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OPTIMIZED MECHANICAL PERFORMANCE OF WELDED AND MOLDED BUTT JOINTS: *PART II – WELD AND KNIT LINES INTEGRITY*

Abstract

Recent developments were oriented on the analysis of the mechanical performance at local (knit lines and welds) and bulk (molded part) areas, with the influence of molding and welding conditions. It has been found that for non-reinforced and reinforced nylon, the mechanical performance in the knit planes and welded areas are approximately equal to the mechanical performance of a base resin (matrix).

The observations on similarities and differences in the formation of knit and weld lines are presented in Part I of this paper. Analysis of mechanical performance at weld at knit lines of various nylons discussed in Part II.

Introduction

Mechanical performance, of the injection molded and welded thermoplastic components, is very critical for the various industrial applications (automotive under-the-hood, bumpers, appliances, power-tools, etc.) [1-4]. High performance non-reinforced, fiber-glass reinforced and glass/mineral versions of nylon 6 based plastics were utilized in many applications [4-6]. The automotive and power-tools industries have developed a culture of reliability and cost effectiveness, in which high risks and adventures are not encouraged.

There are many design and technology cases for welded plastic components, which require multiple gated injection molding systems. Mechanical performance of these welded, injection molded multiple gated plastic parts such as chassis/bodies, air intake manifolds, etc., depends from uniform distribution and orientation of flows and welds, and the material property patterns.

The process of weld (weld inter-phase) formation during welding (Figure 1) is similar to knit line formation in injection molding. Basic similarities and differences in formation of weld and knit lines were discussed in Part I of this article. Specific data on localized mechanical properties in knit and weld areas is very important for the structural analysis and life assessment of various highly stressed multiple gated and welded plastic parts such as air intake manifolds, resonators, fluid reservoirs, chassis, etc.

Experimental

Materials, Specimens and Test Procedures

The tensile strength of material, at the knit line and weld is “key data” – the first step in the design of multiple gated and welded thermoplastic parts, molding and welding process optimization, and comparative analysis of material suitableness for molding with following welding. In this study, we used the following grades of nylon 6 based plastics (all heat stabilized - HS series):

- Non-reinforced /non-filled nylon.
- Short[a] fiber-glass reinforced plastics with the level of reinforcement from 6 wt.% to 63 wt.% GF.
- Mineral filled plastic (40 wt.% MF).
- Mineral filled and short fiber-glass reinforced (25 wt.% MF + 15 wt.% GF).
- Impact modified plastic (5 wt.% IM).
- Impact modified and short fiber-glass reinforced (5 wt.% IM + 33 wt.% GF).

Mechanical performance of the weld was obtained using welded together rectangle injection molded plaques with the following two sizes: 150 x 55 x 4 mm and 150 x 55 x 6 mm. Sizes (length x width) of the welded plaques are 150 (or 100) mm x 120 mm (approximately). Weld area is equal to 600 (or 400) mm^2, respectively, for the plaques 150 mm and 100 mm long. For the tensile test, we used welded specimens machined from welded plaques with cross-section in weld area (width x thickness = 10 x 4 mm).

To illustrate the influence of knit lines on mechanical performance of analyzed plastics, the multipurpose test both sides gated specimens (ISO 3167, with the thickness equal 4 mm) were used. Tensile properties of plastics were obtained using one side gated ISO specimens. ISO 527 tensile test procedures were used in this investigation. Five tensile specimens were tested at every condition. All tests were conducted at

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[a] Short fiber-glass reinforcements are (in average): 11-13 μm in diameter, and 240-320 in length.

23°C for "dry-as-molded" and "dry-as-welded" conditions[b] (Tables 3-10).

Welding and Injection Molding Procedures

Both injection molding and welding conditions were optimized by criteria of mechanical performance (comprehensive tensile properties). Prior to injection molding, all materials were dried by ASTM requirements.

For welding, we used various joining technologies such as linear vibration, orbital vibration, hot plate (contact method), ultrasonic and infra-red/laser transmission. The influence of the following key welding process variables were taken into account for linear vibration welding (as an example):

- Weld amplitude.
- Weld clamp and hold/cooling pressure.
- Melt-down (collapse).
- Welding, holding/cooling time.

In linear vibration welding, we used Mini-Welder-II type[c] machine. For bigger sizes, welding machines used plaques, which were too small (and clamp pressures are very high for process optimization). Optimization of vibration welding conditions (including temperature of inter-phase) for nylon based plastics were discussed in [7-8].

