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Forward to Better Understanding of Optimized Performance of Welded Joints: *Local Reinforcement and Memory Effects for Polyamides*

ABSTRACT

A comparative study of the mechanical performance of welded polyamide joints is evaluated. Under optimized welding (linear and orbital vibration, hot plate, transmission laser) conditions, the tensile strength of welded polyamide/nylon (filled and fiber-reinforced) is close or slightly higher (up to 14%) than the tensile strength of the base polymer (non-filled polyamide).

In this study, the influence of two important effects (local reinforcement and "memory") on the mechanical performance of polyamide/nylon welds is analyzed and discussed. The results presented in this study will help plastic part designers, material developers and manufacturers, choose optimized welding conditions for polyamide/nylon parts in a wide range of industrial applications.

INTRODUCTION

Short fiber-glass reinforced nylon based plastics are the materials of choice for a variety of welded structural components in automotive under-the-hood, lawn and garden and power tool applications. For optimized design of welded hollow components, we need to apply a wide variety of engineering properties for reinforced thermoplastics and welded joints too.

Previously, we reported to ASM'95 and SPE (Antec'96) our findings related to local reinforcement effects in the weld inter-phase for linear vibration welding [1-2] technology. In our presentations to SPE (Antec'99), Global Powertrain Congress (GPC'99) and Polyamide'2000 Congress, we analyzed the kinetics of the weld-melt temperature for linear vibration and hot-plate welding technologies [3-4]. In the above discussed reports to ASM'95 [1] and SPE (Antec'96) [2], we analyzed the mechanical performance of nylon 6/polyamide 6 (PA 6) and nylon 66/polyamide 66 (PA 66) joints with respect to various welding parameters, such as:

- Weld amplitude
- Clamp pressure
- Melt-down
- Thickness of inter-phase
- Cooling and hold time.

Under optimized welding conditions, the tensile strength of welded nylon butt joints was equal to or 14% higher than tensile strength of the base polymer (matrix). The same mechanical performance of the welded nylon was seen for orbital vibration welding technology [3].

In the current study we discuss "smart behavior" for welded fiber-glass reinforced polyamide/nylon. "Crystalline memory" effects are typical for semi-crystalline polymers such as polyamide/nylon.

For this comprehensive investigation, we used:

- Advanced scanning electron microscopy (SEM) to study short fiber-glass orientation and distribution in bulk (injection molding) and local (weld inter-phase) areas
- *Thermovision 900®* infrared measurement system for comprehensive, real-time analysis and thermal imaging.

For optimized vibration welding conditions, the maximum temperatures of the weld-melt (in inter-phase) were significantly above (85 - 90 °C) the melt point of the welded PA 6 and PA 66 (T_m = 223 °C and 261 °C, respectively).
J. Vetter and G. W. Ehrenstein observed [5] for polypropylene (PP) based plastics, an increase of maximum temperature in the weld-melt/in weld inter-phase of not more than 10 °C above the melting point (T_{mp}). In this [5] report to SPE (Antec'99), the authors discussed the results of the physical modeling for semi-crystalline high density polyethylene (HDPE) showing the values of maximum temperatures in the weld inter-phase above 250 °C compared to melting point (T_{mp} = 126°C).

Ch. Bonten presented to Antec'99/SPE his analysis [6] on the acting mechanisms in weld interface of semi-crystalline thermoplastics (HDPE and cross-linked polyethylene PE-X). Mechanical performance of welded joints was affected by crystallization across the boundary layer and weld-melt temperature kinetics (above melting point T_{mp}).

For a better understanding of the role and influence of the processing temperature of the melt (in injection molding) and weld-melt (in welding) on mechanical performance of semi-crystalline molded (welded) thermoplastics, we performed a comparative study for polyamide/nylon 6 and polyamide/nylon 66 (non-filled and fiber-glass reinforced) plastics.

Mechanical performance of injection molded and welded nylon was evaluated using static (tensile and flexural) and dynamic (impact, DMA) tests. The static (tensile and flexural) and dynamic mechanical (DMA) properties were evaluated at a wide range of end-use temperatures, typical for welded nylon parts in automotive under-the-hood, small engines for lawn & power, and similar applications.

Melt temperatures (for an injection molding) were varied from 225 °C to 310 °C. These values are significant above (up to 87 ^{0}C) to the melt point of nylon 6 (T_{mp} = 223 °C). Presented results will help product developers, designers, technologist, and manufacturers, by given them suggestions on the optimized temperature conditions of a melt and weld-melt inter-phase area.

Comprehensive studies of the mechanical performance of welded polyamide 66 with respect to plastic composition were published by H. Potente, M. Uebbing and E. Lewandowski [7]. A comparative study of nylon 6 and nylon 66 welded joints, influenced by temperature and moisture, was published by I. D. Froment [8]. D. Grewell, in a comprehensive study [9] for the orbital welding technology, repeatedly achieved similar [3] tensile strength for PA 6 joints.

Presented in these studies [7-9] are results on mechanical performance of PA 6 and PA 66 joints were applied [10-14, etc.] in the design of vibration welded air intake manifolds (AIM), resonators, etc. Reported in [7-11] tensile strength data for welded joints are very similar for both plastics (PA 6 and PA 66) and is equal to 65 - 72 MPa (for 30-35 wt.% fiber-glass reinforcement).

PART 1 -- BULK AND LOCAL REINFORCEMENTS EFFECTS: FIBER-GLASS ORIENTATION IN MOLDED PARTS AND WELDS

The relative benefits and disadvantages of using fiber reinforcements in polyamides were summarized in [14]. In general, fiber reinforcements cause large property changes for injection molded parts at modest cost premium.

The effect of reinforcements strictly depends from two dominant factors:

- Level of fiber-glass (GF) and mineral fillers (MF) loading (reinforcement) by wt.% or volume
- Short fiber-glass (GF) orientation & local distribution.

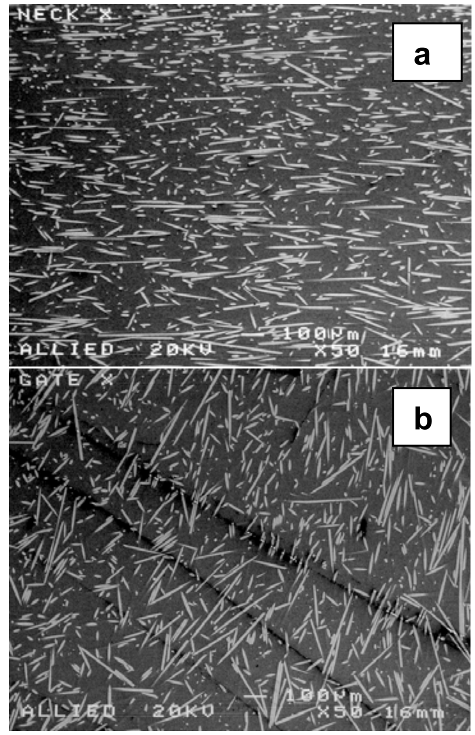

Figure 1. Fiber-glass orientation in injection molded ISO 3167 multipurpose specimen (PA 6, 33 wt.% GF): **a** – fiber orientation at flow direction in narrow parallel-side portion, **b** – fiber orientation in “end”/gate portion.

A short fiber-glass loading increase of 0 to 63 wt.% increases tensile strength by as much as 280% (Table 1).

The tensile (flexural) strength and modulus reaches a maximum value in the flow (longitudinal) direction and up to 50% less in the transverse (perpendicular to flow) direction. For 33 wt.% GF PA 6, this decrease might reach up to 50 - 60% of the similar value in flow direction due to micro-cracks and fiber-glass orientation. Fiber-glass orientation in two areas of a multipurpose injection molded test specimen (ISO 3167) are shown in Figure 1.

