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Ixef® PARA

Design Guide

SPECIALTY POLYMERS

Table of Contents

List of Tables

List of Figures

Ixef® Polyarylamide (PARA)

Ixef® PARA, a Composite Material

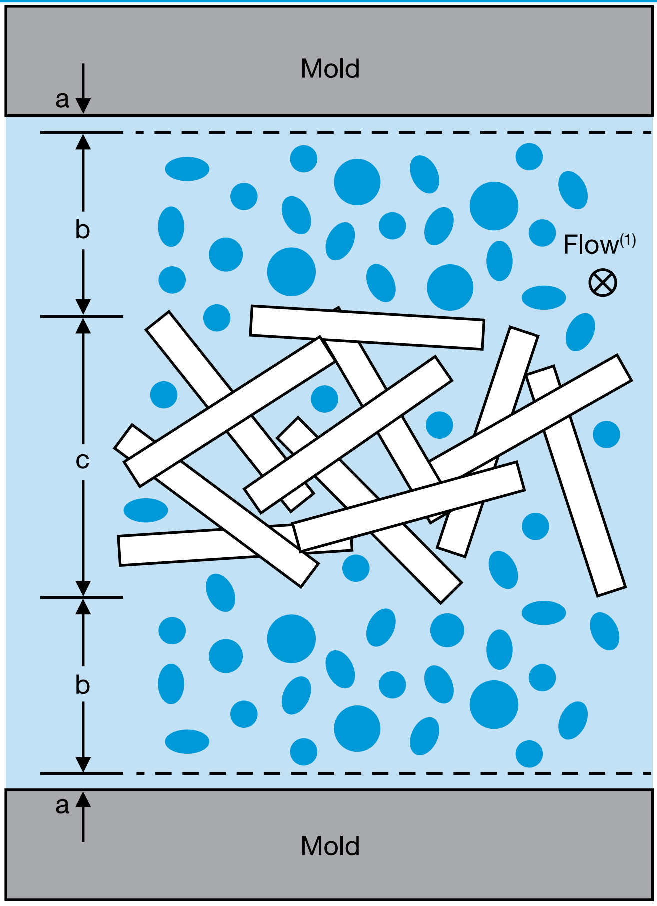
Ixef® PARA compounds are a family of thermoplastic products reinforced with glass fibers and/or mineral fillers.

Although the properties can vary from grade to grade, the most striking characteristics of parts manufactured from Ixef® PARA compounds can be summarized as follows:

- **Very high rigidity**
  Tensile modulus up to 23 GPa at 20°C (68°F).
- **Excellent resistance to mechanical stresses**
  Flexural strength can attain 400 MPa at 20°C (68°F).
- **Easy processing, also for thin-walled sections**
  Good injectability and high productivity even with high fiber content.
- **Low mold shrinkage, highly reproducible**
  Precision molding, absence of sink marks and close dimensional tolerances can be achieved.
- **Conception of miniaturized parts**
  Rigidity, injectability of complex, thin shapes.
- **Excellent surface finish**
  Superb surface appearance for reinforced products, even with a high glass fiber content.
- **Very low coefficient of linear thermal expansion**
  Value comparable to that of metals.
- **High thermo-mechanical properties**
  Flexural modulus at 140°C (284°F) up to 7 GPa.
- **Very low creep**
  Deformation less than 1% after 1,000 hours under 50 MPa at 50°C (122°F), for example, for certain compounds.
- **Slow rate of water absorption**
  Like all polyamides, polyarylamide has a certain sensitivity to water. Even so, the semi-aromatic character of polyarylamide induces a lower and slower water absorpion in Ixef® PARA compounds than that found in items molded in PA 6 and PA 66, which are more sensitive to humidity.

Ixef® PARA compounds are composite materials. Parts manufactured by injection molding are thus not isotropic, but instead exhibit a stratified structure.

