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Reinforcement Challenges and Solutions in Optimized Design of Injection Molded Plastic Parts

ABSTRACT

The mechanical performance of injection molded glass-fiber reinforced plastic parts is highly anisotropic and strongly depends on the kinetics (orientation and distribution) of the glass-fiber, and part geometry. Similarly, the bulk and local mechanical performance at the ribs, walls and welds is influenced by these glass-fibers and the specific processing technology (including joining) used, as related to melt-flow and melt-pool formation and glass-fiber re-orientation. The purpose of this study is to show:

- the relationship between short glass-fiber orientation at the pre-welded beads, ribs and wall areas for injection molded and subsequently welded parts,
- the short-term mechanical performance of welded butt-joints that have various geometry and thickness, namely “straight” and “T-type” welds.

Findings on the optimized mechanical performance of these two different types of butt-joints (“straight” and “T-type”) with respect to design and geometry, will help designers with material selection, welding, processing, and design optimization (ribs, walls, etc.).

INTRODUCTION

Short glass-fiber[1] reinforced thermoplastics are the materials of choice for a variety of injection molded and welded structural components in automotive applications. Various welding technologies, such as frictional (linear vibration, orbital vibration, spin and ultrasonic), hot plate (contact and non-contact) and laser (non-contact and contact/trough-transmission), are applied for manufacturing many thermoplastic components. To optimize their design and short- and long-term mechanical performance, we need to utilize a variety of engineering properties, related to reinforced thermoplastics, molded walls and ribs, and welded joints (Figures 1-2). These important engineering properties depend on the thermoplastic composition, compounding, and the molding/welding processing conditions.

Figure 1. Example of design geometry for ribs and weld areas in injection molded automotive part.

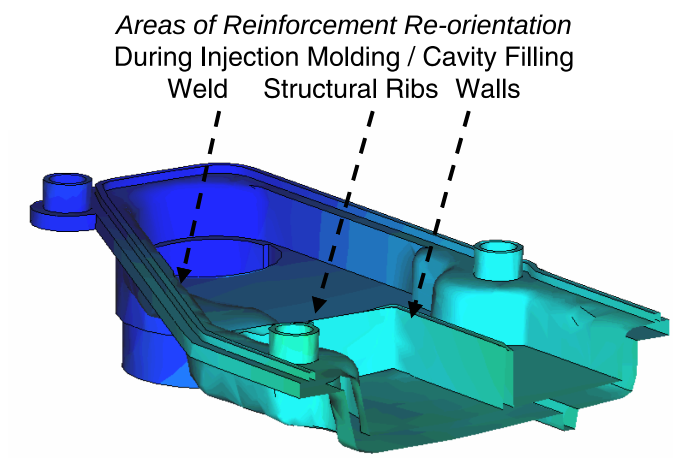

Figure 2. Example of Moldflow® simulation for injection molded part (for details see Figure 1). Range of color shades indicate filling time, i.e., dark blue=start.

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1 The diameter of widely used short glass-fiber is typically in the range of 8µm to 17µm, and their length in injection molded parts of 200 µm to 350 µm.

Thickness of plaque, mm		Wt. % GF	Joint (B) Strength	Relative Strength	Relative to Matrix
T1	T2				
4.0	6.25	0	79.3	0.97	0.97
4.0	6.25	6	83.1	0.96	1.01
4.0	6.26	14	90.7	0.71	1.11
4.0	6.25	25	90.2	0.56	1.10
4.0	6.26	33	85.6	0.46	1.04
4.0	6.25	45	81.9	0.39	0.99
4.0	6.26	50	80.5	0.37	0.98
4.0	6.25	63	72.2	0.28	0.88

Figure 1 shows an example of complex by geometry injection molded and linear vibration welded component which contents local design geometry for walls, ribs and weld areas. The Moldflow® simulated flow patterns and limited information about glass-fibers orientation are shown in Figure 2.

The mechanical performance of the various walls, ribs and welds (Figure 1), is a critically important parameter in thermoplastic part design optimization and end-use performance characterization. Precise, improved design of injection molded and subsequently welded parts requires the use of specific engineering properties, as related to optimized rib and weld performance and may influence end-use part performance [1-2]. Previously, the linear vibration welding process and short-term mechanical performance of welded joints was described in [3-11]. Also in a previous report to SPE 2001 (Antec), our findings revealed the effects of local reinforcement in the weld inter-phase, on linear vibration welding techniques [12]. In a presentation at SAE 2001 we discussed the kinetics of the weld melt temperatures for various nylons using linear vibration and hot-plate welding technologies [8].

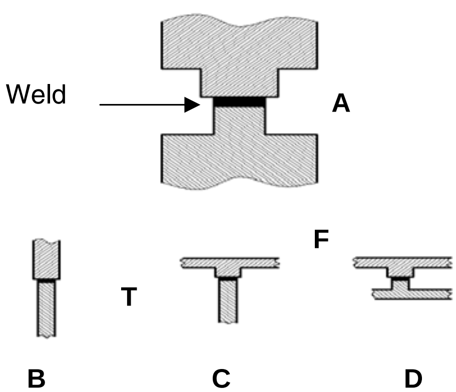

Figure 3. Welded joint design basics. Agenda: A—standard; B—straight; C—T-type; D—shear/lap; F-flange (T-type joint); T – vertical wall/plaque.

