

THE BENEFITS OF PROCESS AND MATERIAL OPTIMIZATION FOR DESIGN OF WELDED PLASTIC PARTS: NYLON BASED THERMOPLASTICS

INTRODUCTION

In recent years, demand has risen sharply for nylon based materials across many Appliance market segments. One example is the increased usage of non-filled, fiberglass-reinforced, and filled nylon products to replace metals and thermosets in the lawn & garden equipment (leaf blowers, chain-saws, gas-tanks) and power tools. The welded nylons are used in many appliances [1-3]. The design of these critically stressed welded components requires advanced analysis of structure; noise, vibration, and harshness (NVH), and welded joints using short-term and long-term strength and cyclic life criteria [4].

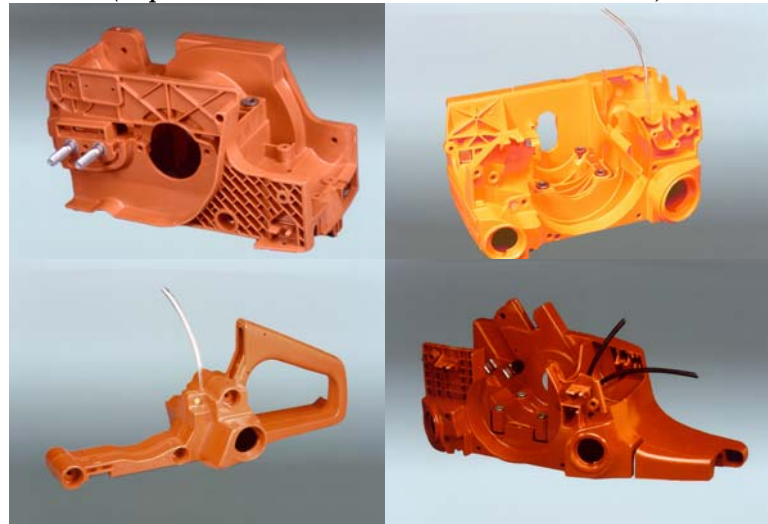
A variety of thermal and mechanical joining processes are available for thermoplastics, including linear vibration (LVW), orbital vibration (OVW), spin welding (SW), hot plate (H-P), electromagnetic, ultrasonic, infrared, and laser, etc. Choosing the best joining method for thermoplastics requires a thorough understanding of the design, purpose of the joint / assembly, and characteristics of the joining processes under consideration. In addition, engineers should know the geometry of the component, nature of plastic materials used, the internal and external load, time / temperature requirements, and other environment conditions, and specific criteria required in the final assembly (aesthetics, noise, vibration, dimensional stability, etc.). In selecting a joining method for appliance plastic parts makers are increasingly turning to frictional welding technologies.

BASICS AND BENEFITS OF FRICTIONAL WELDING TECHNOLOGY

Frictional welding (FW) technology is a reliable joining method for injection molded, blow-molded, extruded and thermoformed hollow components (Fig. 1-4). The growing popularity of FW for the appliances can be attributed to its flexibility and low cost. Linear vibration welders are complete plastic assembly systems designed to join from small to large or irregularly shaped thermoplastic parts up to 48 x 20 in. (1220 x 508 mm) wide. Additionally, LVW is a fast joining process, with cycle times on the order of 0.5 to 12 sec. Typical cycle times are 30 sec. (including both welding and cooling time), which is approximately 1 / 50 the cycle time of other methods and substantially less energy is required.



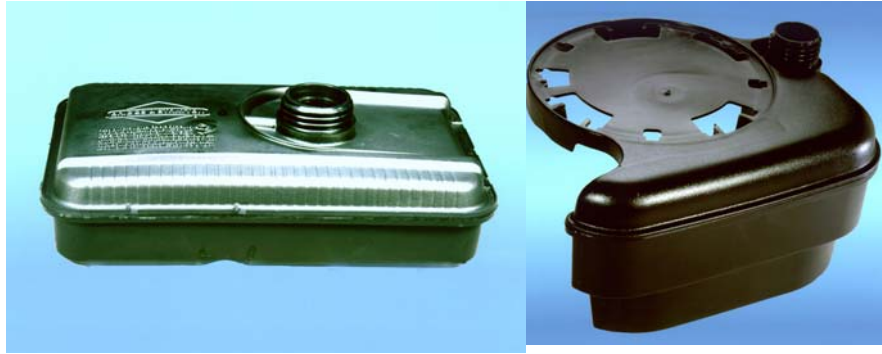
**Figure 1: Vibration-Welded Gas Tank for Chainsaw
(Capron® 8233G RD-6410 resin and other colors)**