Table 1. Efficiency of Fiber-Glass Reinforcement on Tensile Strength of Molded Polyamide/Nylon 6

GF wt.%	Tensile Strength of Plastic (σ_{pl}), MPa	Efficiency of Reinforcement $k_{gf} = \sigma_{pl}/\sigma_m$
0	82	1.000
6	85	1.036
14	125	1.524
25	160	1.951
33	185	2.256
45	208	2.536
50	220	2.683
63	229	2.793

Table 2. Efficiency of Fiber-Glass Reinforcement on Tensile Strength of Welded Nylon 6 (Linear Vibration Welding Technology)

GF wt[1] %	**Tensile Strength of Weld σ_w, MPa**	**Efficiency of Welding $f_{wpl} = \sigma_w/\sigma_{pl}$**	**Efficiency of Welding $f_{wm} = \sigma_w/\sigma_m$**
0	81.0	0.988	0.988
6	83.1	0.977	1.013
14	90.7	0.725	1.106
25	90.2	0.564	1.100
33	85.2	0.461	1.039
45	82.1	0.395	1.001
50	80.5	0.365	0.981
63	79.2	0.345	0.965

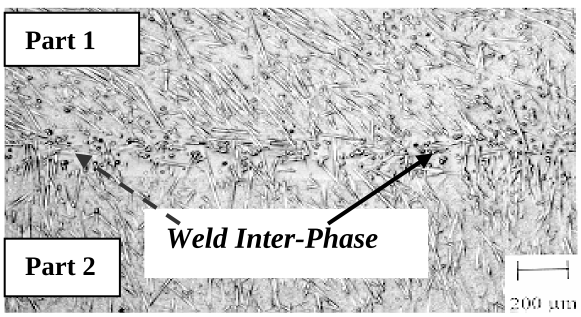

Figure 2. Local reinforcement effects at the weld inter-phase (a part of fibers are crossing the weld inter-phase). PA 6, 33 wt.% GF.

The observed increase [1-4, 13] in the tensile strength of welded butt joints (from 72 up to 85,2 MPa for 33 wt.% fiber-glass reinforcement, Table 2) was explained by the following:

- As a result of local reinforcement in the weld inter-phase, some fibers (oriented randomly) are crossing the weld interface (Figure 2)
- Optimized thermo-mechanical and weld inter-phase formation (melt-down, thickness of inter-phase) for re-melted layers of plastic(s) to be joined
- Diffusion of the joined layers.

PROCESSING TEMPERATURES – INJECTION MOLDING (MELT) AND WELDING (WELD INTER-PHASE)

At the initial phase of our investigation [1-2], due to technical limitations, we were not able to evaluate the time-temperature kinetic at the weld inter-phase (T_m). Processing and crystallization parameters for PA 6 and PA 66 are different (Table 3).

[1] Level of reinforcement or filler by weight.

Later we developed time-temperature kinetics data for the weld-melt inter-phase during the linear vibration welding process for various PA 6 and PA 66 joints.

Table 3. Basic Thermal Properties of PA 6 and PA 66 (in °C)

Parameter / Property	**PA 6**	**PA 66**
Melt Point Temperature (T_{mp})	~ 220	~ 260
Crystallization Temperature (T_{cr})	~ 190	~ 230
Glass-Transition Temper. (T_g)	~ 50	~ 60

The temperatures of the weld-melt T_{mw} (in weld inter-phase for 33 wt.% fiber-glass reinforcement) at the steady state were significantly above (of 85-90 °C) the melting points (T_{mp}) of PA 6 and PA 66 (Tables 3 and 4). The melting point value T_{mp} (for the same plastic) can vary as much as 10°C depending on the method of measurement (Tables 3-6).

Table 4. Maximum Weld-Melt Temperatures ($T_{mw,\,max}$), °C in Weld Inter-Phase for Polyamide (33% GF Reinforced by Weight) Based Plastics at Optimized Linear Vibration Welding Conditions [3]

Type of PA	**Melting Point (T_{mp}), °C**	**Melt-Weld Temperature ($T_{mw,max}$), °C**
PA 6	223	270 ~ 285
PA 66	261	295 ~ 320

Observed weld-melt temperature (T_{mw}) increase [3-4] is in sufficient correlation with the data presented in [6] and is in some disagreement with the part of data published in [5].

The manufacturers recommended molding (melt temperature T_{mi}) conditions for various fiberglass reinforced PA 6 plastics are very similar (Table 5, [14 and Trade Literature]). All melt temperatures T_{m1} and T_{m2} , recommended (by "manufacturer 1" and "manufacturer 2" respectively) are higher than melt point temperature for non-reinforced polyamide/nylon (T_{mp}).

Some small differences between T_{m1} and T_{m2} values were disclosed for two grades only: for the non-reinforced and highly fiberglass reinforced (50 wt.%) grades (Table 5). Temperature difference Δ_m =(T_{mi} - T_{mp}) increases monotonically (from 17-47 to 58-82°C) with increasing of the short fiber-glass content from 0 to 63 wt.% (Table 6).

Table 5. Manufacturers Recommended Molding/Melt Temperatures for PA 6 Based Plastics [15]

Type of PA	**Melt Temper. (T_m), °C**	**Melt Point Temper. (T_{mp}), °C**	**Temper. Differences $\Delta_m = T_m - T_{mp}$**
Homo	240 ~ 270	215	25 ~ 55

Polymer			
Impact Modified	250 ~ 280	205 ~ 215	45 ~ 65
Glass Fiber	255 ~ 305	215	40 ~ 90
Miner Filled	270 ~ 305	215	55 ~ 90

Similar values of the weld-melt temperature (T_{mw}) may also be obtained using recommendations developed for contact hot plate technology [3, 11, 15]. For optimized hot plate welding of semi-crystalline plastics, H. Potente and A. Brubel recommended keeping the hot plate/tool temperature T_{ht} above (of 70 °C) the melt point T_{mp} of the welded plastic [15].

Table 6. Thermoplastic Manufacturers Recommended Molding/Melt Temperatures For Fiber-Glass Reinforced PA 6 Plastics. Legend: *1 And *2 – Recommendations Provided By Manufacturers (1) And (2), Respectively

GF wt.%	**Melt Temper.*1 (T_{m2}), °C**	**Melt Temper.*2 (T_{m2}), °C**	**Temperature Differences $\Delta_m = T_{m1} - T_{mp}$**
0	240 ~ 270	250 ~ 270	17 ~ 47
14	260 ~ 280	270 ~ 290	37 ~ 57
25	271 ~ 293	270 ~ 290	48 ~ 70
33 (35)	271 ~ 293	270 ~ 290	48 ~ 70
40 (45)	271 ~ 293	270 ~ 290	48 ~ 70
50	271 ~ 305	280 ~ 300	58 ~ 82
63	271 ~ 305	280 ~ 300	58 ~ 82

For optimized contact hot plate welding conditions it is necessary to keep the hot plate/tool temperature T_{ht} slightly higher ($T_{ht} > T_{mw}$, by 10°C approximately) than the weld-melt temperature (T_{mw}) of the welded plastic, due to heat losses between "heating" and contact phases of the hot plate processing process [3-4, 16].

Data is shown in Tables 3-6 for the values of processing (molding and welding) temperatures (T_{mw}) showing that optimized mechanical performance of polyamide/nylon based plastics which was achieved at a sufficient higher melt temperatures ($T_{mw} \gg T_{mp}$). For semi-crystalline plastics (including polyamide/nylon), these effects may be related to the physicochemical characteristic of the base polymer, one must eliminate the influence of impurities, additives, short fiber-glass reinforcements, nucleating agents, and crystalline memory [17-18]. Some effects of increasing values of T_{mp} for linear vibration and contact hot-plate welding conditions may be related to influence of a clamp pressure (p_w) at weld-melt (inter-phase) area.

From a thermodynamic point of view, the melting point(T_{mp}) is the temperature at which the crystal and the melt are in equilibrium. For theoretical considerations, the last vestige of crystallinity disappears at that temperature. The melting point temperature (T_{mp}) for nylon, reported by a several laboratories and using a number of techniques, has been summarized in [15]. For the PA 6 the melt point temperature (T_{mp}) values may be at range from 215 to 230°C [15, 18, and Trade Literature]. We used the melting point (T_{mp}) value equal to 223°C for PA 6 and 261°C for PA 66 (Table 4).