Table 1. Influence of Short Glass-fiber Reinforcement (from 0 wt.% GF to 63 wt.% GF) of Straight Butt-Joints (PA6, at 23°C, in dry-as-molded and welded conditions – DAM). Agenda: T1 and T2 – T-type joints (see Figure 5a and Figure 5b respectively).

Under optimized welding conditions, the tensile strength of welded nylon butt-joints was equal to or 11% higher (Table 1) than the tensile strength of the base (matrix) polymer. The same mechanical performance of the welded nylon was seen [11] using orbital vibration welding methods (Table 2).

Table 2[2]. Mechanical Performance (at 23°C, in dry-as-molded and welded conditions – DAM) of Butt-Joints With Respect to Plastic Composition and Design for Nylon Based Plastic (longitudinal and orbital oscillations, optimized processing conditions [8-12])

Direction of Oscillation	Tensile Strength MPa
Linear – Longitudinal	85.6
Linear – Perpendicular	84.6
Linear – By Angle (45°)	85.2
Orbital	87.2

Using optimized linear vibration welding conditions, the maximum temperatures of the weld melt (in the inter-phase area) were significantly above (85 - 90°C) the melt point of welded nylon 6 and nylon 66 (T_m = 223°C and 261°C, respectively). In our report to SPE 2000 (Antec) we associated these maximum temperatures with “memory effects” of semi-crystalline thermoplastics [12]. All of our results presented at SAE and Antec [8-12] were produced for straight butt-joints (Figure 3), with similar and dissimilar (Figure 3b, Table 1) weld thickness and made with varying linear and orbital vibration welding parameters (Table 2), such as weld amplitude, weld pressure, melt-down, hold/cooling time, thickness of inter-phase. T-type joints (Figure 3c) are very commonly used in many applications [1-4, 6-7, 13-14], where welded reinforced thermoplastics (such as nylon, PET, etc.) are required.

Table 3. Influence of Type of Specimens and Models Used on Butt Weld Performance (33 wt.% short fiber-glass nylon 6, longitudinal oscillations, amplitude frequency = 220 Hz, at 23°C, in dry-as-molded and welded conditions – DAM). Agenda: T – type butt joint (see Figure 3c and Figure 5a)

Type of Specimen	Tensile Strength MPa
Straight (Figures 3b)	85.6
T – type (Figure 3c)	84 - 86

INTERDICTING REMARKS ON INFLUENCE OF JOINT GEOMETRY OF WELDED BUTT-JOINTS (STRAIGHT AND T-TYPE) ON MECHANICAL PERFORMANCE

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[2] Note on used glass-fiber reinforced nylon for Tables 1-4, 7-9: The average tensile strength of the base plastic (non-reinforced matrix) is 82 MPa, St. Dev = 1.3. Mechanical test/performance data was produced at 23°C, in dry-as-molded conditions – DAM (content moisture in wt.% *max* “as received” /DAM equal 0.2%).

In our previous report to SAE 2001 we analyzed [8] the influence of joint design on short-term mechanical performance of straight and T-type nylon butt-joints (Figure 3). Using optimum design and welding conditions, the mechanical performance of 33 wt.%[3] glass-fiber reinforced welded nylon 6 was similar for both designs (Table 3).

These results conflict with data published [3, 6-7] for 33 wt.% glass-fiber reinforced nylon 66 (Table 4), continuously reinforced polypropylene (PP), un-filled polycarbonate (PC) and poly(butylene terepthalate (PBT) plastics (Table 5-6). These discrepancies may relate to the type of plastics - amorphous and/or semi-crystalline – the geometry of the specimens, linear vibration welding and molding processing conditions, thermoplastic composition, etc. Our study involves the next step in experimental evaluation of the mechanical performance of linear vibration welded, 33 wt.% glass-fiber reinforced nylon 6 and focuses on:

- Accuracy of this evaluation using the same equipment (molding, welding and testing), processing and testing parameters for the same lot of commercially available nylon 6 grade.
- Repeatability in processing (molding and welding) parameters and mechanical test results.
- In-depth analytical investigation into the influence of part and weld design on the kinetics of glass-fiber orientation, including structural and micro-structural changes.

Table 4. Mechanical Performance (at 23°C, in dry-as-molded and welded conditions – DAM) of Butt and T-Joints, Welded From Similar Plaques with Thickness = 3.2 mm, With the Influence of Processing Condition, for 33 wt.% Short Fiber-Glass Reinforced Nylon 66. Longitudinal Oscillations, Frequency = 200 Hz) [6-7]. Agenda: B – butt joint, T – type joint

Pressure MPa	Melt-down mm	Strength MPa		Strength T/B Ratio
		Butt	T	
0.38	2.00	69.1	24.5	0.354
1.00	1.00	62.6	24.2	0.386
1.00	3.00	58.6	15.1	0.258
2.50	0.59	54.2	23.7	0.437
2.50	2.00	54.4	20.6	0.378
2.50	3.42	49.7	19.1	0.384
4.00	1.00	50.1	17.9	0.357
4.00	3.00	49.1	15.7	0.320
4.62	2.00	48.4	21.7	0.448

EXPERIMENTAL INVESTIGATION OF MECHANICAL PERFORMANCE

ANALYSIS OF MECHANICAL PERFORMANCE OF LINEAR VIBRATION WELDED BUTT-JOINTS: STRAIGHT WITH T-TYPE

The material analyzed in this investigation was heat stabilized 33 wt.% short glass-fiber reinforced nylon 6[4]. This commercially available grade is widely used for various welded structural components in automotive under-the-hood applications (air intake manifolds, resonators, auto-seats, cooling fans, etcetera). For this investigation, non-colored (natural) material was used exclusively.