Figure 1: Cross-Section of an Injected Part



(1) Note: The material flow is perpendicular to the cross-section

A part seen in cross-section perpendicular to the flow direction presents a series of layers (Figure 1):

a = First, a skin zone of around one micron composed of pure polymer, which gives the part its surface appearance

b = Then, an intermediate layer where the fibers are clearly oriented in the direction of the flow, caused by the shear stresses which are at their maximum close to the wall of the mold during injection

c = Finally, a core region where the fibers tend to orient themselves in a plane perpendicular to the flow direction (since the fibers are less subject to shear in the middle of the part)

The qualitative and quantitative distribution of the orientation layers is influenced primarily by the following parameters:

- The thickness of the cavity. The finer the thickness, the more glass fibers are oriented in the flow direction.
- The rheological and thermal characteristics of the material. An increase of material temperature or of the mold increases the thickness of the skin zone, which improves the surface appearance.
- The processing conditions. The higher the injection speed, the more the fibers are oriented in the direction of the flow.

Ixef® PARA, a Semi-Crystalline Material

The resin used in all Ixef® PARA compounds is a semi-crystalline polymer: polyarylamide. The term **semi-crystalline** indicates that there is a crystalline phase, corresponding to the matrix zones in which the macromolecules are spatially arranged in a regular manner, and to an amorphous phase characterized by disorder of the macromolecules (Figure 2).

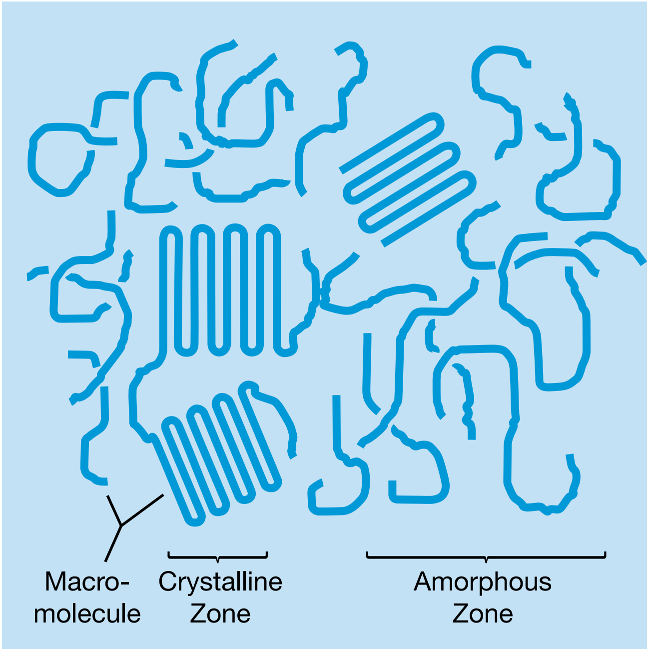
A solid semi-crystalline polymer can present different states depending on the temperature and/or the speed of stress:

- The vitreous state (zone below the glass transition temperature (T_g)), where the macromolecules are theoretically frozen, irregardless of whether or not they belong to the amorphous or crystalline phases.
- The rubbery state (zone between the T_g and the melting temperature (T_f)): one can consider that the amorphous phase is in the liquid state (possible movement of the macromolecules) while the macromolecules in the crystallites remain frozen.

The glass transition temperature thus characterizes the change of state: from vitreous to rubbery. The melting temperature corresponds to the melting of the crystallites.

The level of crystallinity obtained depends heavily on the thermal history of the material, and particularly on the molding parameters: processing temperature, mold temperature, molding cycle time, post-treatment after molding (annealing).

Figure 2: Diagram of the Crystalline and Amorphous Zones in a Semi-crystalline Polymer



To develop a high crystallinity of Ixef® PARA compounds under normal injection molding conditions, it is essential to bring the temperature of the mold to between 120°C and 140°C (248°F and 284°F).

Under these conditions, the injected parts exhibit excellent dimensional stability, an exceptional surface appearance, and very good mechanical properties, even at high temperatures.