The freezing points are frequently about 30°C lower then the melting points (T_{mp}). The following solidification temperatures can be used for polyamide [17]:

- PA 6, from 170 to 190°C
- PA 66, from 215 to 240°C.

In some laboratory experiments for PA 6, crystallization has been carried out much closer to the melting point (T_{mp}) at 205 °C to 215°C [16-17].

We did not find published correlation between plastics composition (level of fiber-glass reinforcement, fillers, impact modifiers, etc.), the weld-melt temperature T_{mw} (or for hot tool temperature T_{ht}), weld clamp pressure (p_w) and welding time (t_w) for linear vibration and contact hot-melt [18] (extrusion or in-mold injection) welding technology also.

EXPERIMENTAL (PART 1) – TEST PROCEDURES AND NEW MODELS FOR WELDING PROCESS ANALYSIS AND OPTIMIZATION

USED MATERIALS (POLYAMIDE/NYLON)

The thermoplastics analyzed in this investigation (injection molding, welding and testing) were heat stabilized PA 6 and PA 66. Limited data will be presented for PA 46 also. Commercially available PA 6, PA 66 and PA 46 plastics are widely used for design of the various welded structural components. These semi-crystalline plastics have a wide loading range of short fiber-glass (GF) reinforcement, mineral fillers (MF), etc. (Table 7).

Because the fiber-glass reinforcements and mineral fillers possess different thermal properties (thermal conductivity, heat capacity, etc.) from the base polymer, they affect the thermal properties of the plastic's heating, welding and cooling time. Melting point data may vary because the method of measurement, oligomer contents, additives, reinforcements, fillers, and crystalline form can alter the result (Tables 3-5) [15, 18].

Table 7. Composition of Polyamide/Nylon Based Plastics (% wt., by weight) for a Structural and Welded Components

Type of PA	Fiber-Glass (GF)	Min. Fillers (MF)	GF / MF	Specific Gravity g / cm^3
PA 6	5 - 63	12 – 40	15/25	1,13-1,15
PA 66	5 - 72	15 – 40	16/24	1,13-1,15
PA 46	15 - 45	10 – 30	16 /24	1,18

MECHANICAL TEST PROCEDURES FOR WELDED BUTT JOINTS

Quality control and quality assurance of the welded components, tensile, impact and burst tests are usually applied [1-12, 14, 16]. One very important parameter needed for the design (Figures 3 and 4) of weld-bead(s) is the tensile strength of a welded joint at break (with the influence of processing technology including time-temperature effects).

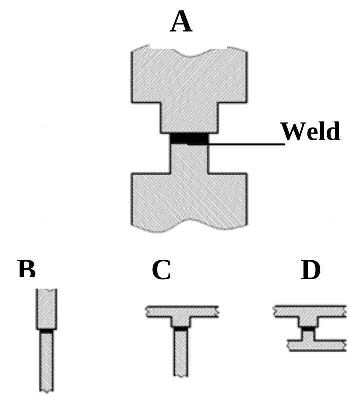

Figure 3. Welded joint design principles (types and configuration). Legend: **A** – joint design; **B** – butt joint (straight); **C** – butt joint (T – shape); **D** – shear/lap joint.

The tensile strength of a weld at 23°C ("dry as molded" and "welded as dry" conditions[2]) is "key data"- the first step in the plastic component design, welding process optimization, and comparative analysis of material suitableness for welding application.

Not all thermoplastics, static (tensile) and dynamic (Izod, Charpy) properties are sensitive to the fine structural changes of thermoplastics related to processing (molding and welding) temperatures.
For welded butt joints, basic tensile test data was obtained from rectangle specimens (10 mm by width, 125 mm by length) cut and machined from the welded plaques (Figures 5-6) and multi-purpose universal welding & testing specimens (Figure 7).

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

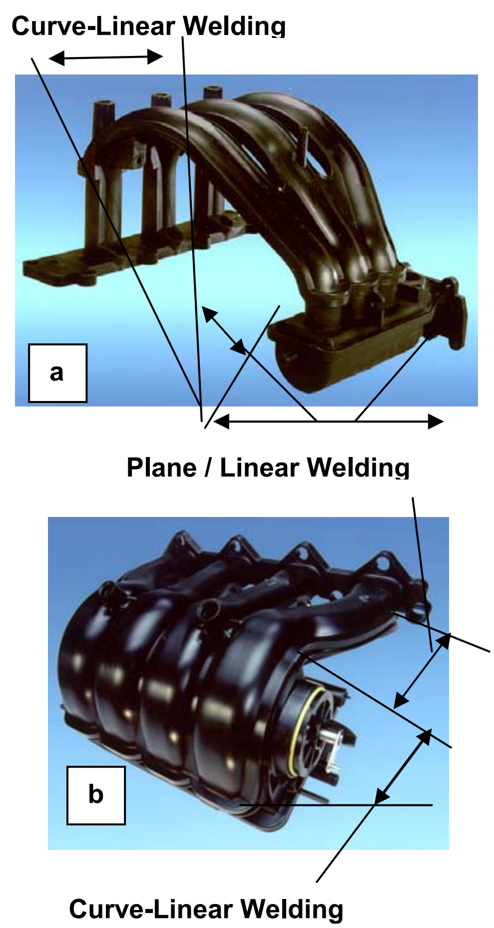

Figure 4. Linear Vibration Welded Plastic Air Intake Manifolds. Legend: **a –** three cylinders; **b –** four cylinders.

For each welding processing conditions, a minimum of five specimens were tested using ISO 527 (or ASTM D 638) procedures. All tensile and burst test results were used for performance optimization. Samples with high tensile strength were selected to perform the morphology analysis in the weld zone (inter-phase). ISO 537 (or ASTM D 732) test procedures were used for an evaluation of the shear strength of welded lap joints.

Because the fiber-glass reinforcements and mineral fillers possess different thermal properties (thermal conductivity, heat capacity, etc.) from base polymer, they affect the thermal properties of the plastics and to heating, welding and cooling time. Melting points data may vary because the methods of measurement, oligomer contents, additives, reinforcements, fillers, and crystalline form can alter the result [15, 18].

Differential scanning calorimetery (DSC) methods was successfully applied for an analysis of the structural changes in nylon [19]. In addition to traditional evaluation methods [1-12, 14, 16] dynamical mechanical analysis (DMA) was also applied in this investigation.

A Rheometrics RDA-II torsional rheometer was used with the torsion rectangular geometry. All conditions were in accordance with ASTM D 5279. Sample size was a bar nominally 60 mm long, 10 mm wide, and 4 mm thick. A frequency of 1 Hz and strain of 0.05% were used. Temperature steps of 5°C were made from –50°C to 210°C with an isothermal time at each temperature steps of 3 minutes.

THE KEY MECHANICAL PROPERTIES NEEDED FOR WELDED PARTS DESIGN, DESIGN ANALYSIS AND OPTIMIZATION

Plastic selection for welded automotive under-the-hood components must be based on end-use requirements for used thermoplastic in total (bulk) and local (weld inter-phase) areas.

For mechanical performance prediction of welded components, we need to use the various physical and mechanical properties (at total and local areas) of injection molded PA with the influence of processing (molding and welding) and end-use (time, temperature, moisture, strain rate, etc.) conditions.

Physical and mechanical properties needed to be conducted at various end-use environmental and mechanical loading conditions typical for under-the-hood applications.

The following base/key mechanical properties at total and local areas are very important for welded components design:

- Short-term properties;
- Long-term properties.

Short-term mechanical performance of plastic and welded specimens is important for quality control to ensure the constant properties of used materials and processing technologies (injection molding and welding).

Basic short-term properties of thermoplastic and weld, more important for design of welded components, are presented in Table 8.