LINEAR AND ORBITAL VIBRATION WELDING PROCESSING PARAMETERS AND WELDING MACHINES

All specimens and models were welded using a small, laboratory-scale universal, linear vibration welding machine (Mini-Welder-II type[5] - Figure 4). Larger welding machines provide excessive clamp pressure on the small specimens, because the minimum clamp force is more than 3 kN. During a process optimization study for nylon based plastics [7-10], the basic process parameters, such as weld amplitude, weld pressure, melt-down and cooling/hold time, were varied in a wide range. The linear vibration frequency was equal to 240 Hz (nominal). In this study we used previously optimized and fixed processing settings [7-11]. Meltdown was the only non-fixed parameter, varying approximately from 1.0 mm to 2.0 mm. Orbital welding was performed using DVW type machine (welder designed for joining of small by sizes plastic parts).

[3] By weight (wt. in %)

[4] In this investigation we used nylon 6 – Capron 82xx seies. Capron® - is a registered trademark for BASF Corporation polyamide/nylon plastic products.

[5] Mini-Welder-II is trade name of welding machine from Branson Corporation (Danbury, CT).

Figure 4. Laboratory Scale Linear Vibration Welding Machine Mini-Welder II.

EXPERIMENTAL PROCEDURES

A wide range of quality control and quality assurance tests are used for pre and post-assembled parts. These include flexural, tensile, impact and burst tests, and are usually applied in mass production of welded thermoplastic parts.

One very important parameter needed for proper design of the weld-bead(s), is the tensile strength (at break) of a welded joint with respect to processing, including time-temperature effects [8]. The tensile strength of a weld at 23°C ("dry as molded" and "welded as dry" condition[6]) is a key parameter. It is the first requirement needed for component design, welding process optimization, and comparative analysis of material weld-ability[7].

For straight or T-type butt-joints, basic tensile test data (nominal tensile stress at break) was obtained from rectangular specimens 10 mm wide by 125 mm long. These specimens were cut and machined from welded plaques (Figure 5).

Table 5. Mechanical performance of Butt-joints (at 23°C, dry-as-molded and welded conditions) with the Influence of Processing Conditions for Non-Filled Thermoplastic (longitudinal oscillations, frequency = 120 Hz, tensile strength of plastic = 66.5 MPa [3]. Agenda: T1 and T2 – thickness of plaques (see Figure 5b)

Thickness of plaque mm		Weld Pressure MPa	Melt-Down mm	Joint Strength MPa	Relative Strength of Joint
T1	T2				
Polycarbonate (PC)[8]					
3.0	12.0	0.90	0.57	64.5	0.970
3.0	12.0	3.45	0.57	63.0	0.947
Poly(butylene terepthalate)[9]					
3.2	6.1	0.9	0.58	15.6	0.26
3.2	6.1	3.45	0.55	16.4	0.27

Table 6. Mechanical Performance of T-joints (at 23°C, dry-as-molded and welded conditions) with the Influence of Design and Processing Conditions for PC (longitudinal oscillations, frequency = 120 Hz) [4]

Thickness of plaque mm		Weld	Melt-	Joint	Strength
T	F[10]	Pressure MPa	Down mm	Strength MPa	T/B Ratio
3.0	3.0	0.90	0.62	37.7	0.567
3.0	3.0	3.45	0.57	31.1	0.467
3.0	5.8	0.90	0.56	45.2	0.680
3.0	5.8	3.45	0.56	21.4	0.322

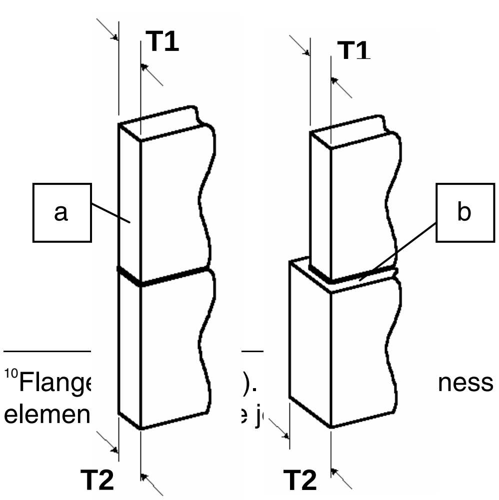
T-type and multi-purpose universal welding & testing specimens are shown in Figures 5 a,b and 6 a,b,c respectively. For each welding processing condition, a minimum of five specimens, were tested using ISO 527 protocols. All tensile test results were used for performance optimization. Samples with high tensile strength were selected for morphology (glass-fiber orientation and distribution) analysis at the weld zone (inter-phase).

TECHNICAL ADVANTAGES OF MODELS AND SPECIMENS

Accurate design of plastic parts and welding processes requires precise design of the weld beads (Figures 3 and 8), specimens (Figures 5 and 6) and models (Figure 7). In addition, properly simulated weld processing conditions, including thickness and temperatures at the inter-phase, are necessary. The performance (mechanical) test and processing conditions should be similar to real-world (production) conditions also. The applied design principles and testing methods used in this report are in a process of continual improvement [8-13, 15-16]. In this study, welded butt-joint models are presented, as seen in Figures 5-7). These models were designed to reflect real time-temperature analysis and to simulate welding for critically loaded plastic components, such as welded air intake manifolds, resonators, fluid reservoirs, etc.