**Figure 2: Design Versions of a Various Welded Tanks
(Capron® 8233G, in various colors)**

This makes FW technologies considerably more cost effective than the hot plate, laser, or electromagnetic methods [4]. FW methods of joining technologies (LVW, OVW and SW) all share the following welding phases:

- Placement of plastic parts to be joined in nest with gripping provided by specially designed tools;
- Materials heated in areas where the joints are to be formed;
- Local melting in jointed surfaces areas;
- Contact / pressing together of surfaces to be joined;
- Cooling in the joint interface and other areas;
- Removal of joined / welded part from welding tool / nest and machine.



**Figure 3: Welded Gas Tanks, Capron® BU50I BK-102
(Ultra-tough, Impact modified nylon 6)**

The LVW, OVW, and SW welding present an internal heating process using friction. The process of FW entails rubbing two thermoplastic components together at such a frequency (typically in the range of 120 to 240 Hz). At this frequency, material actually produces frictional (Coulomb) heat, which results in a melt at their interface, and the subsequent melding / joining of the parts together (see Figures 2-4). The displacement may either be linear, orbital, or angular displacement. FW produces high-strength joints in nylon-based thermoplastics.



**Figure 4: Vibration-Welded Leaf Blower (left) and Fluid Reservoir (right)
(Capron® 8233G HS RD6410 resin and other colors, and Capron® 8231G HS natural)**

For all FW methods, the temperature in the weld inter-phase is a function of processing parameters such as time, clamp-pressure, amplitude, frequency, and meltdown, and it depends also on the physical characteristics of the polymers. The OVW method is also based on friction, which uses an electromagnetic drive to create relative motion between two plastic components. OVW technology allows motion to be programmed in many ways, and it also provides more freedom in designing the weld areas [4].

For high-performance of joints, the following eight processing and weld-inter-phase parameters are critical:

1. Welding amplitude (variable in process), in inches (or mm):
 - pre-melt (heating)
 - melting;
2. Clamp pressure (variable in process), in psi (or MPa):
 - pre-melt;
 - hold / sealing (cooling);
3. Thickness of inter-phase of pre-heated layer(s), in inches x 10^{-5} (or microns):
 - melt collapse / melt-down;
 - final thickness of interface (in local areas);
4. Temperature in $^{\circ}\text{F}$ (or $^{\circ}\text{C}$):
 - in local and weld inter-phase areas during the melt formation phase;
 - at start and final temperatures at hold / sealing (local cooling) phase;
5. Meltdown / melt collapse, in inches x 10^{-3} (or mm).
6. Process duration (time, in seconds):
 - pre-melt (heating);
 - melting;
 - hold / sealing (cooling);
7. Direction of oscillation:
 - linear vibrations (longitudinal;
 - perpendicular to thickness of wall / bead;
 - by angle);
8. Vibration frequency (in Hz, typically in range from 120 to 240 Hz).

When applying LVW and OVW technologies, we need to be aware of the following information:

- Weight (of the upper fixture + nested part) and design limitations in the sizes of the part placed in upper nest / fixture;
- Limitations on the weld-plane configuration and maximum value of out-of-welded plane angle;
- Difficulties (to achieve optimized mechanical strength / life performance of joint) in using dissimilar plastics with different melt temperatures (of greater than 50°C or 122°F);
- Dimensional limitations (in non-isometric melt distribution in local areas of possible gaps) in reinforced plastics and for non-optimized molding conditions.

For nylon-based plastics, it is necessary to reach a melt thickness (meltdown) in the range 0.7 - 1.5 mm [4-8]. The LVW and OVW processes are less sensitive to dimensional tolerances because they both are self-adjusting in the contact areas. It is critical to maintain the required wall stiffness (via angle and thickness) in the direction perpendicular to the direction of oscillation [4].

REMARKS ON MECHANICAL PERFORMANCE OF WELDED JOINS

The tensile strength of welded joints is one of the most important mechanical performance parameters for critically stressed plastic components. For non-reinforced thermoplastics (polypropylene, polyester, etc.), the percentage of tensile strength retention with different welding techniques is in the range of 30 – 90 %. For non-reinforced nylon 6 and nylon 66, a butt weld joint's strength is nearly equivalent to the strength of the base material. However, for glass-fiber-reinforced thermoplastics, the maximum achievable weld strength is usually thought to be 70 – 80 % of the strength of the base material or matrix.