During injection molding conditions, we used the recommendation [9] based on the design experiment approach (Taguchi Method) where the following processing variables were taken unto account:

- Melt and mold temperatures.
- Injection and hold pressure.
- Cooling and holding time.
- Back pressure.

Information on the effects of injection molding variables on mechanical performance of nylons is not abundant and a part of published results are discrepant. But what does exist for non-nylons gives us the following guidelines [1, 10]:

- Increasing both melt and mold temperatures will increase weld line tensile strength.
- Excessive melt temperatures will degrade the joined polymer causing a general strength reduction of the bulk, including weakness at the weld plane.
- Fill rate and packing pressure effects are positive in limited areas only.

Higher melt temperature promotes polymer molecular knitting and chains entanglement at the weld inter-phase and yield less net orientation. Increasing mold temperature promotes slow cooling. In most cases, the mold temperature effects (they are positive) are not so effective as the melt temperature effects. Effects of these complex changes can also depend on a particular grade of thermoplastic, molded part design, and mold and melt temperature levels.

Knit Line Strength

The effects of the inherent knit line integrity were analyzed in [1, 10-11]. In these studies, we evaluated the effects of the knit line on tensile strength (Tables 1 and 2) of several thermoplastics (polysulfone – PSU, styrene acrylonitrile – SAN, polypropylene – PP, and polyphenylene sulfide – PPS, high-density polyethylene – HDPE, nylon 66). For non-filled plastics, the tensile strength of the knit line is equal to approximately or less (up to 17%) to tensile strength of the base material (Table 1). It was found for fiber-glass reinforced plastics, that the percentage of loss in strength, at the weld line, is greatly increased (up to 80%, Table 2). However, absolute knit line strength doesn't increases as more or stronger reinforcement is added.

The loss of strength at the knit line fiber-glass reinforcement is caused by:

- There is a sharp V-type notch at the knit plane surfaces that acts as the stress-strain concentrator.
- Fiber-glass orientation in the knit inter-phase occurs at the right angles to the principal melt flow patterns (Figures 2-3).
- This orientation is contributed to the strength reduction in the knit line (inter-phase area).
- Incomplete molecular entanglement or diffusion.
- Possible presence of the contamination or micro-voids at the knit line (inter-phase).

The absolute value of the melt and mold temperatures affect the microstructure formation at the skin and core areas . For injection molded nylon 6 based plastics, rapid quenching produces a skin with lower cristallinity than at core, which cools more slowly. The melt front is influential to flow rates – slow rate will form elliptic flow configuration that affects the development of the V-type notch.

Mechanical performance of various fiber-glass reinforcement nylon 6 plastics at the knit-line area is shown in Table 3. When the tensile strength of the thermoplastic increases from 82.5 to 229 MPa (at the

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[b] ASTM D-4066 specified for nylon/polyamide 6 moisture content wt.% *max* "as received" equal 0.2%.

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

range of glass-reinforcement from 0 to 63 wt,% GF), tensile strength retention for the knit-line/plane decreases from 99.2 to 36.5% (see Table 3). The analysis of the presented results are showing that the tensile strength at the knit line remains the same for evaluated levels of fiber-glass reinforcement (from 0 to 63 GF wt.%) and is equal (approximately) or slightly above of the tensile strength of non-reinforced plastic (83.3 ÷ 89.2 MPa). Similar results were obtained for nylon 66 based plastic (Table 4) with the same level of fiber-glass reinforcement.

Tensile strength of mineral filled (MF) plastic is increasing slightly (Table 5), and at the same time, tensile strength at knit line decreases by 14.5% (for 40% MF nylon). Impact modifiers (IM) reducing the tensile strength of nylons by 35% approximately (Table 6). The combined effect of fiber-glass reinforcements (33 wt.% GF) and impact modifiers (5% IM) is reducing tensile at knit line strength by 60% approximately. However, absolute knit line strength decreases significantly for impact modified plastics (Table 5).

Weld Line Strength

In our reports to Antec [7-8], we presented results on optimized mechanical performance of various nylons based plastics. In these studies, we evaluated mechanical performance of welded joint for the following widely used welding technologies:

- Linear vibration.
- Orbital vibration.
- Hot plate (contact).
- Ultrasonics.
- Infra-red/laser (through-transmission).

Data on the efficiency of five welding technologies for 33 GF wt.% nylon 6 plastic is presented in Table 7. For the data comparison, we used the following two, welding factor, parameters:

- Welding factor f_{wm} related to the tensile strength of the base material/polymer. Weld factor f_{wm} = tensile strength of the weld/tensile strength of non-reinforced plastic (base resin)
- Welding factor f_{wpl} related to the tensile strength of the reinforced plastic. Weld factor f_{wpl} = tensile strength of the weld/tensile strength of reinforced plastic.