Figure 3: DSC Analysis of a Part Injected in a Mold at 120°C (248°F)

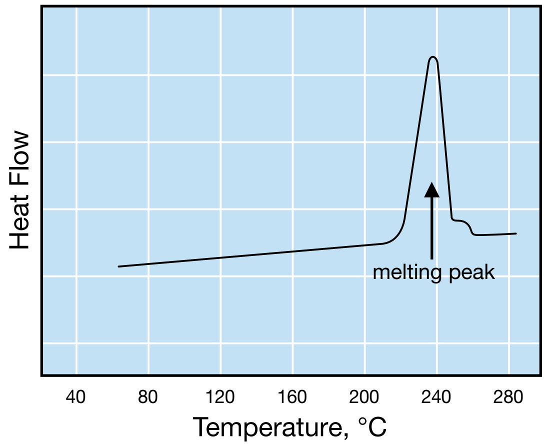
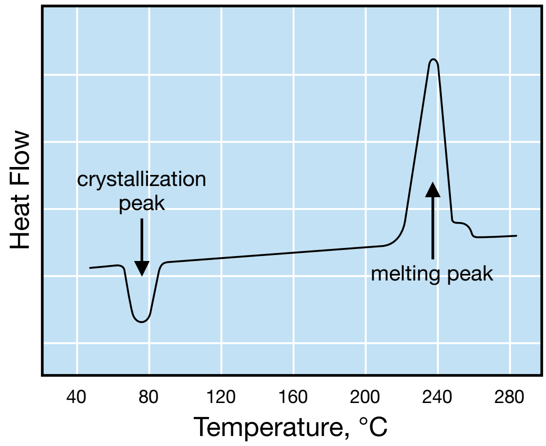


Figure 4: DSC Analysis of a Part Injected in a Mold at 60°C (140°F)



By contrast, if the temperature of the mold is less than 120°C (248°F), the injected parts will not obtain the maximum level of crystallinity throughout its thickness. If these are subsequently exposed to temperatures above the glass transition temperature, they will crystallize and thus undergo an annealing process which will affect their dimensional stability. Water pickup can aggravate this phenomenon by lowering the glass transition temperature.

The amorphous state is thus more unstable than the crystalline state: dimensional variations over time, greater sensitivity to solvents and water.

Crystallization phenomena can be studied by Differential Scanning Calorimetry (DSC). This analytical method involves comparing the energy liberated or absorbed by a test material with that of a reference material subjected to the same heating and cooling rates.

The above figures compare a DSC analysis of a part made of Ixef® PARA injected in a mold at 120°C (248°F) (above the T_g) (Figure 3) with that of the same part but using a mold at 60°C (140°F) (below the T_g) (Figure 4).

The peak near 80°C (176°F) in the case of the part manufactured in a 60°C (140°F) mold corresponds to the energy released during crystallization of resin which was not fully crystallized during injection. This peak does not appear in the case of the Ixef® PARA part made in a 120°C (248°F) mold.

Mechanical Properties

Short-Term Mechanical Properties

Tensile Properties

Among the mechanical tests, the tensile test is one of the most frequently performed because it corresponds to a uniform, mono-axial stress (ISO 527).

The tensile test, performed by deforming a specimen at constant speed, allows determination of several important characteristics:

- The tensile modulus E
- The breaking stress σ_R
- Elongation at break ε

Figure 5 presents the stress [σ_R] - strain [ε] diagram, which illustrates that Ixef® PARA compounds do not behave like perfectly elastic materials. Instead, they possess a visco-elastic behavior whose viscous component remains low.

Ixef® PARA compounds possess good tensile mechanical characteristics, as shown by Table 1.

The tensile test also makes it possible to determine the Poisson ratio (the ratio of the fractional contraction in breadth to the fractional increase in length when the material is stretched) in a direction perpendicular to the direction of stress.

$$\upsilon = \frac{\varepsilon_y}{\varepsilon_x}$$

Under the reference conditions (20°C/68°F, dry product), the average value to be considered for the Ixef® 1022 grade is 0.35.