In the basic study on welding process optimization and mechanical performance evaluation, we used a butt-joint design recommended for air intake manifolds, consisting of two beads 4 mm and 6 mm thick (Figures 5 and 8). Sizes of the injection molded rectangle plagues are as follow (length × width x thickness):

- 150 (or 100) mm × 60 mm × 6.25 mm
- 150 (or 100) mm × 60 mm × 4 mm.



[6] ASTM D-4066 specified for nylon/polyamide 6 moisture content wt.% *max* "as received" equal 0.2%.
[7] Mechanical performance of the thermoplastic and weld, needed for design, may be presented at equilibrium (at 50%RH, 23°C) moisture conditions also [6].
[8] Tensile strength of PC = 66.5 MPa.
[9] Tensile strength of PBT = 59.8 MPa.
[10] Flange ...). ... ness (in mm) of T-elemen ... e j...

Figure 5. The general principles of butt-joint geometry. Agenda: a–similar thickness welds when T1=T2; b–dissimilar thickness welds when T1<T2

Sizes of the welded plaques are approximately 150 (or 100) mm × 120 mm wide. The weld area is equal to 600 or 400 mm^2 respectively for the plaques 150 mm and 100 mm long respectively. Specific design applications (such as highly stressed welded components) are needed to evaluate the influence of weld-bead design (bead height), glass-fiber/fillers orientation and molding conditions on tensile strength of butt-joints.

It is possible to utilize T-type joints in various industrial applications (Figure 4 a, b, c) by welding the aforementioned molded rectangle plaque to a T–shape component. The thickness of the plaque weld bead may be varied from 1,6 mm to 6.25 mm.

An evaluation of butt-joint performance using the rectangle plaques and T-type elements/specimens has many advantages:

- Simple molding and welding tools
- Availability of the injection molded plaques
- Convenient configuration and sizes of test specimens.

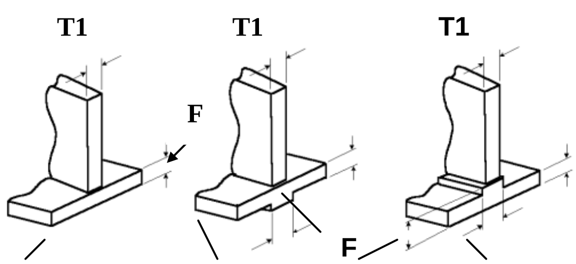


Figure 6a Figure 6c Figure 6b

Figure 6 (a, b, c). Principles of T-type joint geometry (**a –** similar by thickness parts, **b –** with T-shape weld-bead, **c –** reverse position of Tr-shape weld-bead). F is the thickness of T-element at the future joint area.

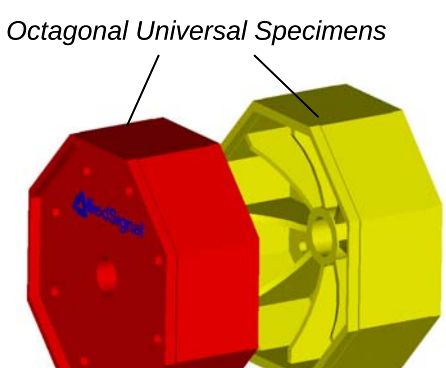


Figure 7. Multi-purpose universal welding & testing system (Consists from welded together two octagonal specimens [15]. Thickness of weld beads may vary from 2.5 to 6 mm. U.S. Patent # 6,193,133).

The advantages of a universal specimen (Figure 7) allow us to evaluate the efficiency of the welding process for butt-joints having various bead thickness, by combining the following thickness: 2.5 mm; 4.0 mm; 5.0 mm and 6 mm. The octagonal shape of the universal specimen [15] and thickness and geometry of the beads may vary 16].

TESTS RESULTS AND DISCUSSIONS

Short-term mechanical performance data (tensile stress at break, at 23°C, dry-as-molded conditions) for straight butt-joints (Figures 5a and 5b) and T-type joints Figure 6 a, b, c), made with optimized linear vibration welding conditions, is summarized in Tables 7-9.

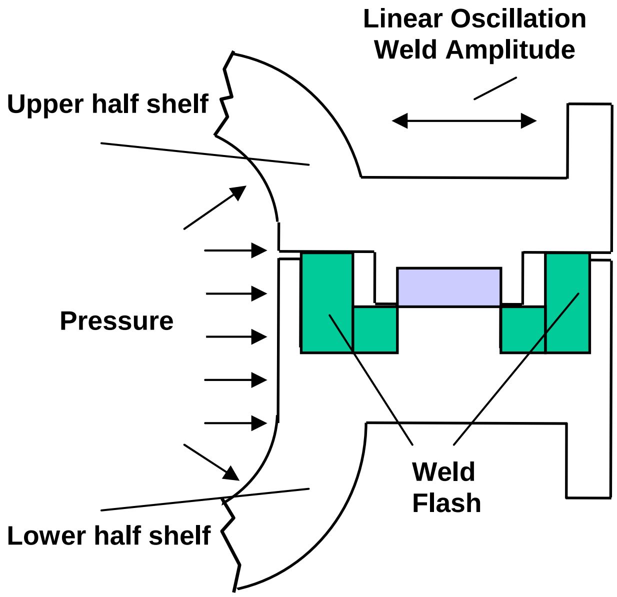


Figure 8. Butt-joint design principles for automotive linear vibration welded hollow components [1, 13-14].