For nylon 6 based plastics, four of the analyzed welding technologies (including infra-red/laser transmission) are three times more efficient than ultrasonic welding (see Table 6). Slightly higher mechanical performance for various ultrasonically weld nylon 6 and nylon 66 (Table 8) was published in [12]. The absolute weld line strength doesn't increase or decrease for fiber-glass reinforced nylon. Similar results were obtained for nylon 66 based plastic (Table 7) with the same level of fiber-glass reinforcement.

Linear vibration welding technology is widely used for joining of various hollow multiple gated injection molded parts. Infra-red/laser transmission welding technology is new but will have a wide application also. Weld line data, obtained for these technologies, is critically important for the plastic parts design and process optimization. Table 8 is showing efficiency of vibration and infra-red/laser technologies with the influence of fiber-glass reinforcement. Analyzed in this table range of reinforcement (from 0 to 45 wt.% GF), the tensile strength at weld line is approximately equal to the tensile strength of non-reinforced nylon 6. Some increase of the tensile strength was found at the range of fiber-glass reinforcement (GF) from 14 to 25 wt.%.

Information on the effects of welding parameters on mechanical performance of nylons is not abundant, and a part of these results are discrepant. The vibration welding optimization studies [7-8] gives us to present the following guidelines:

- Weld amplitude increase and weld pressure decrease will increase weld line tensile strength.
- Melt-down and thickness of inter-phase increase will increase weld line tensile strength.
- Increasing weld-melt temperatures (above melting pint) will increase weld line tensile strength.
- Direction and shape of oscillations do not affect mechanical performance of weld line.

An Analysis of Mechanical Performance of the Knit and Weld Lines

For mechanical performance prediction of welded multiple gated components, we need to use the various physical and mechanical properties (at total and local areas) of injection molded thermoplastics with the influence of processing (molding and welding) and end-use environmental and mechanical loading conditions. Fiber-glass reinforcements display (Figures 2-4) leads to clearly defined anisotropy of mechanical properties in GF thermoplastics.

Tensile strength of knit and weld lines are critically important for the plastic selection for various industrial applications where welded parts will be stress-strain bearing. Table 9 shows the influence of fiber-glass reinforcement (from 0 to 63 wt.%) on the tensile strength at knit and weld lines for nylon 6 based plastics. Both results are very similar, and they are very close to tensile strength of non-reinforced plastic (base polymer).

Influence of combined effects of fiber-glass reinforcements (GF), fillers (MF) and impact modifiers (IM) is presented in Table 10. Weld line strength is slightly above of the strength at the weld line. As we discussed previously, the influence of impact modifiers (IM) is significant. The analysis of the presented (Tables 9 and 10) results is showing that mechanical performance of the knit and weld lines are very similar.

Concluding Remarks

For non-reinforced (or non-filled) nylon, the tensile strength at knit line and weld (inter-phases) is approximately equal to the tensile strength of base resin (matrix). Fiber-glass reinforced and fiber-glass/mineral nylons have the tensile strength at knit lines welds, which are different (significantly less) from the tensile strength of reinforced/filled plastic due to flow patterns and local fiber-glass re-orientation at knit lanes and welds (inter-phases). At the same time for these plastics, the tensile strength at knit lines welds remains the same as for non-reinforced plastics or slightly higher than the tensile strength of used resin (matrix).

The impact modifiers significantly reduce tensile strength at knit lines and welds. For plastics with combined composition, the allowable working stress at knit lines and welds should be reduced with the influence of additives (fiber-glass reinforcements, fillers, impact modifiers, etc).

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Keywords

Polyamide; knit line; weld line; reinforcement.

Table 1. Tensile Strength at Knit Line for Non-Reinforced Plastics

Type of Resin	**Tensile Streng. MPa**	**Tensile Strength at Knit Line, MPa**	**Tensile Strength Retention, %**	**Refer. [ ]**
PSU	65.0	65.0	100	1, 14
SAN	80	60	80	1, 14
PP	30	29.4	86-97.6	1, 14
PP	35	33.6-35	96-100	1, 14
PPS	60	50	83	14
HDPE	25	23	92	14
PA 66	85	-	83-100	14

Table 2. Effects of Reinforcement on Tensile Strength at Knit Line for Fiber-Glass Reinforced Plastics

Type of Resin	**Glass-Fiber, wt. %**	**Plastic Strength, MPa**	**Knit Line Strength, MPa**	**Tensile Strength Retention %**
PSU	30	115	70	62
SAN	30	110	45	40
PP	20	65	30	47
PP	30	-	-	34
PPS	10	70	25	38
PPS	40	140	28	20
PA 66	10	-	-	87-93
PA 66	30	-	-	56-64

Table 3. Effects of Reinforcement on Tensile Strength at Knit Line of fiber-glass reinforced nylon 6 based plastics.