Table 8. Short-Term Properties Needed for Welded Parts Design, Design Analysis & Optimization

Mechanical Properties	Bulk Areas	Weld
Tensile		
Strength at yield	+	-
Strength at break	+	+
Strain at break	+	-
Tensile modulus	+	+
Poisson's ratio		
Compressive		
Strength	+	-
Young modulus	+	-
Shear		
Shear Strength	+	+
Flexural		
Strength at break	+	+
Strain at break	+	-
Resistance to Fracture		
Impact		
Un-notched	+	+
Notched	+	+
Fracture Mechanics		
Fracture toughness	+	+
Friction/Wear		
Coefficient of friction	+	+

The following long-term properties of used thermoplastic and weld are more important in predicting of the service time of welded components (Table 9):

Table 9. Long-Term Properties Needed for Welded Parts Design, Design Analysis & Optimization

Mechanical Properties	Bulk Areas	Weld
Tensile		
Creep modulus	+	-
Creep rupture strength	+	+
Creep curves	+	-
Tensile-tensile fatigue curve (*S-N*)	+	+
Fatigue crack propagation	+	+
Compressive		
Stress relaxation	+	-
Flexural		
Creep modulus	+	-
Creep rupture strength	+	+
Creep curves	+	-
Flexural fatigue curve (*S-N*)	+	+

For welding technology (linear vibration, orbital, hot plate, etc.) selection and welding process optimization we need additionally to obtain the following properties:

- Thermal conductivity
- Specific heat
- Viscosity-shear rate data;
- Melt density
- Melt point temperature
- Crystalline melting temperature
- Glass-transition temperature.

USED MODELS AND SPECIMENS

Correct design of plastic parts and welding processes require apply properly designed various weld beads (Figure 3), specimens, models and properly simulated welding processing conditions (including temperatures in inter-phase). The test and processing conditions should be similar to manufacturing and end-use conditions also.

Utilized in this investigation were molded and welded specimens/systems, applied test and measurement methods, and design principles of the joints, which are in a process of continuous improvement. Presented below (Figures 5-6, 8-9) are welded butt joints models, designed with the influence of the specifics related to the real time-temperature analysis and image handling, and welding processes simulation for critically loaded plastic components, such as welded air intake manifolds (Figure 4), resonators, fluid reservoirs, etc.

Optimizing Models of Butt Joints: From Injection Molded Rectangle Plaques to Multi-Purpose Octagonal Systems

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

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

Sizes (length × width) of the welded plagues are 150 (or 100) mm × 120 mm (approximately). Weld area is equal to 600 (or 400) mm^2 respectively for the plaques 150-mm and 100 mm long.

Specific design applications (highly stressed welded components) are needed to evaluate the influence of weld-bead design (height of a bead), fiberglass and fillers orientation, and injection molding conditions on tensile strength of the butt joints.

It is possible to utilize these applications in the **T**-type /shape butt joints by welding together the above-mentioned injection molded rectangle plaque (thickness = 4 mm) and **T**–shape component with the bead 6 mm thick (Figure 6).

Figure 5. Mode of welded straight butt joint (consists from two welded together molded plaques. Thickness of plaques is 6mm and 4 mm) and machined/cut test specimen (width = 10 mm). Thickness of the weld beads may vary from 1.6 to 6.25 mm.

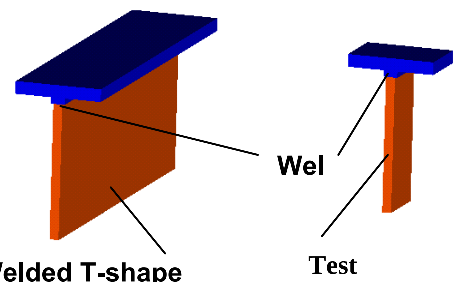

Figure 6. Mode of welded T-shape butt joint (consists from welded together T-element and molded plaques. For T-element thickness of the weld bead is 6 mm. Thickness of the plaque is 4 mm) and machined/cut T-shape test specimen (width = 10 mm). Thickness of the weld beads may vary from 1.6 to 6.25 mm.

A thickness of the plaques (weld beads) may be varied (the following thickness is available also: 1,6 mm and 3,2 mm). Maximum cross-section in the weld areas for these specimens is equal to 600 mm^2 (for weld beads 4 mm and 6.25 mm thick).

An evaluation of the butt joint performance using the rectangle plaques (Figure 5) and **T**-shape elements (Figure 6) has a lot of advantages (simple molding and welding tools, availability of the injection molded plaques, etc.), convenient configuration and sizes of the test specimens.

The mechanical performance of both analyzed models (Figures 5 and 6) is very similar (Table 8). These specimens may be successfully welded in a small (Mini-Welder-**II** type[3], Figure 7) and mid-size welding machines only (due to limitations on the minimum clamp force).

Figure 7. Linear Vibration Welding Machine Mini-Welder-II

For a bigger sizes of the welding machines these specimens (Figure 5-6) are too small (and clamp pressure is very high), because minimum clamp force is more than 3 kN.

Table 8. Influence of Type/Design of Used Specimens and Models on Butt Weld Performance (PA 6, 33 wt.% GF, at 23 °C, DAM)

Type of Specimen	**Tensile Strength, MPa**
Straight (Figure 5)	85.6
T – type (Figure 6)	84 - 86

More efficient welding process modeling and joints performance evaluation has been designed with a special “multi-purpose universal weld & test system” (Figure 8).

This system (Figure 8) consists from two welded together multi-purpose octagonal specimens. The following basic concerns and problems, design and technology issues have been taken in to account for design of this universal welding & testing system:

- Possibility to mode welding conditions similar to recommended for use in the production
- Correlate sizes and design of plastic parts and welded specimens with the size of available welding machine, value of minimum clamp force, etc
- Possibility to have similar plastic state in weld bead areas (polymer structure and morphology, mechanical properties, etc.) for injection molded plastic parts and welded specimen
- Multi-purpose application of developed weldability data for plastic part design and optimized welding processing conditions.

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

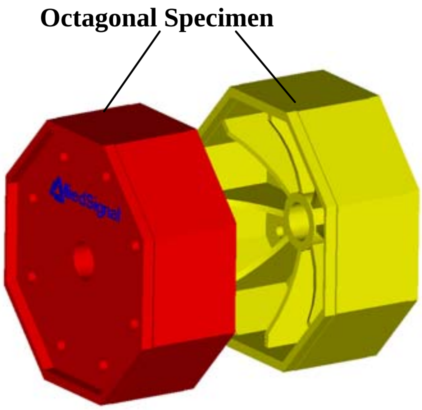

Figure 8. Multi-purpose universal welding & testing system (Consists from welded together two octagonal specimens. Thickness of weld beads may vary from 2.5 to 6 mm).

Octagonal configuration and design advantages of universal specimen (Figure 8) allows to evaluate efficiency of injection molding and welding process for the butt joint:

- With the various directions (Table 9)
- At various thicknesses of the beads (by combining the following thickness: 2,5 mm; 4,0 mm; 5,0 mm and 6 mm; Table 10).

Table 9. Influence of Shape and Direction of Oscillation on Weld Performance (PA 6, 33 wt.% GF, at 23°C, DAM)

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

Table 10. Influence of the Weld Design Version on Weld Performance (PA 6, 33 wt.% GF, at 23°C, DAM)

Sizes of Butt Joint, mm	**Strength, MPa**
Desimilar	
2.5 + 4; 2.5 + 5; 2.5 + 6	84 - 86
4 + 5; 4 + 6	84 - 86
Similar	
2.5 + 2.5; 4 + 4; 5 + 5; 6 + 6	82.5 – 85.3

Maximum weld bead (contact) area is equal to 3,600 mm^2 (approximately). These multi-purpose universal specimens may be used for orbital vibration, hot plate, infrared (diffusion) welding also.

"Universal weld & test system" may be utilized in the industrial applications for design, material and process optimization, where mid- and full-size welding machines are used. The shape of the specimen (octagonal) and a thickness of the beads may vary.

The mode of the straight butt joints (Figures 5-6) and the universal welding & testing system (Figure 8) are convenient for direct weld-melt temperature measurement and images handling, using infrared (IR) systems.