The lower tensile strength of welded joints in glass-reinforced thermoplastics is usually attributed to a change in fiber orientation at the welded-joint inter-phase. It is generally thought that the fibers align along the weld line, perpendicular to the stress applied in the tensile-strength measurement [6-7]. For 30 wt-% glass-fiber reinforced (GF) nylon 6 and 66, the maximum weld strength (at 73°F / 23°C) (reported in [6]) is 9,410 psi (64.9 MPa). In order to optimize the processing technology for LVW and support the design of nylon based components, we analyzed [5, 8] the influence of glass-fiber (GF)

loading over the range of 0.0 to 63 wt-% on the tensile strength of nylon 6 and 66. In addition, the effects of critical VW process parameters (e.g. set clamp and weld pressure, amplitude, meltdown, weld and hold / cooling time) were tested in parametric fashion.

MATERIAL AND WELDED JOINT DESIGN REQUIREMENTS RELATED TO OPTIMIZED JOINT PERFORMANCE

In order to optimize vibration-welded joint performance for highly stressed structural components, material properties and part-production techniques must be carefully evaluated. The most important parameters for plastic joints are [4]:

- Joining and production (molding and welding) flexibility for multi-piece parts;
- Specific performance requirements (strength, life / durability, chemical resistance, mechanical test conditions, etc.) to vibration weld plastic components and assembled parts;
- Desirable level of welded-joint hermetic seal (burst and backfire pressure);
- Specific requirements of welded-joint geometry (shape, size, and stiffness), joined parts' dimensional stability, and tolerances;
- Type of welded joint design (butt, shear / overlap);
- Short-term mechanical properties of joints by tensile, flexural, or combined-load conditions, and impact-strength criteria;
- Long-term mechanical properties of joints by creep and fatigue strength and life criteria;
- NVH performance;
- Desirable level of quality in weld areas (internal and external surface smoothness, aesthetics aspects, no defects, cracks, voids, inclusions, etc.).

For VW joining technology, the most important requirements for the welded materials are [5, 8-10]:

- Type of joining materials (similar, dissimilar);
- Thermoplastic compositions (type of matrix, type of fillers and reinforcement);
- Optimized content of reinforcement elements, fillers and additives, pigments, etc.;
- Short- and long-term mechanical properties of joined materials and mechanical properties of matrix with the influence of loading, welding, time / temperature, and environment conditions;
- Dimensional stability of joined materials.

In general, manufacturers of plastic components are looking for tensile strength values of 7,250 to 8,750 psi (50 – 60 MPa) at ambient conditions of 73F (23C) to match the mechanical performance of aluminum [4]. The performance of the welded joint has a major impact on the ability of manufacturers to meet these requirements. As a base material, 30 - 35 wt-% glass-reinforced (GF) nylon 6 and 66 products meet the above mentioned tensile strength requirements. Another important design and material requirement for VW components is dimensional stability. Post-mold warpage will impact the tolerances of joined surfaces, clamp and welding pressure conditions, and will contribute to the creation of residual stresses.

EXPERIMENTAL PROCEDURES

Vibration-Welding Equipment and Processing Parameters

The LVW and OVW of butt joints were made at Branson Ultrasonics Corporation. A modified MiniWelder-II® and CV-12® machines were used for LVW and OVW, respectively (Fig. 5). The key LVW and OVW parameters were as follows:

- Weld Amplitude: 1.02 ~ 1.80 mm (0.040 ~ 0.070 in.);
- Melt-down / Melt-collapse: 0.50 ~ 5.0 mm (0.197 ~ 0.197 in.);
- Weld Frequency: 210 ~ 240 Hz;
- Hold / Cooling Time: 2 ~ 10 sec.



Figure 5: Frictional Vibration Welding Machines (left – MINI-II, right – CV-12)

Used Materials, Models and Test Procedures

The thermoplastics used in this investigation were natural and colored nylon 6 based plastics (Table 1). Limited data will be present for nylon 66 also. We also evaluated the performance of LVW joints using mineral-filled (40% by weight) and glass / mineral-filled (15% glass fiber, and 25% mineral-filled, both by weight) nylon 6 plastics.