GF Wt. %	**Tensile Strength of Plastic, MPa**	**Knit Line Strength, MPa**	**Tensile Strength Retention, %**
0	82	85.8	99.2
14	125	89.1	66.6
33	185	89.2	46.2
50	220	83.3	37.8
63	229	83.8	36.5

Table 4. Tensile Strength at Knit Line for nylon 6 and nylon 66 based plastics (0 and 33 wt.% GF)

Type of Resin	**GF wt. %**	**Tensile Strength of Plastic, MPa**	**Weld Line Strength., Mpa**	**Tensile Strength Retent. %**
PA6	0	86.5	85.8	99.2
PA66	0	85.2	84.5	99.2
PA6	33	192.9	89.2	46.2
PA66	33	190.8	88.5	46.3

Table 5. Effects of Various Reinforcements (GF), Fillers (MF) and Impact Modifiers (IM) on Tensile Strength at Knit Line for 6 based plastics.

GF wt. %	**MF wt. %**	**IM wt. %**	**Tensile Strength of Plastic MPa**	**Knit Line Strength MPa**	**Tensile Strength Retent. %**
0	0	0	86.5	85.8	99.2
0	40	0	90	77	85.5
15	25	0	126	90	71.1
0	0	4	54	51.6	95.5
33	0	0	192.9	89.2	46.2
33	0	5	152	62	40.8

Table 6. Efficiency of Welding Technologies for Fiber-Glass Reinforced Nylon 6 Based Plastics (33 Wt. % GF, Optimized Processing Conditions)

Type of the Welding Technology	**Weld Factor** f_{wm}	**Weld Factor** f_{wpl}
Linear Vibration	1.08	0.46
Orbital Vibration	1.10	0.47
Hot Plate (Contact)	1.12	0.48
Ultrasonics	0.34	0.15
Laser (Transmission)	0.92	0.41

Table 7. Influence of Fiber-Glass Reinforcement & Fillers on Efficiency of Ultrasonic Welding Technology for Nylon 6 and Nylon 66 Similar and Dissimilar Joints

Type of Resin and Joint Design (Similar or De-Similar)	**GF wt. %**	**MF wt. %**	**Tensile Strength of Weld, MPa**
Similar Joints			
PA 6 + PA 6	0	0	25 – 40
PA 66 + PA 66	0	0	20 – 30
PA 6 + PA 6	25/25	0	30 – 35
PA 6 + PA 6	30/ 30	0	25 – 35
PA 6 + PA 6	0	30	40 – 45
Dissimilar Joints			
PA 6 + PA 66	30/30	30	20 – 24
PA 66 + PA 66	0/30	0	25 – 30

Table 8. Influence of Fiber-Glass Reinforcement on the Tensile Strength of Similar Joints of Linear Vibration and Laser Welded Butt Joints (Optimized Processing Conditions)

Wt. %, GF	**Tensile Strength of Fiber Glass Reinforced Plastic (MPa)**	***Vibration Welding Technology*** Tensile Strength of Weld (MPa)	***Laser Welding Technology*** Tensile Strength of Weld (MPa)
0	82	81	≥ 82
14	125	90.7	78.2
25	160	90.2	76.9
33	185	83.6	75.4
45	208	80.1	70.4

Table 9. Influence of Fiber-Glass Reinforcement on the Tensile Strength of Knit and Weld (Nylon 6 Based Plastics. Optimized Processing Conditions)

Wt. %, GF	**Tensile Strength of Plastic (MPa)**	**Tensile Strength of Knit Line (MPa)**	**Tensile Strength of Weld , (MPa)**
0	82	85.5	81
6	85		83.1
14	125	89.1	90.7
25	160		90.2
33	185	89.2	85.6
45	208		82.1
50	220	83.3	80.5
63	229	83.8	79.2

Table 10. Effects of Various Reinforcements (GF), Fillers (MF) and Impact Modifiers (IM) on the Tensile Strength (at 23^0C, Dry As Molded) at Knit and Weld Lines (Nylon 6 Based Plastics. Optimized Processing Conditions)