Special Model for Welding Process Analysis in Curve-Linear Joining Areas

This curve-linear model of the butt joints (Figure 9) was designed to analyze thermos-mechanical material behavior at welding processing conditions similar, which are used in design and manufacturing of air intake manifolds (AIMs), resonators, fluid reservoirs, etc.

Welded air intake manifolds (AIM) typically consist from 2-4 welded together an injection molded pieces/parts (Figure 4). Shape of the welds at a runner area is curve-linear.

Design of the curve-linear parts requires an additional information on a clamp pressure, meltdown, tolerances, gaps, and temperature distribution at curve-linear areas. At the current time, reported [1-14] weldability data of semi-crystalline plastics was developed for the plane welded joints. We did not find the similar weldability data for welded nylons (or other thermoplastics) at curve-linear joining areas.

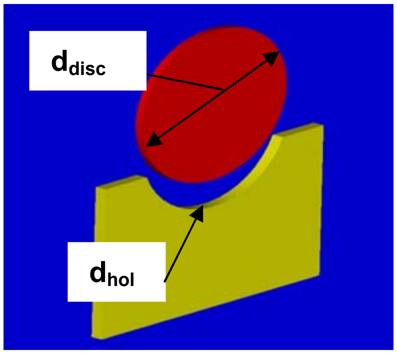

Figure 9. Curvilinear mode of the welded joint (injection molded disc and plaque will be joined together by linear vibration welding). Thickness of weld beads may vary from 1.6 to 6.25 mm.

It is possible to simulate curve-linear design and processing conditions by welding together disc and plaque with half-hole (Figure 9). For this mode we used injection molded disc (thickness = 4 mm, diameter $\boldsymbol{d_{disc}}$ = 100 mm) and special plaque (thickness = 6.25 mm). Sizes (length x width) are 150 mm x 100 mm and nominal diameter of the half-hole in the plaques $\boldsymbol{d_{hole}}$ = 100 mm. Diameter $\boldsymbol{d_{hole}}$ was varied (from 100 mm to 101 mm). The simulation of various tolerances and meltdown permit us to optimize mechanical performance of the weld in curve-linear joining areas. Sizes of joining curve-linear elements (disc and plaque) can be varied from 40 mm to 100 mm.

The following advantages and limitation are for the discussed models (Figures 5-6, 8):

- All three models of the butt joints are allowing to analyze and optimize vibration welding process and material behavior at various motions (longitudinal, perpendicular to part thickness and by an angle)
- For curve-linear joint areas is it possible to apply vibration motions perpendicular to thickness of the curve-linear wall only (Figure 9).

Special Two Shelves Model for Analysis of Sealing and Weld Performance By Burst Pressure

Burst tests (static, cyclic and dynamic) are typical for the final phase of the performance evaluation of the welded components. The burst tests data (ultimate pressure, failure analysis) is used in optimized performance evaluation of the welded hollow/multi-shelves components, when requirements to part sealing and hermetic are critical.

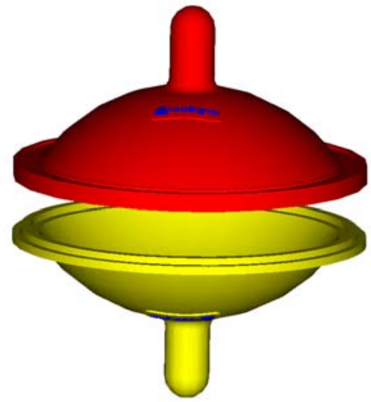

Figure 10. Two Shelves Model. Thickness of weld beads may vary from 2.5 to 6 mm.

Burst tests of two shelves models (Figure 10) are allowing to evaluate material behavior, optimize molding and welding procedures (including time-temperature profile), accuracy of the FEA of the welds and joined parts, sealing/hermetic (Figure 11), etc. under end-use loading conditions.

Dynamic burst test is more sensitive to structural changes of polymer, possible defect, then static tensile due to non-linear stress-strain distribution in the weld areas, and strain rate effects.

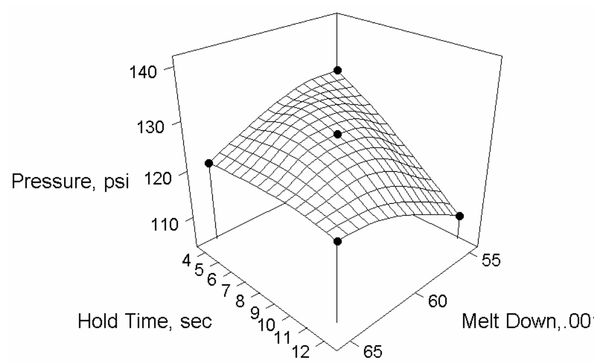

Figure 11. Example of Welding Process and Design Optimization: Burst Pressure Data for Vibration Welded AIM [14].

PART 2 -- MEMORY EFFECTS IN POLYAMIDE/NYLON

EXPERIMENTAL (PART 2) – TEMPERATURE KINETICS AT THE WELD-MELT (WELD INTER-PHASE)

Weld-melt (melt-pool) temperature ($\boldsymbol{T_{mw}}$) is one of the most important parameters affecting the performance of any welded joints (butt , lap/shear or mixed mode) during joining process. For the weld-melt temperature ($\boldsymbol{T_{mw}}$) measurement during welding process we used *Thermovision 900®* infra-red (IR) system for comprehensive, real time analysis and image handling (Figures 12-13).

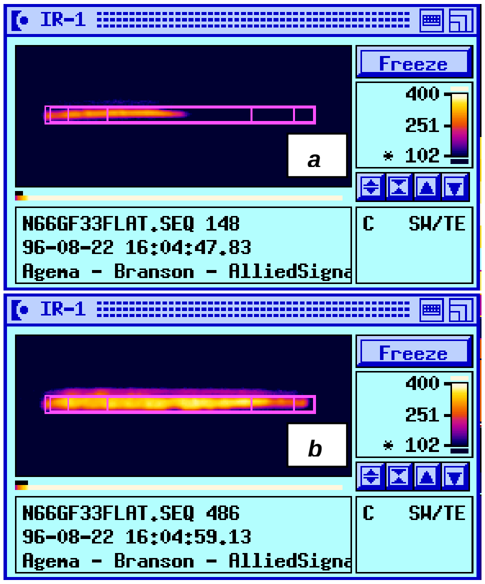

Figure 12. Temperature distribution in the weld inter-phase for butt joint, PA 66, 33 wt.% GF. Legend: ***a*** - heating initiation phase; ***b*** - at final phase of heating.

We measured the time-dependent temperature (t_w - T_{mw}) distribution and melt-weld (***mw***) propagation in the weld interface (at five local areas with the same size) during the linear vibration welding process (Figure 12).

The results were obtained at various longitudinal linear vibration welding conditions (amplitude-pressure-melt-down, heating and cooling/hold time), at vibration welding frequency =210 Hz.

Figure 13 show time-temperature profile (t_w - T_{mw}) for the various grades/compositions of PA 66:

- non-reinforced/non-filled (Figure 13 a)
- short fiber-glass reinforced (Figure 13 b)
- short fiber-glass reinforced and mineral filled (Figure 13 c).

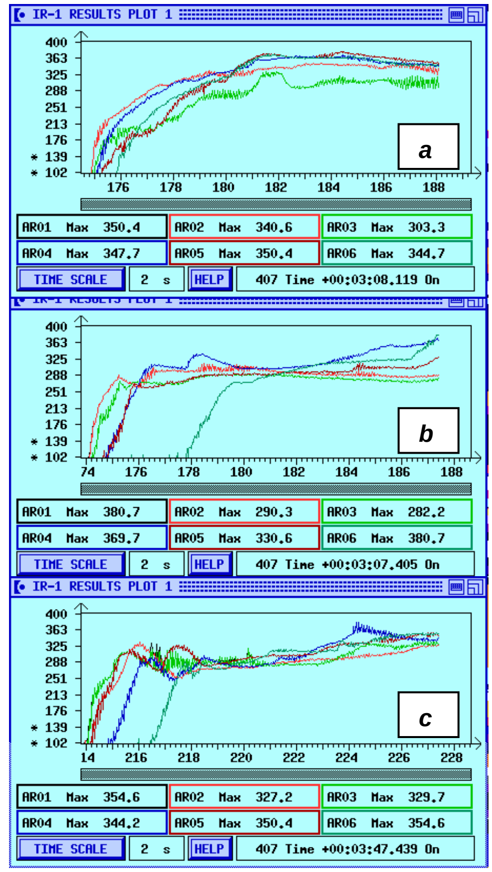

Figure 13. Time-temperature profiles (optimized LVW conditions, butt joint, and PA 66). Legend (type of used plastics): ***a*** -- non-reinforced/non-filled; ***b*** - 33 wt.% fiber-glass reinforced; ***c*** - fiberglass reinforced and mineral filled.