Table 1: Fiber-glass (GF) Loading Levels and Melting Points for Tested Materials

Polymer	GF Levels as Tested (%)	Melting Point of Material (°C / °F)
Nylon 6	0, 14, 24, 33, 45, 50, 63	223 / 433
Nylon 66	0, 33	261 / 501
Nylon 66 / 6 Copolymer	30%	238 / 460

For evaluated welding (LVW and OVW) technologies, we used the recommended butt joint design (consisting of 2 beads, 4.00-mm and 6.25-mm thick) and welded together the following injection-molded rectangular plaque:

- 3.9 (or 4.7) x 2.6 x 0.250 in. (100 (or 150) × 65 × 6.25 mm);
- 3.9 (or 4.7) x 2.6 x 0.160 in. (100 (or 150) × 65 × 4 mm).
- Sizes (length × width) of the welded plaques are approximately: 3.9 (or 4.7) x 5.0 in. (100 (or 150) × 125 mm).

In quality control and performance evaluation of the welded components and plaques, tensile- and burst-test methods were usually used [4-8, 10]. The tensile strength of welded joints or specimens is a key parameter for the material selection, component design, joint-performance evaluation, and welding optimization. At the same time, most of the plastic weld performance data have been obtained by testing the tensile strength of welded butt joints. The tensile test results are also very important for joint design evaluation and improvement, and new materials development for welded parts. The test

data was obtained from rectangle tensile specimens (10 mm width, 125 mm length) cut and machined from welded plaques (150 or 100 mm × 125 mm). For either LVW or OVW processing conditions, a minimum of 5 specimens were tested using ISO 527 procedures. The tensile specimen, which has a uniform butt weld at mid-length, is then subject to a constant displacement / strain rate. The specimen is loaded until it fails. All tensile test results were used for the performance optimization. Samples with high tensile strength were selected to perform the morphology analysis in the weld zone (inter-phase).

RESULTS AND DISCUSSIONS

Plastic Optimization: Influence of Fiber-Glass Reinforcement and Color

Tensile strength of butt joints depends on fiber-glass content in welded nylon 6 based plastic (Tab. 2).

Table 2: Influence of Glass-Fiber Reinforcement (wt-% GF) on Tensile Strength of Weld

GF% (by weight)	Tensile Strength of Plastics (MPa)	Tensile Strength of Weld (MPa)
0	81	79.3
6	85	83,1
14	125	90,7
25	160	90,2
33	185	85,6
50	220	80,5
63	254	62.2

These results (developed at optimized LVW conditions, see next section) indicate that all butt-weld joints in this study have a tensile strength higher than non-reinforced nylon 6. For the fiber-glass reinforced nylon 6 plastics, the maximum tensile strength of 90 MPa occurs between 14 wt.% and 25 wt.%. This is the highest weld strength found in the reinforced nylon 6, 66, 46 and HTN grades. Mechanical performance of colored products is presented in Table 3. For plastics with optimized pigments content the mechanical performance is equal or slightly above of the tensile strength of non-pigmented plastic (due to improved frictional conditions for pigmented nylon 6 products). Some pigments versions may be as the “killers” of mechanical performance of the weld.

Table 3: Influence of Color Version (Capron® 8233G)

Amplitude, mm	Natural	Black	Gray	Red	Blue
Strength, MPa	81.6	85.6	83.8	88.4	86.1

Process Optimization: Six Important Parameters of Frictional Welding (FW) Process

The influence of the following six welding parameters influential on mechanical performance of the weld were investigated in this study:

- Welding amplitude;
- Melt-down / Melt-collapse;
- Thickness of inter-phase;
- Clamp pressure;
- Temperature in °F (or °C);
- Shape and direction of oscillation.

Nylon 6 based Capron® 8233G glass-fiber reinforced plastic (33 wt% GF) colored in black was used for this study. Tensile test data was developed at room temperature conditions for dry as molded specimens (Tables 3-9)¹.

¹ In the Tables 4 – 9 the maximum tensile strength typed in “Bold”

Table 4: Influence of Weld Amplitude

Amplitude, mm	0.75	1.15	1.50	1.8
Strength, MPa	73.8	75.7	80.6	85.6

Table 5: Influence of Weld Pressure

Weld Pressure, MPa	0.65	0.85	1.25	3.5	5.6
Strength, MPa	73.7	85.6	80.4	65.7	58.3

Table 6: Influence of Melt-down (Weld Collapse)

Melt-down, mm	0.5	1.2	1.5	2.0	3.5	6.2
Strength, MPa	74.5	77.4	85.6	87.9	89.3	95.8