ANALYSIS OF OPTIMIZED MECHANICAL PERFORMANCE OF STRAIGHT BUTT-JOINTS

For the evaluated range of weld thickness (2.5 mm to 6.25 mm) with similar and dissimilar straight butt-joints (Figure 5a and 5b respectively), the tensile strength at break remains un-changed[11] (Table 7).

Table 7. Influence of Weld Design Type on Straight Butt Weld Performance (33 wt.% short fiber-glass nylon 6, longitudinal oscillations, amplitude frequency = 220 Hz, at 23°C, in dry-as-molded and welded conditions – DAM)

Sizes of Straight Butt-joint mm	Strength, MPa
Dissimilar	
2.5 + 4.0; 2.5 + 5.0; 2.5 + 6.0	84.0 – 86.0
4.0 + 5.0; 4.0 + 6.0	84.0 – 86.0
Similar	
2.5 + 2.5; 4.0 + 4.0; 5.0 + 5.0; 6.0 + 6.0	82.5 – 85.3

Table 8 shows that with increase of meltdown from 0.5 mm to 6.2 mm, for straight joints (Figure 5), the tensile strength of the weld also increases for linear longitudinal oscillation conditions. This increase may exceed the tensile strength of the base polymer (matrix) by 17%. The high strength of the straight butt weld with respect to the performance of the plastic matrix has been reported previously for linear longitudinal [8-9], linear cross-thickness, linear by angle (direction of 45°) and orbital vibration oscillations [10-12]. Similar results were reported [6-7] for two semi-crystalline plastics.

Table 5 shows performance data for two welded amorphous plastics. It shows that they achieved relative strength equal to 0.95-0.97 for polycarbonates (PC) and 0.26-0.27 for poly(buthelene) terephalate (PBT) based plastics respectively. With increased melt-down the perimeter of inter-phase, which is responsible for the tensile strength (at 23°C, dry-as-molded and dry-welded), increases also.

Table 8. Mechanical Performance (at 23°C, in dry-as-molded and welded conditions – DAM) of Butt-Joints with the Influence of Design and Processing Conditions for 33 wt.% Short Fiber-Glass Nylon Based Plastic (longitudinal oscillations, amplitude frequency = 220 Hz), T-type Butt-joints

Thickness mm		Melt Down mm	Joint Strength MPa	Relative Strength of Joint	Relative to Matrix Strength
T1	T2				
4.0	6.25	0.50	74.5	0.40	0.91
4.0	6.25	1.2	85.6	0.46	1.04
4.0	6.25	2.0	87.9	0.47	1.07
4.0	6.25	3.5	89.3	0.48	1.09
4.0	6.25	6.2	95.8	0.52	1.17

Table 9. Mechanical performance (at 23°C, in dry-as-molded and welded conditions – DAM) of straight and T-joints for 33 wt.% short fiber-glass reinforced nylon 6. Longitudinal oscillations, amplitude frequency = 220 Hz)

Design Version		Melt-down mm	Relative Strength		Relative Strength Ratio T/B
T1	T2/F		Butt	T	
Butt-joints (T1 with T2)					
4.0	4.0	1.0	0.92	0.53	0.576
4.0	4.0	1.5	0.99	0.47	0.475
4.0	4.0	2.0	0.99	0.42	0.424
4.0	6.0	1.0	0.95	0.65	0.684
4.0	6.0	1.5	1.00	0.54	0.540
4.0	6.0	2.0	1.05	0.60	0.571
4.0	6-Tr	1.0	(0.95)	0.74	0.779
4.0	6-Tr	1.5	(1.00)	0.57	0.570
4.0	6-Tr	2.0	(1.05)	0.49	0.467
4.0	6-T	1.0	(0.95)	0.96	1.010
4.0	6-T	1.5	(1.00)	0.99	0.990
4.0	6-T	2.0	(1.05)	1.06	1.010

In our calculation of the nominal stress of butt weld at break, we used the nominal value of a plane cross-section of the inter-phase, without the influence of geometric changes at weld area. The importance of these geometric changes for mechanical performance, was described previously in [6]. All tested straight butt-joints made from 33 wt.% nylon 6 failed at the weld inter-

[11] Data shown in Table 7 was obtained for three various commercial avilable lots of 33wt.% nylon 6 at optimized welding conditions.

phase only. Outside of the weld inter-phase, damage (plastic necking) was observed in un-filled nylon straight welds.

Table 9 shows a comprehensive analysis of the influence of design on mechanical performance of T-type butt-joints (Figures 6 a, b, c). The increase of meltdown (in a range from 1.0 mm to 2.0 mm) for similar thickness welded plaque joints, Figure 6 a) leads to a decrease of the weld breaking strength. This decrease is equal to 25% and 16% for plaques 4 mm and 6 mm thick, respectively. For the optimized design version Figure 6b), the mechanical performance achieved was insensitive to melt-down in the same range (Table 9).