Time-temperature kinetics for non-reinforced/non-filled plastic is described by smooth (t_w - T_{mw}) curve (Figure 12 a) for both polyamide/nylon (6 and 66). Duration of pre-heating phase, when temperature of the melt-pool (T_{mw}) will reach level above melting point (T_{mp}) is equal 6 and 8 sec for PA 6 and PA 66 (respectively). Heating generation process (t_w - T_{mw}) for short fiberglass reinforced plastics is more dynamic (Figure 13 b).

The 2-3 second plastic pre-heating phase is too short for the heat to penetrate through all inter-phase areas; an additional 4-6 seconds are needed for this purpose. Reinforcement and fillers are affecting to thermal properties of PA. Specific heat increases for short fiber-glass reinforced plastic (from 1,5 to 1,7 J/gK with increasing fiber-glass content from 0 to 30 wt.%), thermal conductivity decreases (from 0,24 to 0,23 for PA 6 and from 0,27 to 0,21 for PA 66 at the same range short of fiber-glass reinforcement) [15].

The distribution of weld-melt temperature (T_{mw}) in local areas was not isochronal (uniform in duration); it was dependent on the flatness of welded surfaces, nest/welding tool design and heat transfer-out. When linear vibration welding machine is shut off, the weld penetration continues to increase because the clamp pressure causes the molten interface to flow until it solidifies. During the shutting off phase the interface, temperature has a tendency to increase (for 30-40°C on average, see Figure 13 a, b).

The maximum temperature ($T_{mw, max}$) of the weld-melt (melt-pool) was equal to the melting point of welded polymers or blends + (85-100 °C). The results in this study are close to data presented in [3] and slightly different from the hot tool temperature (T_{th}) data for the hot plate technology [16]. These differences may reflect the difference in used methods, calibration, measurement procedures, and effects observed and analyzed during this investigation.

MELT-MEMORY EFFECTS

A factor effecting the crystallization process of slowly or moderate slowly crystallizing polymers is called the "crystalline memory" and its results are usually lumped together under the umbrella of "memory effects". It is manifested as the formation of a defined degree of macromolecular order in the welded interface/phase, as well as a rise of the melting temperature (T_{mp}) of the semi-crystalline systems in the melt-pool [17, 19]. Melting under conditions that do not erase completely "crystalline memory" may result in microscopic or submicroscopic fragments of previous crystals remaining in the melt, and during cooling of the melt serve as the predetermined nuclei of fresh crystallization.

The number and size of the nuclei which remain in the melt, depends on the following three factors [18]:

- The temperature of any previous crystallization (since the higher this temperature the more perfect the crystallites and the higher their melting point T_{mpi});
- The temperature of melting (the higher this temperature the more complete id destruction of the crystallites formed previously;
- The duration of time (t_{mi}) the specimen of semi-crystalline plastic is held in the molten state (since the dispersal of the crystallites is not an instantaneous process).

Welding of thermoplastics "memory effects" reflect the thermal history of the molded part and, in addition, are affected by the melt temperature (T_{mp}) and welding time (t_{wm}) spent in the molten state. The highest temperature at which the polymer crystal may survive is the equilibrium melting point T_{mo}. For PA 6, the equilibrium melting point (T_{mo}) may place at about 270°C. Other the equilibrium melting point (T_{mo}) values obtained for PA 6 by various extrapolations and range from as low as 215°C to as high as 306°C.

Table 11. Memory Effects of Polyamide/Nylon (Virgin Polymer, Non-Reinforced/Non-Filled) Based Plastics (at the Same Heat/Cooling Rate)

Type of PA	**PA 6**	**PA 66**	**PA 46**
Melt. Point, ($T_{mp,}$), °C	221.6	262	287
Anneal Temp. ($T_{a,}$), °C	270	290	305
Glass Transition Temperature ($T_{g,}$), °C	54.8	63.3	76.7

Anneal temperature T_a (the temperature at which the melt is kept in order to remove the nuclei) must be higher than T_{mo}. Anneal temperatures (for PA 6) as low as 260°C were sufficient to eliminate memory effects, but 270°C and even 280°C are now recommended at temperatures at which memory effects are completely erased. In all of these, it is assumed that $T_a \geq T_{mo}$. A similar results [12-14, 17 were observed (in pellets) of several polyamide/nylon (Table 11-13).

Relation of the Injection Molding to Welding Conditions

During frictional (linear and orbital) vibration and hot plate/tool welding processes, mating parts are clamped under the applied pressure (p_w), which is a very important parameter for the mechanical performance of the weld. The vibration welding process, depending on the part size, tolerances and mechanical properties of welded nylon, will typically operate with clamp pressure (p_w) of approximately 3.5 MPa [5-6, 8, 12].

Variations in the applied pressure (p_w) of the amorphous phase of semi-crystalline polymers, may affect the glass transition (T_g), melt (T_{mp}) and annealing (T_a) temperatures. It is difficult to measure the glass transition temperature (T_g) exactly. Melting point temperatures (T_{mp}) are 150°C above the glass transition temperatures (T_g). The glass-transition temperature (T_g) depends upon the measurement technique and may vary from 41 to 75°C [15, 13 and Tables 3-4 and 11].

Pressure-volume-temperature (PVT) data for PA 6 and PA 66 plastics was primarily developed in a range of pressures from 50 to 200 MPa (Table 12).

Table 12. Changes in Glass Transition Temperatures (T_g, °C) as Function of Applied Pressure (p)

Type of PA	**at Atmospheric Pressure (p_{atm})**	**at Pressure (p_{200}) = 200 MPa,**
PA 6	52	99
PA 66	60	106

The glass-transition temperature (T_g) increases by 80-85% with increasing pressure from atmospheric to 200 MPa.

For PA 66 the effect of pressure (p) on melting point (T_{mp}) and crystallization temperature (T_{cc}) is summarized in [15], where T_{mp} and T_{cc} in (°C) and p in MPa[4]

$$T_{mp} (f_p) = 266,8 + 0,2285\, p \qquad (1)$$

$$T_{cc} (f_p) = 243,1 + 0,1871\, p \qquad (2)$$

We did not find similar data (equations) for PA 6.

The molding pressure ($p_{m.}$) profile may vary as a function of melt temperature (T_m), mold-tool geometry and plastic composition. Injection and packing pressures are generally within the range of 3,5 to 12,5 MPa. For optimal welding conditions (linear vibration or orbital vibration welding) a nominal clamp pressure ($p_{w, nom}$) in weld inter-phase is within the range of 1,2 to 2,2 MPa (approximately). The influence of clamp or molding pressure on the melting point (T_{mp}) will not be significant (in a range of accuracy of temperature measurement technique/method).

<u>*Melt Temperature: Relationship to Crystal Structure and Mechanical Performance of Polyamide/Nylon*</u>

The high melt-pool, and mold (cavity) temperatures delay freezing to facilitate filling long, thin sections (this is similar to localized re-melting and melt-pool formation processes in weld bead areas). It also encourages greater crystallization of the semi-crystalline resins, which affects both mechanical properties and dimensions.

Relations between processing (molding - T_m, and welding- T_{mw}) temperatures for non-reinforced/non-filled nylon 6 are presented in Table 13. Optimized mechanical performance of welded butt joints (Table 10) was achieved at maximum for a weld-melt (melt-pool) temperature above (from 47 °C to 70 °C) of the crystalline melting point (Table 13).