Table 7: Influence of Thickness of Inter-phase

Thickness, μm	40	120	300
Weld Pressure, MPa	5.6	3.5	0.85
Strength, MPa	58.3	65.7	85.6

Table 8: Optimized Welding Temperature in Inter-phase

Plastic Type	Melt Point Temperature, C°	Temperature in Weld Inter-phase, C°
Nylon 6	223	270 ÷ 285
Nylon 66	261	295 ÷ 320

Table 9: Influence of Shape and Direction of Oscillations

Type of Oscillation	Longitudinal	Perpendicular	By Angle (45 °)	Orbital
Strength, MPa	85.6	84.6	85.2	87.2

Analysis of presented data in Tables 4-9 will allow to discuss the following practical recommendations:

- Weld amplitude \uparrow - mechanical performance \uparrow ;
- Weld pressure \uparrow - mechanical performance \downarrow ;
- Melt-down (melt-collapse) \uparrow - mechanical performance \uparrow (for longitudinal oscillation);
- Thickness of the weld inter-phase \uparrow - mechanical performance \uparrow ;
- Temperature of the weld-melt *above* melting point of plastic – mechanical performance \uparrow ;
- Direction and shape of oscillations do not affects mechanical performance of the weld.

An analysis of combined effects of the several welding parameters on mechanical performance of the weld requires preparation of DOE study. Practical recommendations and achieved results (weld pressure, meltdown, amplitude with burst pressure) for welded Capron® 8233G HS BK-102 were discussed in [11].

Local Reinforcement Effects in Weld Interface (at Optimized Welding Conditions)

Details of the glass-fiber orientation in nylon's weld interface area were presented in [8]. Optical microscopy was used to study the morphology of the samples (fiberglass orientation, local reinforcement effects, presence of microporosity, small inclusions, etc.), while image analysis was used to quantitatively characterize the fiberglass state including diameter, length, and breakage, and positioning of the welded components (penetration, meltdown, etc.).

Furthermore, a study of the weld-zone fracture surfaces on both technologies by scanning electron microscopy suggested that there is no excessive breakage of glass fiber at the weld interface. This technique allows one to determine quantitatively the effects of local reinforcement on the weld fracture surfaces. Table 2 and Table 10 summarizes the results of the tensile strength of GF-reinforced, nylon-6 based plastics and welded butt joints from LVW technology, optimized processing conditions, and longitudinal vibrations [5, 8].

**Table 10: Mechanical Performance of Similar Nylon Joints
(30 – 33 wt-% GF), at 23C, Dry as Molded**

Joints Design Versions Similar Materials	Tensile Strength of Weld (MPa)
Nylon 6 + Nylon 6	85.6
Nylon 66 + Nylon 66	83.2
Nylon 66 / 6 Copolymer +Nylon 66 / 6	84.9

The results may also be compared (see Tables 11-12, data for nylon 6 based plastics) with the tensile strength of the base matrix *m* / polymer (or to the tensile strength of the welded plastic *pl*), using welding factor f_m (or f_{pl}) correspondingly. Welding factors f_m and f_{pl} are equal to the following ratios (1 and 2):

$$f_m = \text{tensile strength of weld} / \text{tensile strength of base polymer} \quad (1)$$

$$f_{pl} = \text{tensile strength of weld} / \text{tensile strength of reinforced (or filled plastic)} \quad (2)$$

It was reported previously that for GF-reinforced thermoplastics, the maximum weld strength for the butt joints is approximately equal to or less than the strength of the matrix or base materials [6-7]. The reduction in tensile strength was attributed to the changes in the glass-fiber orientation at the welded joint, where the glass fibers align along the weld plane, perpendicular to the applied stresses. Fig. 6 explains strength reduction effects typical for the non-optimized welding conditions.

**Table 11: Influence of Glass-Fiber Reinforcement (wt-% GF)
on the Welding Factors at Optimized LVW Conditions**

GF% (by weight)	Weld Factor f_m	Weld Factor f_{pl}
6	1.07	0.98
14	1.14	0.73
25	1.14	0.56
33	1.08	0.46
50	1.02	0.37
63	0.78	0.25

Table 12: Efficiency of Welding Technologies at Optimized Processing Conditions

Method of Welding Technology	Weld Factor f_m	Weld Factor f_{pl}
Linear Vibration	1.08	0.46
Orbital Vibration	1.1	0.47
Hot Plate	1.12	0.48