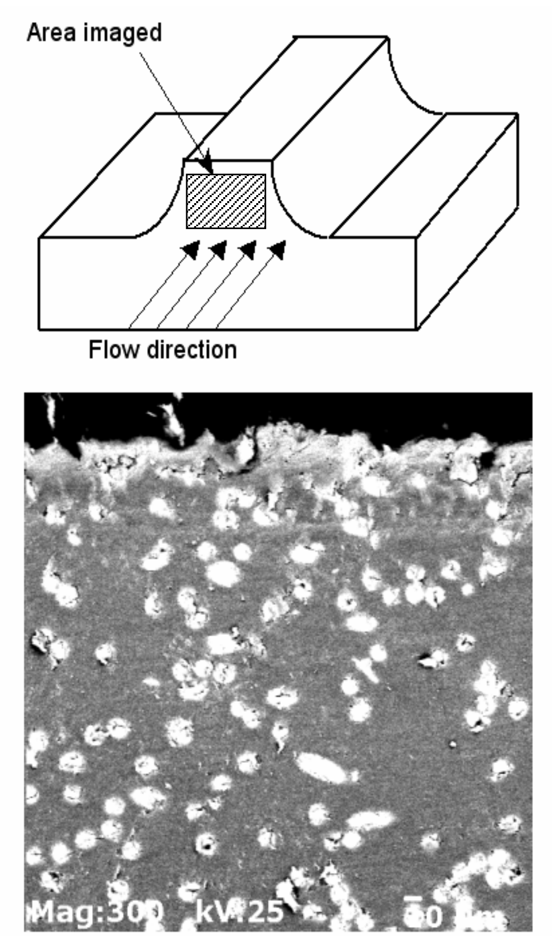


Figure 9. Glass-fiber orientation at injection molded "tooth" area of weld bead (for 33 wt.% short fiber-glass reinforced nylon 6)

The relative strength of T-type joints (Figure 6) varied from 0.5-0.7 for design versions "a" and "c" respectively, and was in a range of 0.96-1.06 for design version "b", which is a result of applied design (glass-fiber) optimization (re-orientation). Figure 9 shows glass-fiber orientation effects (reinforcement challenges) for T-type elements containing additional "tooth". For the optimized design, the relative strength ratio (strength of T-type to strength to straight joint) ranged from 0.99-1.01. T-type butt-joint allowed us to reach a similar high mechanical performance, which was demonstrated previously with straight butt-joints (Figure 10). All tested T-type butt-joints made from 33 wt.% nylon 6, failed at the weld inter-phase only. Outside of the weld inter-phase, damage (plastic necking) was observed for un-filled nylon straight welds.

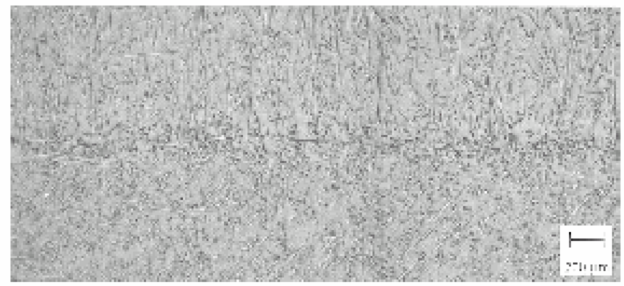


Figure 10. An example of glass-fibers re-orientation at weld inter-phase (melt-pool) for 33 wt.% short fiber-glass reinforced nylon 6. A part of glass-fiber is crossing inter-phase at optimized welding conditions.

In our report to ATTCE[12] 2201 [17] we discuss the influence of glass-fiber orientation on mechanical performance (tensile strength σ_c) of injection molded fiber-glass reinforced nylon based thermoplastics by the following equation:

$$\sigma_c = \frac{v_f \sigma_f}{(1 - L_c / 2L_{average}) C_o(t, RH)} + v_m \sigma_m(t), \qquad (1)$$

where:

- $\sigma_m(t)$ is strength at yield of polymer (matrix) at temperature *t*, in MPa.
- $L_{average}$ - is average fiber-glass length, in mm or in μm.
- $C_o(t, RH\%)$ - is the orientation factor with the influence of temperature *t* and moisture (RH) effects. Value of C_0 is in the following range:

$$1 \geq C_0(t, RH) \geq 0.3$$

The orientation parameter $C_o(T, RH)$ is equal to 1 for longitudinal (at flow direction) orientation. The tensile strength at this direction reaches *maximum* value. For perpendicular to flow direction, this value may decrease by 30% - 50% (approximately) from the plastic strength at flow direction (at test temperature *t* and moisture in plastic).

The orientation of any single fiber may be calculated from its elliptical profile by the following equation:

$$\cos(\vartheta) = \frac{d_{\min or}}{d_{major}} = \frac{4A_{ellipse}}{d_{major}}, \qquad (2)$$

[12] ATTCE – Automotive & Transportation Technology Congress & Exhibition (SAE International and Messe Dusseldorf).

where: ϑ - is the angle the fiber-glass axis makes with the melt-flow direction: $d_{\min or}$ - is the minor axis, $d_{\min or} = d_f$; d_{major} - is the ellipse major axis, and A - is the area of the ellipse. The $\cos(\vartheta)$ data is the key factor in calculation of the value of orientation factor/parameter $C_o(t, RH\%)$.

Presence of "tooth" at T-type joint positively changed glass-fiber orientation at areas melt-pool formation which need to be considered with met-down parameter also (Table 9). From other side it is critically important to apply optimized parameters during injection molding and prevent possible creation of voids at thick cross-section (Figure 11).