GF wt. %	MF wt. %	IM wt. %	Tensile Strength of Plastic MPa	Knit Line Strength MPa	Weld Strength MPa
0	0	0	82	82	81
0	40	0	90	77	81.5
15	25	0	126	90	84.8
0	0	4	54	51.6	50.8
33	0	0	192.9	89.2	85.6
33	0	5	152	62	61

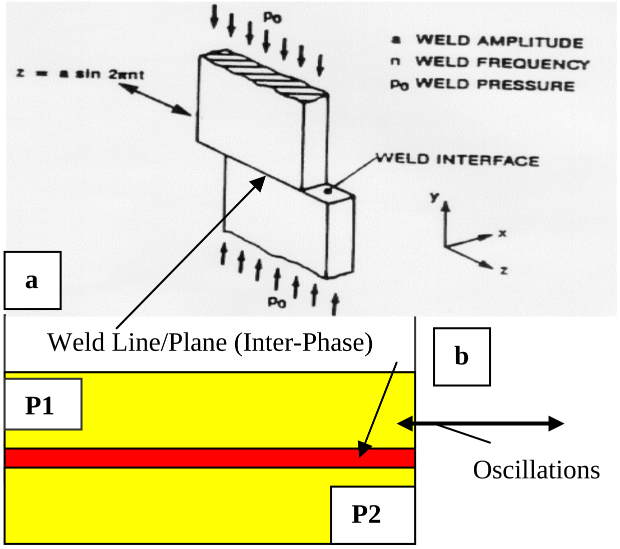

Figure 1. Weld line (inter-phase) formation during welding processing technology. Legend: a – linear vibration welding; b – inter-phase; P1 – heat affected area at part 1; P2 – heat affected area at part 2.

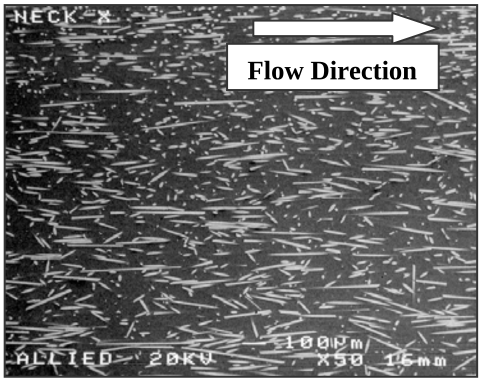

Figure 2. Example of orthotropic (unidirectional) fiber glass orientation in molded specimen (one side gated). Data obtained using injection molded nylon 6, 33 wt.% GF multipurpose specimen (ISO 3167) at flow direction.

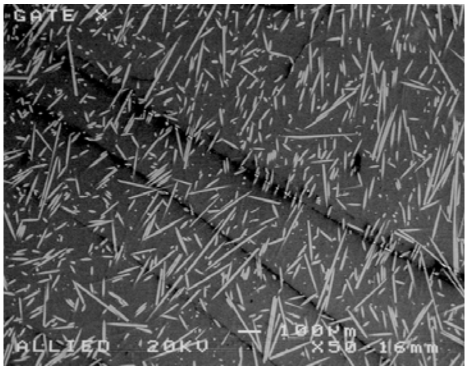

Figure 3. Example of random fiber-glass orientation in molded part (out of weld and knit lines area). Data obtained from injection molded nylon 6, 33 wt.% GF.

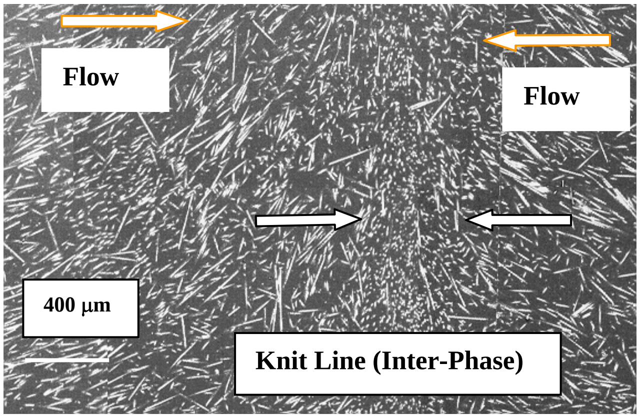

Figure 4. Example of fiber-glass orientation at knit (weld) inter-phase area in molded part (doubled/two sides gated). Data obtained using injection molded nylon 6, 33 wt.% GF.

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