Fibers do not cross interface

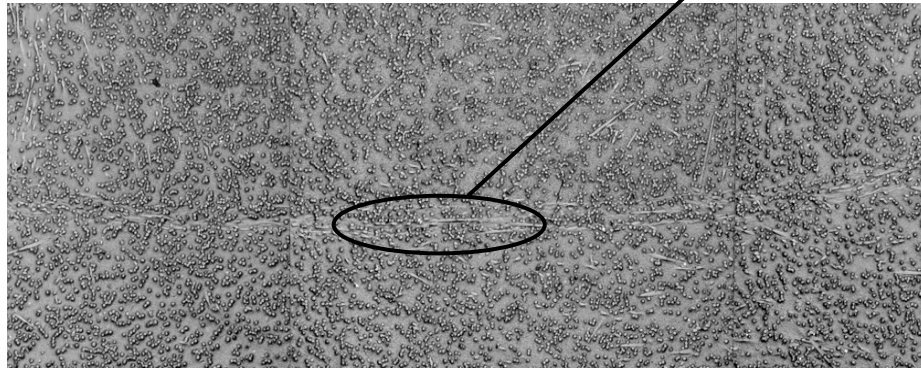


Fig. 6: Fiber-Glass Orientation at Non-Optimized (Standard Set-Up) LVW Conditions

The orientations of glass fibers are found to be the following:

- at the weld interface, local area fibers were oriented mostly along the weld-melt flow direction;
- throughout most of the rest of the specimen, the fiber orientation was random, depending on part design and molding conditions, etc.

The effects of inter-diffusion at polymer-polymer interface for amorphous and semi-crystalline materials have been reported before [9-10]. The minor chain repetition model explained the effects of healing and strengthening non-reinforced plastics during the welding process time. In this study, the effects of strength and performance improvement for welded joints were explained [5, 8] from the dynamic mode of glass fiber re-orientation in joining process time.

For OVW technology, it is possible to select among circular (orbital), straight (linear), or elliptical weld paths. The tensile strength of OVW is slightly higher than for LVW technology (see Table 12). By nature of heat generation, an orbital / circular and elliptical path is more efficient (at the optimized welding parameters) at fiberglass re-orientation and polymer blending.

Fibers do cross interface



**Fig. 7: Fiber-Glass Orientation at Optimized LVW Conditions
(Local Reinforcement Effects in Weld Inter-phase)**

With the optimized welding parameters in LVW and OVW, some of the glass fibers were found to orient perpendicular or at an angle (see Figure 7) to the weld plane across the interface [5, 8, 12]. This local reinforcement effect for LVW and OVW methods were observed for both nylon 6 and 66 polymers. In reference [5, 8] we explained the effects of fiber orientation in dynamic terms of the vibration process and thickness of the interface comparable with the length of short glass-fibers. For nylon 66 plastics, we achieved the performance of weld similar to that in nylon 6 for LVW and OVW techniques [12].

CONCLUSIONS

- Morphology studies using microscopy have revealed the fiberglass distribution and orientation in the bulk of the material and at the interface. *Under the optimized LVW and OVW processing conditions*, part of the glass fibers were found to orient perpendicular or at an angle to the weld plane, and they were also found to cross the interface.
- These local reinforcement effects were found to be very repeatable for the butt joint welded from similar and dissimilar plastics.
- Comparing studies of LVW and OVW joining technologies demonstrated that the OVW process is very efficient for nylons and may be used as an alternative to LVW and ultrasonic technologies for the welding of small components.
- For both LVW and OVW technologies, the maximum tensile strength measured at the weld was achieved in materials with 14 to 24% GF-reinforcement (by weight).
- For colored plastics the optimized type, and pigments content and dispersion will not affect the mechanical performance of the weld.
- Optimization studies will allow to present the following practical recommendations:
 - Weld amplitude \uparrow - mechanical performance \uparrow ;
 - Weld pressure \uparrow - mechanical performance \downarrow ;
 - Melt-down (melt-collapse) \uparrow - mechanical performance \uparrow (for longitudinal oscillation);
 - Thickness of the weld inter-phase \uparrow - mechanical performance \uparrow ;
 - Temperature of the weld-melt (in weld inter-phase) is *above* (by 60 ~ 70 °C) melting point of plastic – mechanical performance \uparrow ;
 - Direction and shape of oscillations do not affect mechanical performance of the weld.
- The presented optimized weld mechanical performance and material data will allow designers to recommend LVW and OVW technologies in plastic product development for welding applications and welded components manufacturing.

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