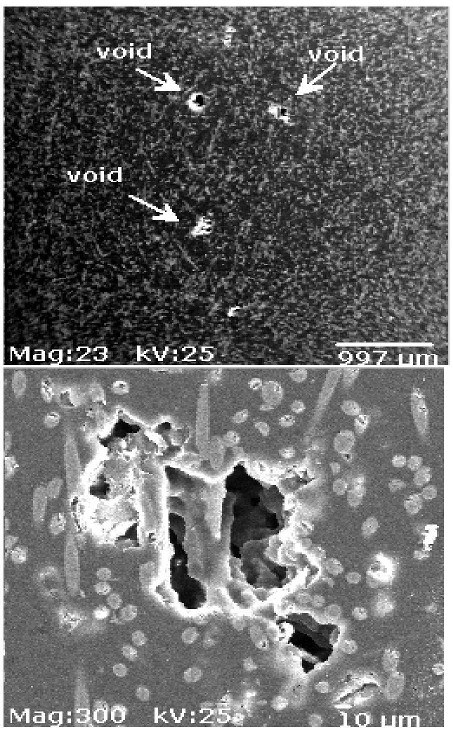


Figure 11. An example of micro-voids formation during non-optimized injection molding of glass-fiber reinforced thermoplastic

A VIEW OF FUTURE INVESTIGATION

The analysis presented here on mechanical performance of straight and T-type nylon welds/joints, is in disagreement with some data previously published for amorphous and semi-crystalline plastics [3-7]. Detailed analysis of similarities of the observed mechanical performance requires evidence to be shown on glass-fiber re-orientation effects at weld areas. These results will be discussed of a following paper to the future meeting of SAE International.

Injection molding simulation software has been commercially available since the late 1970's, notably from companies such as Moldflow® and C-Mold® (now part of Moldflow)® [2]. These two programs have been very useful in gaining insight into the flow behavior during the molding process and allows us to predict useful information about fiber orientation, based on any particular part design or molding process. However, until recently these programs were only able to predict fiber orientation in 2.5-dimensional simulations, whereby the thickness is prescribed numerically on a shell representation of the part.

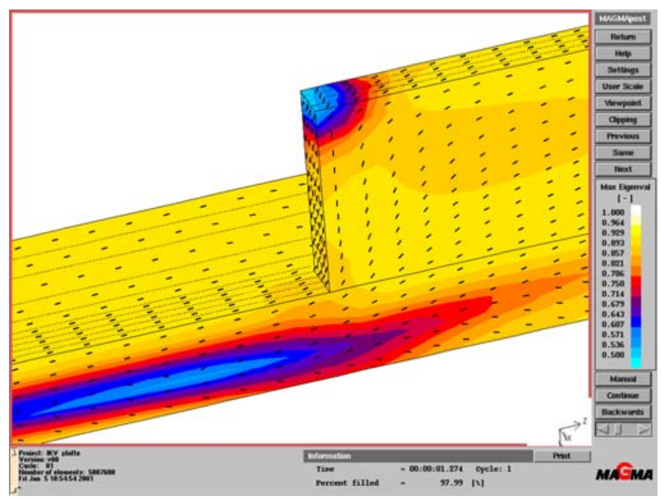


Figure 12. SigmaSoft™ analysis close-up plot showing predicted fiber orientation through thickness. Fiber principle direction is indicated by the black lines. Degree of orientation is shown with color-bar[13] on right—yellow (light) indicates highly aligned, blue (dark) is random.

Unfortunately, the resulting fiber orientation predictions throughout the thickness of the part are not easy to interpret and the accuracy of the prediction has been somewhat unreliable

Highly aligned
(yellow)

[13] SigmaSoft™ results are always produced in color with varying density. Unfortunately, this report is printed in black and white and only shows degrees of gray.

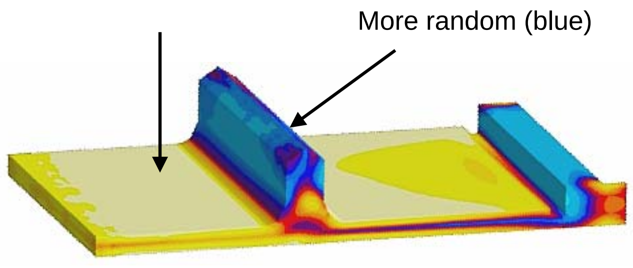


Figure 13. SigmaSoft™ analysis of plate with rib, similar to welding sample specimen. Random orientation is observed in center rib (weld) area.

A newly developed software package (SigmaSoft™) has advanced the technology to use a true, three-dimensional numerical representation of the molded part, enabling us to investigate and predict fiber orientation throughout the thickness explicitly.

To address these issues, there are several ways to approach an estimation of fiber orientation via computer simulation and existing knowledge of strength and part geometry. Figure 12 shows a typical analysis result plot, indicating the principal direction vectors along with a color pattern to illustrate the degree of fiber alignment anywhere in the part. More importantly, we can investigate the fiber orientation within the pre-welded geometries and then tailor the part design to promote favorable fiber alignment. Figure 13 shows analysis results for a typical plate/rib configuration, illustrating a beneficial scenario for optimizing strength within the rib area, due to the random fiber orientation within the center rib. With thickness increase from 2 mm to 6 mm, mechanical performance of glass-fiber reinforced plastics will also increase from 60% to 100% for the cross-flow direction (Figure 14).

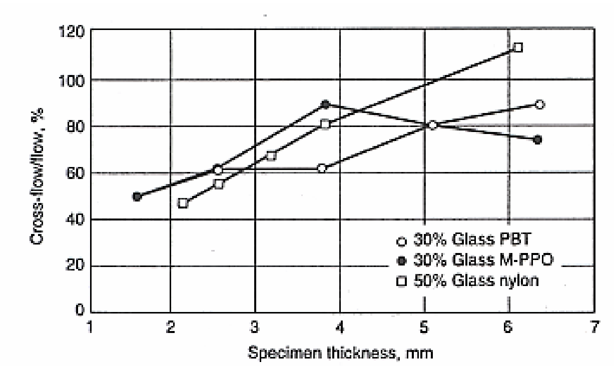


Figure 14. The influence flow direction, part/specimen thickness on mechanical performance of injection molded glass-fiber reinforced thermoplastics (nylon, PBT and M-PPO based) [1].

