BASF Corporation

BASF

THE EFFECTS OF WELD GEOMETRY AND GLASS-FIBER ORIENTATION ON THE MECHANICAL PERFORMANCE OF JOINTS – *PART I: WELDS DESIGN ISSUES*

Abstract

The mechanical performance of injection molded glass-fiber reinforced [thermo]plastics components is anisotropic and depends on the fiber orientation and distribution. The purpose of this comprehensive analysis is to show the relationship between short-fiber orientation at the pre-welded bead and wall areas, and the mechanical performance of welded butt-joints that have various geometry and thickness, namely "straight" and "T-type" welds.

Findings on the mechanical performance of these two different types of butt-joints by the design and geometry butt-joints will help designers and technologists with material selection, welding processing, and design optimization. In a subsequent paper (Part II)[1], we related these findings to the kinetics of glass-fiber re-orientation and micro-structural changes and how they influence part and weld design.

Introduction

Short glass-fiber[2] reinforced plastics are the materials of choice for a variety of welded structural components. Various welding technologies, such as frictional (linear vibration, orbital vibration and spin), hot plate, laser (infrared) are applied in manufacturing of these components. To optimize their design and mechanical performance, we need to utilize a variety of engineering properties, related to both the reinforced plastics and welded joints. The mechanical performance of the weld (Figure 1) is a critically important parameter in plastic part design. Previously, the linear vibration welding process and mechanical performance of welded joints was described in [1-5]. Precise and advanced design of welded parts requires use of specific engineering properties, related to optimized weld performance, which may influence on end-use performance of the part [1, 4-7]. Also in previous report to ANTEC'96, our findings revealed the effects local reinforcement effects in the weld inter-phase on linear vibration welding technology [7-8].

In a presentation at ANTEC'99 we discussed the kinetics of the weld-melt temperatures for various nylons using linear vibration and hot-plate welding technologies [9]. Under optimized welding conditions, the tensile strength of welded nylon butt-joints was equal to or 11% higher (Table 1) than tensile strength of the base polymer (matrix). The same mechanical performance of the welded nylon was seen [9] for orbital vibration welding technology (Table 2). With optimized linear vibration welding conditions, the maximum temperatures of the weld-melt (in inter-phase area) were significantly above the melt point of welded nylon 6 and nylon 66. In our report to ANTEC'2000 we associated these maximum temperatures with "memory effects" of semi-crystalline thermoplastics [10]. All of our results presented to ANTEC [6-10] were produced for straight butt-joints (Figure 2, similar and dissimilar in thickness of welds) made with various linear and orbital vibration welding parameters. T-type joints are very commonly used for many applications [4-6, 9-10], where welded nylon is required.

Remarks on Mechanical Performance of Welded Butt-joints: Straight and T-type

In our report to SAE'2001 we analyzed [6] the influence of joint design on mechanical performance of the straight and T-type nylon butt-joints. Using optimum design and welding conditions, the mechanical performance on 33 wt.%[3] glass-fiber reinforced welded nylon 6 was similar for both design (Table 3). These results are in disagreement with data published [1, 4-5] for 33 wt.% glass-fiber reinforced nylon 66, continuously reinforced polypropylene (PP) and non-filled polycarbonate (PC) and poly(butylene terepthalate (PBT) plastics (relative strength of joints varied in wide range from 0.27 to 0.97). These discrepancies may relate to the type of plastics - amorphous and/or semi-crystalline – the

1 Part II: Kinetics of Glass-fiber Orientation and Performance at Bulk and Weld Areas" (in progress).

2 The diameter of used short fiberglass is typically in the range of 8 µm to 17 µm, and their length in injection molded parts (or specimens) of 200 µm to 350 µm.

3 By weight in %.

geometry of the specimens, linear vibration welding processing conditions, etc.

This 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, processing and testing parameters for the same lot of commercially available nylon 6 grade.
- Repeatability in processing parameters and mechanical test results.
- In-depth analytical investigation into the influence of part and weld design on the kinetic of glass-fiber orientation, including structural and micro-structural changes.

Experimental - Mechanical Performance of Butt-joints: Straight with T-type

Welding Machine and Processing Parameters

All specimens and models were welded using a small, laboratory-scale universal linear vibration welding machine (Mini-Welder-II type[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 [7-10]. Meltdown was the only non-fixed parameter, varying approximately from 1.0 mm to 2.0 mm.

Material and Mechanical Tests Procedures

The material analyzed in this investigation was heat stabilized 33 wt.% short glass-fiber reinforced nylon 6 - Capron® 8233G HS[5]. This commercially available grade is widely used for various welded structural components in automotive under-the-hood applications (air intake manifolds, etc.) and power tools such as chainsaws, leaf blowers, etcetera.

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 [6]. 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 2), T-type and multi-purpose universal welding & testing specimens (Figures 3, 4 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 analysis at the weld zone (inter-phase).

