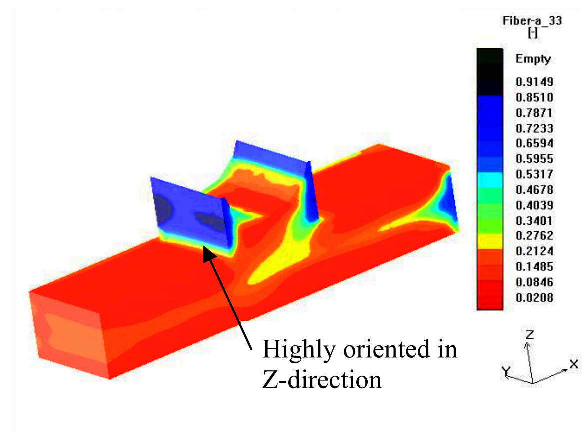
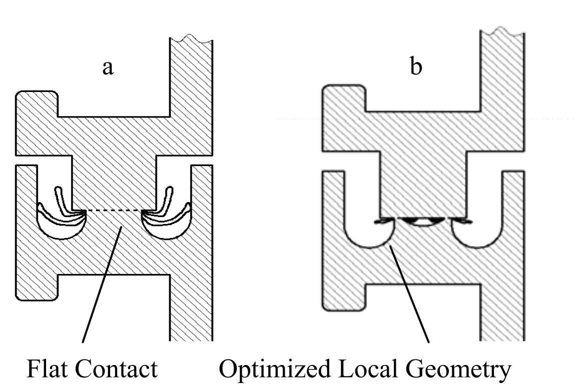


Figure 4. Predicted Z-direction fiber orientation: Smooth Groove



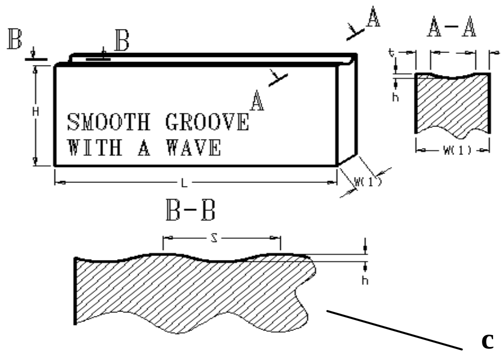


Figure 5. Principles of butt-joint geometry: a – flat configuration; b – an example of non-flat contact conditions (2-D presentation); c – waved geometry.

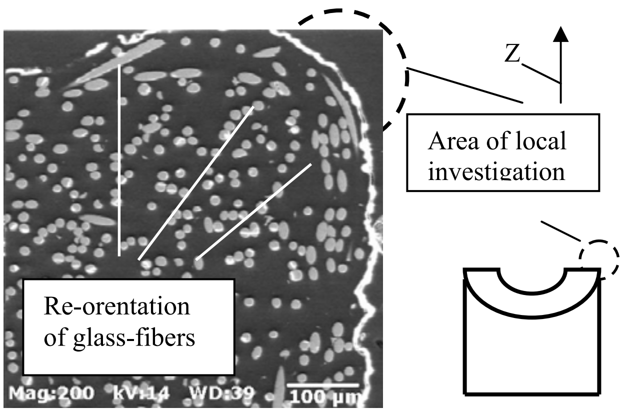


Figure 6. An example of localized and optimized glass-fiber orientation (for smooth groove, see Figure 4).

Keywords

Performance, nylon, glass-fiber, linear vibration, welding, optimized, design.

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