Observed values of the maximum temperatures of the weld interface/melt-pool (T_{mw} , Figures a, b, c) are very close to the anneal temperature (T_a) for evaluated nylon 6 specimens (Tables 5-7, 13). These results help explain observed "memory effects" for welded butt joints and for injection molded nylon plastics. The possibility that "memory effects in weld inter-phase" can dominate is born out by the results of the influence of injection molding processing conditions for PA 6 plastics.

Table 13. Relations Between Processing (Molding and Welding) Temperatures Conditions and "Memory Effects" For PA 6 Plastics (Non-Reinforced/Non-Filled)

Thermal Properties of PA 6 Plastics and Welded Joints (33 wt.% GF)	**Temperature in ^{0}C**
Melting Point (T_{mp})	223
Anneal Temperature (T_a)	270 ~ 306
Recommended Molding (Melt) Temperatures (T_m)	240 ~ 270
Maximum Temperature in Weld Inter-Phase (melt-pool), $T_{mw,max}$	270 ~ 295
Temperature Differences $_1 = T_m - T_{mp}$	17 ~ 47
Temperature Differences $_2 = T_{mw,max} - T_{mp}$	47 ~ 72
Temperature Differences $_3 = T_{mw,max} - T_a$	0 ~ (- 11)

We evaluated the influence of injection molding conditions (at various melt temperature from 225 to 310 °C) on mechanical and thermal properties of two grades of PA 6 plastics (non-reinforced/non-filled and 33 wt.% fiber-glass reinforced). Reported data on mechanical performance include stress at yield and break and the corresponding strains and notched Izod data (Tables 15-16) at room temperature conditions (23 °C).

Table 14. Optimized Mechanical Performance of PA 6, 33 wt.% GF (Capron®[5] series, HS) Butt Joints at Various Welding Technologies

Type of Plastic	**GF, %**	**LVW**	**OW**	**H-P**	**LTW**
8202	0	83,1	83,0	78,2	> 82
8231G	14	90,7	-	-	82,4
8232G	25	90,2	90,4	89,8	76,9
8233G	33	85,2	87,1	84,5	75,4
8234G	45	82,1	-	80,3	70,4
8235G	50	80,5	82,3	-	-
BG45G13	63	79,2	-	-	-

The decrease of tensile strength at yield as function of mold temperature (T_m) is shown in Table 15. Strains at yield, strength at break and notched Izod data are not sensitive to molding conditions. Strains at break reaches maximum value (equal 65%) at 270°C, at low molding temperatures (225-235°C) non-reinforced nylon 6 is very brittle (strains at break are equal to 27-32%, see Table 15).

Table 15. Influence of Injection Molding Conditions (Molding/Melt Temperature) on Tensile Properties of PA 6 (Capron® 8202, Non-Reinforced/Non-filled)

(T_m), ^{0}C	**225**	**235**	**245**	**260**	**270**	**290**
Str. at Yield, MPa	85	82	80	80	81	81
Str. at Break, MPa	50	54	49	49	49	49

[4] Usually 1,0 MPa = 10 bar

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

Strains at Yield	4.1	4.3	4.3	4.3	4.3	4.3
Strains at Br.%	27	32	54	55	68	48
Notch Izod, J/m	187	181	180	191	189	186

The increase of maximum strength, notched Izod and elastic modulus data for fiberglass reinforced (33 wt.%) plastic is shown in Table 11. Strains at break reaches maximum value (equal 3,53%) at 270°C, at low molding temperatures (225-235 °C) fiber-glass reinforced (33 wt.%) nylon 6 is very brittle (Table 12).

Table 16. Influence of Molding Conditions (Melt Temperature) on Tensile Properties of Capron® 8233G (PA 6, 33 wt.% GF)

(T_m), ^{0}C	**225**	**235**	**245**	**260**	**270**	**290**
Max. Strengt, MPa	167	180	181	184	186	188
Strains. at Br. %	3.1	3.3	3.4	3.5	3.5	3.4
Notch Izod, J/m	617	674	692	759	764	766

Injection molded nylons have lower orientation and are predominantly spherulitic. Polyamide/nylon 66 crystallizes are much faster than PA 6. At temperatures close to the melting point temperature (T_{mp}), the crystallization rate is lower and large crystal sizes can be obtained. At lower temperatures far below T_{mp} , the crystallization rate is faster, but smaller crystal, are formed. The presence of the "memory effects" affect aggravates the problem of separating the two effects in polyamide/nylons, as faster nucleation due to the presence of self-nuclei (residual nuclei) as fact of initial crystallization. Injection molding processes generally involve non-isothermal heating, and cooling rate and shearing conditions affect crystallization also.

Table 17. Influence of Injection Molding Conditions (Molding/Melt Temperature) on Flexural Properties of PA 6 (Capron® 8202, Non-Reinforced/Non-filled)

(T_m), ^{0}C	**225**	**235**	**245**	**260**	**270**	**290**
Flexural Strengt. MPa	124	121	121	120	121	118
Strains At Max. Load,%	5.3	5.2	5.2	5.1	5.2	5.3
Flexural Modul., 10^3MPa	3.0	2.9	2.9	2.9	2.9	3.1
Flexural Stress. At 3.5%	109	106	106	106	106	104

Orientation is usually restricted to a surface layer because of the high shear rates near the surface during processing. An improved understanding of physical and mechanical properties and their relationship to processing variables requires the knowledge of crystal structure and morphology of nylon based plastics.

Mechanical performance data is in good correlation with physical structures of evaluated nylon 6. Nylons can occur in more than one crystalline form (α and γ), depending on the conformation and packing of the polymer chains during polymer crystallization. Transforming between the phase occurs upon processing, annealing, and mechanical stresses.

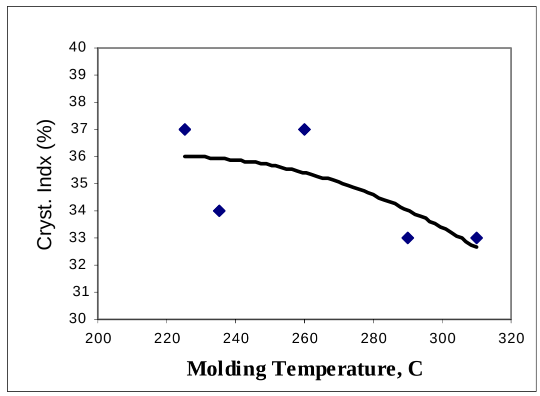

Figure 14. Influence of molding/melt temperatures on CI (crystallinity index).

The peaks (during profile analysis) corresponding to the α and γ crystalline forms by profiling semi-crystalline polymers in which the crystalline fractions is completely in α or γ crystals forms. For molded nylon 6 three different crystal structures were observed based on a different dependence of their properties on density.

The α form crystals were obtained from crystallization at higher temperatures or annealing; γ crystals were obtained at lower temperatures.

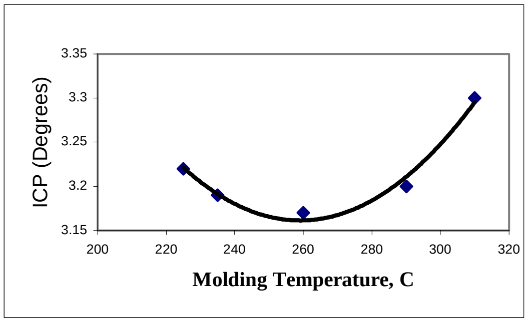

Figure 15. Influence of molding/melt temperatures on ICP.

Quenching gave a disordered, pseudo-hexagonal form, which is called γ* form [16-17]. Injection molding forces molten nylon at high pressure into temperature controlled molds. This results in a three-layered sandwich-type structure, a very thin nearly amorphous skin (with a thickness from 0,1 mm to 1,0 mm), a relatively high crystallinity core and less crystalline inter-phase layer.