The effect of the temperature on the tensile mechanical properties is presented in Figure 7 for the Ixef® 1022 compound.

For the two characteristics, one observes a decrease as the temperature increases. This decrease grows sharper and displays an inflection point at the polyarylamide glass transition temperature (85°C/185°F).

The presence of fibers in Ixef® PARA compounds is responsible for the anisotropic mechanical behavior of injection-molded parts.

Generally, the glass fibers tend to orient themselves in the flow direction (see Figure 1 on page 1 and Figure 6 on page 5). The mechanical properties are thus greatest in this direction.

Figure 8 presents the variation of the tensile mechanical properties (σ_R, E) in relation to the flow direction of the compound in a plate injected using a film gate.

Table 1: Tensile Properties of Ixef® PARA Grades (DAM) (ISO 527)

Grade	σ_R (MPa)	ε (%)	E (GPa)
Ixef® 1002	190	2.0	11.5
Ixef® 1022	280	1.9	20
Ixef® 1032	280	1.8	24
Ixef® 1521	230	1.9	20
Ixef® 1524	230	1.9	20
Ixef® 1622	235	2.6	17
Ixef® 2011	140	1.3	18
Ixef® 2030	140	1.2	21.5
Ixef® 2060	180	1.5	19

Figure 5: Tensile Strength (σ) as a Function of Elongation (ε) of Ixef® PARA-Type Compounds

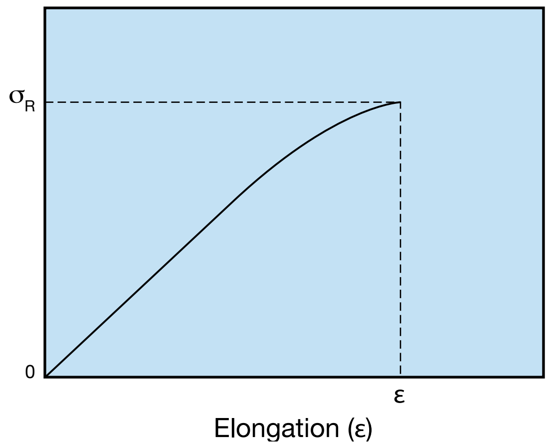


Figure 6: Plate Used to Measure Strength as a Function of the Angle of Application