Advantages of Models and Specimens

Accurate design of plastic parts and welding processes requires precise design of the weld beads, specimens (Figure 2 and Figure 3) and models (Figure 4). In addition, properly simulated weld processing conditions, including thickness and temperatures at the inter-phase, are necessary. The performance test and processing conditions should be similar to real-world conditions also. The applied design principles and testing methods used in this report are in a process of continual improvement [6-11]. In this study, welded butt-joint models are presented, as seen in Figure 2, and Figures 3-4). 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. 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.

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),

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

[5] Capron® - is a registered trademark for BASF Corporation polyamide/nylon plastic products.

[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].

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 3 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 (Figure 2) and T- elements (Figure 3) has many advantages:

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

The advantages of a universal specimen (Figure 4) 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 and thickness of the beads may vary [11].

Discussions

Mechanical performance data for straight butt-joints (Figures 2a and 2b) and T-type joints (Figure 3 a, b, c), made under optimized linear vibration welding conditions, is summarized in Tables 4-6.

Straight Butt-joints

For the evaluated range of weld thickness (from 2.5 mm to 6.25 mm) with similar and dissimilar straight butt-joints, the tensile strength at break remains unchanged[8] (Table 4). Table 5 shows that with increase of meltdown (in the range of 0.5 mm to 6.2 mm) for straight joints (Figure 2b), the tensile strength of the weld is also increasing 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 [6-7], linear cross-thickness, linear by angle (direction of 45°) and orbital vibration oscillations [8-10]. Similar results were reported [4-5] for two semi-crystalline plastics. Analysis [1] of influence of welding conditions on mechanical performance of two amorphous un-filled plastics (PBT and PC) shows that they achieved relative strength equal to 0.95-0.97 for PC and 0.26-0.27 for PBT based plastics respectively. With increased melt-down the perimeter of inter-phase, which is responsible for the tensile strength, increases also.

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

T-type Butt-joints

Table 6 shows a comprehensive analysis of the influence of design on mechanical performance of T-type butt-joints (Figure 3 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 3 a) leads to a decrease of the weld breaking strength. This decrease is equal to 25% and 16% for plaques 4mm and 6mm thick, respectively. For the optimized design version (Figure 3 b), the mechanical performance achieved was insensitive to melt-down in the same range. The relative strength of T-type joints 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 optimization (Figure 3). 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. 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.

A View of Future Developments

The analysis presented here on mechanical performance of straight and T-type nylon joints is in disagreement with some data, previously published for amorphous and semi-crystalline plastics. 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 in Part II[9] of a following paper.

Conclusions

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

---

[8] Presented in Table 7 data was obtained for 3 various lots of 33wt.% nylon 6 at optimized welding conditions.

[9] See footnote # 1.

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

Acknowledgements

Special thanks to Frank Aadahl, Jeff Frantz (Branson Ultrasonic Corporation), Lynn Griffin, Nanying Jia, Roberto Sanchez, Craig Scott and Steve Serna for help in preparing this paper for publishing.

References

1. Stokes, V., "Assessment of Geometries for Determining Strength of Thermoplastic Vibration Welds", Journal of Material Science, pp. 2393-2403, Vol. 35, (2000).
2. Potente, H., Uebbing, M. and Lewandowski, E., "The Vibration Welding of Polyamide 66", Journal of Thermoplastic Composite Materials, Vol. 6, pp. 2-17, January, (1993).
3. Froment, Ian D., "Vibration Welding Nylon 6 and Nylon 66 – A Comparative Study", SPE/Antec'95 Conference Proceedings, Vol. 1, pp. 1285-1289, (1995).
4. MacDonald, J., and Bates, P., "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.
5. Bates, P., Couzens, D., and Kendall, J., "Vibration Welding of Highly Reinforced Thermoplastics Composites", Proceedings of the American Society for Composites – 15-th Technical Conference, pp. 221-228 (2000).
6. Kagan, V. A., "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.
7. Kagan, V., 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).
8. Kagan, V., et al., "Performance of Vibration Welded Thermoplastic Joints", U.S. Patent # 5,874,146 (1999).
9. Kagan, Val A., "Joining of Nylon Based Plastic Components – Vibration and Hot Plate Welding Technologies", SPE/Antec'99 Conference Proceedings, Vol. 1, pp. 1349-1359, (1999).
10. Kagan, V., "Optimizing Welding Temperature of Semi-Crystalline Thermoplastics – Memory Effects of Nylon", SPE/Antec'2000 Conference Proceedings, Vol. 1, pp. 1288-1301, (2000).
11. Kagan, V., et al., "Method and Articles for Evaluating Welding Joints", U.S. Patent # 6,193,133 (2001).

Keywords

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

Table 1[10]. Mechanical Performance of Butt-Joints with Influence of Plastic Composition and Design for Nylon Based Plastic (longitudinal oscillations, optimized processing conditions [6-9]).