CONCLUSIONS

Short glass-fiber reinforced nylon is the thermoplastic material of choice for a variety of injection molded and linear vibration welded structural, highly stressed components in automotive applications. Frictional linear and orbital plastic welding technologies are very efficient joining methods for design and manufacture of various critically loaded thermoplastic parts, where high mechanical performance is a critical factor for end-use performance.

Optimized in weld geometry and glass-fiber re-orientation, T-type butt-joints can attain the same high mechanical performance, as was demonstrated previously for straight butt-joints.

Under optimized injection molding and welding conditions, the tensile strength of straight butt-joints was equal to or higher than the tensile strength of the base polymer (matrix). The results from this investigation provide recommendations for the design of various vibration welded automotive thermoplastic parts with improved mechanical performance.

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REFERENCES

1. G. Trantina, R. Nimmer, Structural Analysis of Thermoplastic Components, 366 pages, McGraw-Hill, Inc., New York (1994).
2. D. V. Rosato, D. Di Mattia, D. V. Rosato, Designing with Plastics and Composites: A Handbook, 979 pages, Van Nostrand Reinhold, New York (1991).
3. V. Stokes, Assessment of Geometries for Determining Strength of Thermoplastic Vibration Welds, Journal of Material Science, pp. 2393-2403, Vol. 35, (2000).
4. H. Potente, M. Uebbing, and E. Lewandowski, The Vibration Welding of Polyamide 66, Journal of Thermoplastic Composite Materials, Vol. 6, pp. 2-17, January, (1993).
5. Ian D. Froment, Vibration Welding Nylon 6 and Nylon 66 – A Comparative Study, SPE/Antec'95 Conference Proceedings, Vol. 1, pp. 1285-1289, (1995).
6. J. MacDonald, and P. Bates, Vibration Welding of Glass Filled Nylon 66 – Effects of Part Geometry, *SAE International - Society of Automotive Engineers,* Detroit, MI, Automotive Plastics: Components, Processes, and Technology SP-1575, 6 pages, 2001.

7. P. Bates, D. Couzens, and J. Kendall, Vibration Welding of Highly Reinforced Thermoplastics Composites, Proceedings of the American Society for Composites – 15-th Technical Conference, pp. 221-228 (2000).
8. V. Kagan, Forward to Better Understanding of Optimized Performance of Welded Joints: Local Reinforcement and Memory Effects for Polyamides, SAE International - Society of Automotive Engineers, Detroit, MI, "Automotive Plastics: Components, Processes, and Technology" SP-1575, 14 pages, 2001.
9. V. Kagan, Lui, Siu-Ching, etc., The Optimized Performance of Linear Vibration Welded Nylon 6 and Nylon 66 Butt-joints, SPE/Antec'96 Conference Proceedings, Vol. 1, pp. 1266-1274, (1996).
10. V. Kagan, et al., Performance of Vibration Welded Thermoplastic Joints, U.S. Patent # 5,874,146 (1999).
11. V. Kagan, Joining of Nylon Based Plastic Components – Vibration and Hot Plate Welding Technologies, SPE/Antec'99 Conference Proceedings, Vol. 1, pp. 1349-1359, (1999).
12. V. Kagan, Optimizing Welding Temperature of Semi-Crystalline Thermoplastics – Memory Effects of Nylon, SPE/Antec'2000 Conference Proceedings, Vol. 1, pp. 1288-1301, (2000).
13. C. S. Lee, and V. Kagan et al., Optimization of Vibration Weld Joint Strength for Plastic Air Intake Manifold, SAE Technical Paper # 980730, pp. 111-115, Detroit, 1998.
14. W. Nelson Kenneth, Vibration Welding: A Low Cost Assembly Process for Thermoplastic Intake Manifolds, SAE International, SP-950230, 10 p., (1995).
15. V. Kagan, et al., Method and Articles for Evaluating Welding Joints, U.S. Patent # 6,193,133 (2001).
16. V. A. Kagan, et. al., Frictionally Welded Thermoplastic Articles Having Improved Strength, U.S. Patent # 6,447,866 (2002).
17. V. A. Kagan, J. S. Chung, and R. McPherson, Family of High Modulus (HMG) Nylon Based Plastics Increases Mileage and Reduce Weight, 15 pages, *SAE International - Society of Automotive Engineers,* Detroit, MI, Technical Paper 2001-01-3432, (2001).

KEYWORDS

Nylon, polyamide, fiber, thermoplastic, mechanical performance, strength.

PHRASE INDEX

Matrix polymer – unfilled plastic (polymer).

DEFINITIONS, ACRONYMS, ABBREVIATIONS

ASTM: American Society of Testing and Materials
ANTEC: Annual Technical Conference of Society of Plastic Engineers (SPE)
DAM: dry as molded
GF: fiber-glass reinforcement
ISO: International Organization for Standardization
PA: polyamide
PBT: poly(butylene terepthalate
PC: polycarbonate
PP: polypropylene
RH: relative humidity
SPE: Society of Plastic Engineers

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