The different level of crystallinity and molecular orientation leads to very complex stress-strain distribution through all these three layers. Typically meltdown value for vibration welded manifolds is at range 1,5-1,8 mm. Part of a thin skin will be removed to melt-flash at initiated phase of heat propagation in weld areas. The melt-pool formation will involve the inter-phase & core areas also.

The width of the crystalline peak is related to the size of crystals. A crystalline index (CI) decreases monotonically with increasing molding temperatures from 225 °C to 310 °C (Figure 14). When an index of crystalline perfection (ICP) is reaching a local minimum (Figure 15), nylon 6 reaches the maximum strains at break (illuminating previous brittleness).

Because ICP is free of the possible errors due to sampling and measurement procedures (sample mounting and instrumental angular correction), it can be measured rather precisely and is using in conjunction with CI (crystalline index) and CSP (crystallite size and perfection). Furthermore, the glass transition temperature T_g is far more sensitive to the frequencies used in its determination than T_{mp} and, at any frequency or heating rate the temperature interval is far wider than that of the melt point temperature (T_{mp}).

Table 18: Influence of Molding Conditions (Melt Temperature) on Glass-Transmission Temperatures (T_g, ^{0}C) for Capron® 8202 (PA 6, Non-Reinforced/Non-Filled) and Capron® 8233G HS (PA 6, 33 wt.% GF)

(T_m), ^{0}C	225	235	245	260	270	290
8202	43	43	42	42	41	39
8233G	38	39	38	39	37	37

Table 18 provides data on glass-transition temperature (T_g) for nylon 6 with the effects of molding (melt) temperatures. In the present report all T_g values (Table 18) have been taken from DAM curves. The glass transition temperature (T_g) decreases slightly (from 43,1 to 38,7 °C) for non-reinforced PA 6.

These results are in a good correlation with data for T_{cc} (temperature of crystallization upon cooling from the melt) as function of melt anneal temperatures (T_a) [16]. For fiberglass reinforced (33-wt.%) plastic T_g reaches local maximum at 260 °C and all temperature changes were not significant.

Kinetics of the dynamic mechanical behavior of nylon as function of molding (melt) temperatures is shown in Tables 14-15.

Dynamics shear modulus is changing differently for evaluated plastics with the influence of molding and test temperatures:

- for non-reinforced plastic value of ***G'*** decreases at all test conditions
- for fiberglass reinforced (33 wt.% GF) ***G'*** reaches a local maximum at melt temperature 280°C approximately) for all test conditions (- 40; 23 and 120°C).

Table 19. Influence of Molding Conditions (Melt Temperature) on Shear Modulus (***G'***, 10^3 MPa) for Capron® 8202 (PA 6, Non-Reinforced/Non-Filled Plastic) at Various Test Temperatures

(T_m), ^{0}C	225	235	245	260	270	290
Tested at –40C	1.0	0.96	0.95	0.94	0.93	0.95
Tested at 23C	1.0	0.9	0.9	0.9	0.9	0.9
Tested at 120C	143	128	126	125	117	120

The changes of the ***G'*** modulus are 4-5% for fiberglass reinforced plastic and 9-10% for non-reinforced plastic (DMA is the key test method, which provides kinetics of deformation properties).

Table 20. Influence of Molding Conditions (Melt Temperature) on Shear Modulus ((***G'***, 10^3 MPa) for Capron® 8233G (Fiber-Glass Reinforced (PA 6, 33 wt.% GF) at Various Test Temperatures

(T_m), ^{0}C	225	235	245	260	270	290
Tested at –40C	1.6	1.6	1.6	1.7	1.7	1.7
Tested at 23C	1.6	1.6	1.6	1.6	1.6	1.7
Tested at 120C	0.5	0.5	0.5	0.5	0.5	0.5

Melt Temperature: Relation to Mechanical Performance of Optimized (Hot-Melt/Extrusion) Welding

Hot-melt, part and mold temperatures are critical factors affecting mechanical performance when joining nylon parts. A multi-cavity injection molding process also requires optimized hot-melt temperature at the joining/sealing phase [19-20]. The sealing phase (Figure 16) is a key element of this technology. For the injection-molded parts, 33 wt.% nylon 6 was used, and un-reinforced, un-filled nylon 6 are used for the hot-melt.

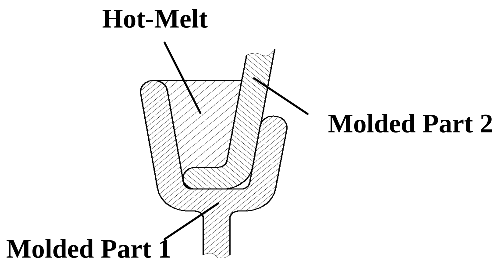

Figure 16. Principles of Hot-Melt joining (over-molding)

For the sealing phase, we used optimized (see "memory effects") molding hot-melt temperatures (Tables 5-7, 9). At optimal temperatures (for hot-melt, and joined parts 1-2) an inter-phase is formed (14).

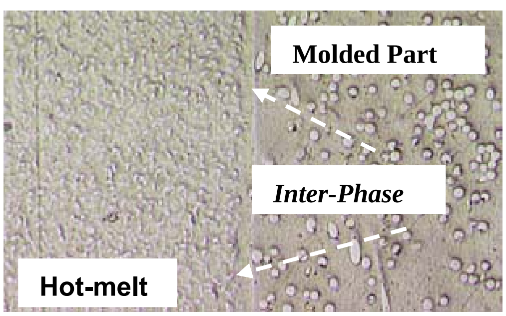

Figure 17. Joint Structure at Optimized Over-Molding Conditions

This multi-layer structure in the joint provides high levels of mechanical performance, when equal strength principles were realized in the design of the joined parts.

CONCLUDING REMARKS

- Optimal mechanical performance of polyamide/nylon joints was achieved using weld-melt (melt-inter-phase) temperatures above the melting point(s) of various polyamide/nylon-based plastics.
- Studies on heat generation and weld-melt propagation in the inter-phase area demonstrate the dynamics of temperature distribution in the inter-phase area and overall. Time-temperature kinetics depends on the plastic composition, because reinforcements and fillers affect the thermal properties of polyamide/nylon.
- The distribution of weld-melt temperatures in localized areas is not isohronus; it is dependent on the flatness of the welded surfaces, welding tool design and heat transfer.
- The maximum temperature of the weld-melt (melt-pool) is 85-100 °C above the melting point of welded polyamide/nylon.
- Melt-point temperature elevates slightly due to applied weld clamp pressure, and decreases slightly for polyamide/nylon 6 molded at high temperatures.
- Increase of melt-weld (weld inter-phase) temperature over the melt point for plastic correlated well with recommended molding temperatures for nylon 6 plastics. Manufacturer recommendations on molding temperatures may be applied for optimized welding conditions of various polyamide/nylon plastics.
- The relations between optimized welding/molding temperatures and "memory effects" will allow technologist to recommend optimized vibration welding conditions for polyamide/nylon made parts.
- The measured glass transition temperature varies with the technique of measurement.

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PHRASE INDEX

Base polymer – unfilled plastic (polyamide).
Melt-pool – volume of melted plastic(s) between welded parts.
Weld interface – boundary between two fused (mixed) polymers. The thickness of interface is equal to 30 nm (approximately).
Weld inter-phase – re-melted layer(s) of plastic(s) between welded together thermoplastic components. The thickness of inter-phase may vary from 30 to 300 μm.
Weld-melt – molten layer(s) of plastic(s) between together welded thermoplastic components.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AIM: Air intake manifold

ASTM: American Society of Testing and Materials

BK: carbon black

DAM: dry as molded

DMA: dynamical mechanical analysis

GF: fiber-glass reinforcement

FEA: finite element analysis

IR: infra-red

ISO: International Organization for Standardization

MF: mineral filled

PA: polyamide

PP: polypropylene

RH: relative humidity

SAE: The Engineering Society for Advancing Mobility Land Sea Air and Space

SEM: scanning electron microscopy

SPE: Society of Plastic Engineers

E – Young's modulus of the plastic

e – strain

ρ**:** density of the plastic

wt.: level of plastic reinforcement or filled by weight in %

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