Thickness of plaque, mm		**Wt. % GF**	**Joint (B) Strength MPa**	**Relative Strength of Joint**	**Relative to Matrix Strength**
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

Table 2. Influence of Shape and Direction of Oscillation on Weld Performance (PA 6, 33 wt.% GF)

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

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)

Type of Specimen	**Tensile Strength, MPa**
Straight (Figure 2)	85.6
T – type (Figure 3)	84 - 86

Table 4. Influence of Weld Design Type on Straight Butt Weld Performance (33 wt.% short fiber-glass nylon 6, longitudinal oscillations, amplitude frequency = 220 Hz)

Sizes of Straight Butt-joint, mm	**Strength, MPa**
Dissimilar	
2.5 + 4.0; 2.5 + 5.0; 2.5 + 6.0	84 - 86

[10] Note for Tables 1-6: Presented mechanical performance data was developed at 23°C, at dry-as-molded conditions – DAM. The tensile strength of base plastic is equal (in MPa): Average = 82.0. St. Dev = 1.3.

4.0 + 5.0; 4.0 + 6.0	84 - 86
Similar	
2.5 + 2.5; 4.0 + 4.0; 5.0 + 5.0; 6.0 + 6.0	82.5 – 85.3

Table 5. Mechanical Performance 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)

Thickness mm		**Melt Down mm**	**Joint Streng. 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 6. Mechanical performance of straight and T-joints for 33 wt.% short fiber-glass reinforced nylon 6. Longitudinal oscillations, amplitude frequency = 220 Hz. **B** – straight type joints (Figure 2). **T** – type joints (Figure 3).

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

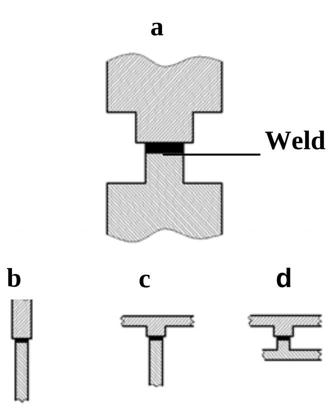

Figure 1. Welded joint design principles. Legend: **A** – joint design; **B** – straight; **C** – T–type; **D** – shear/lap joint.

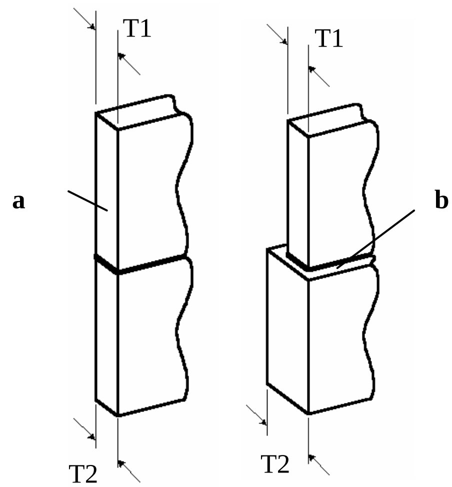

Figure 2. Principle of butt-joint geometry (**a –** similar, and **b -** dissimilar thickness welds)

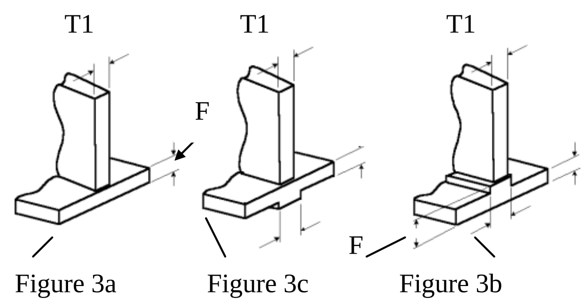

Figure 3 (a, b, c). Principles of T-type joint geometry (**a –** similar by thickness parts, **b –** with T-shape weld-bead, **c –** reverse position of Tr-shape weld-bead). F is the thickness of T-element at the future joint area.

Octagonal Universal Specimens

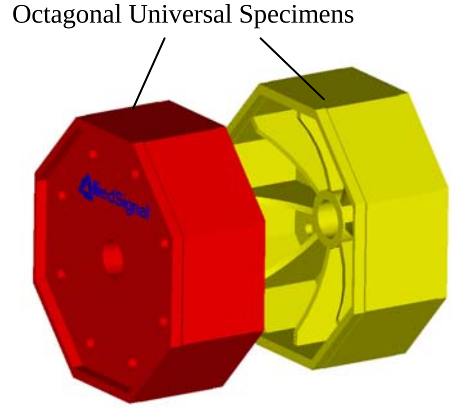

Figure 4. Multi-purpose universal welding & testing system. Consists from welded together two octagonal specimens (U.S. Patent # 6,193,133 [11]).

BASF Corporation
3000 Continental Drive - North
Mount Olive, New Jersey 07828-1234

www.basf.com/usa
www.plasticsportal.com

HELPING MAKE PRODUCTS BETTER™

BASF