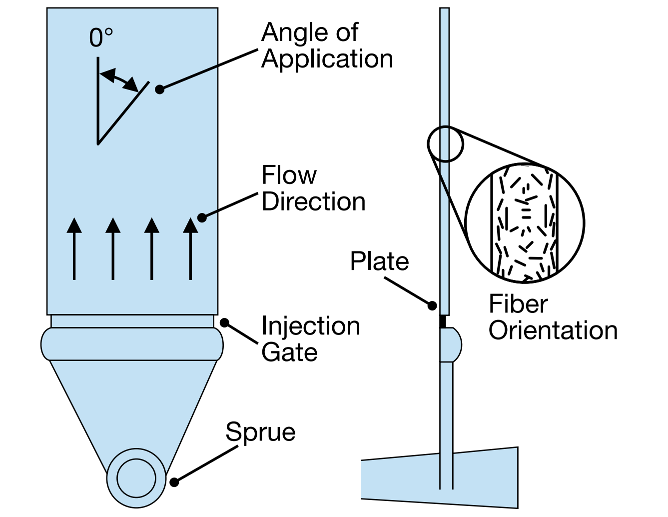


Figure 7: Tensile Properties of Ixef® 1022 (DAM) as a Function of Temperature

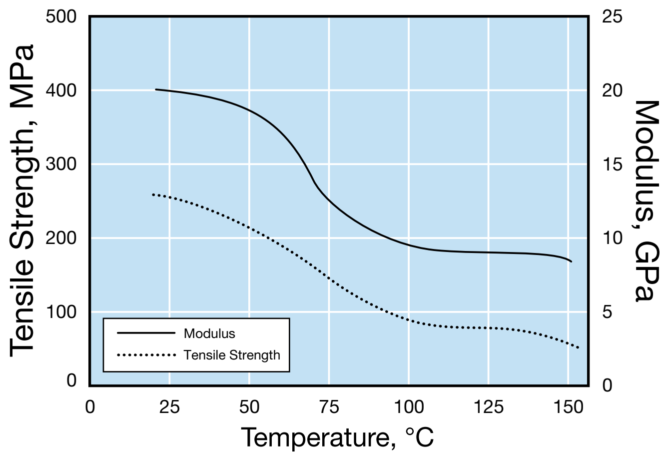
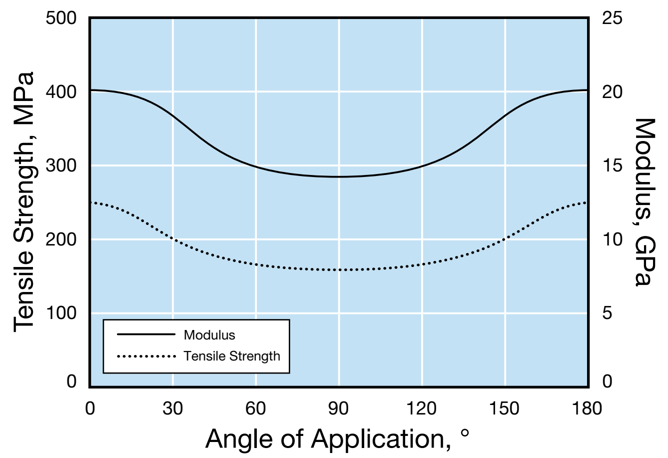


Figure 8: Tensile Properties of Ixef® 1022 (DAM) as a Function of the Angle of Application



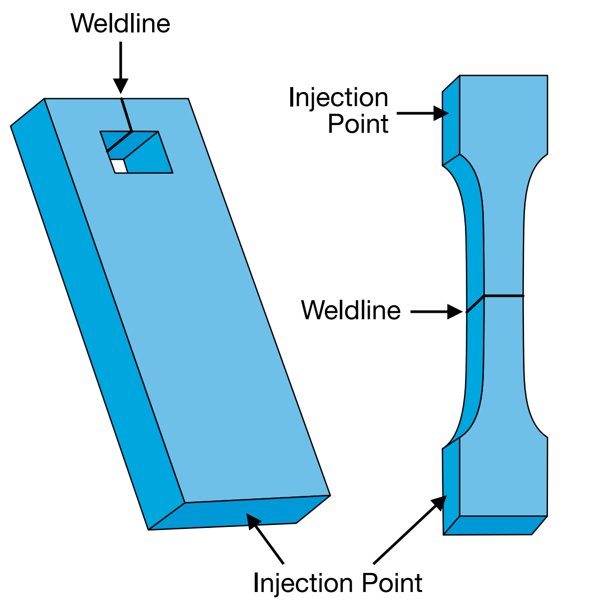
Weldlines are caused by two molten material flows meeting head on. During injection molding, weldlines are formed by multiple gates or by the presence of inserts in the mold (Figure 9). Such weldlines constitute a weak point for all glass fiber-reinforced thermoplastics, including Ixef® PARA resin.

The mechanical strength along a weldline can be maximized by adapting the processing conditions, allowing adequate venting or using overflow tabs which make it possible to modify the flow pattern across the weldline.

The design of the part can also be modified so that the weldlines are located in areas which are subject to less stress.

In the case of the most severe weldline, the tensile strength at break is considered to be around 90 MPa for most Ixef® PARA grades. Obviously, the quality of the weldline is a decisive parameter.

Figure 9: Example of Weldlines



Flexural Properties

The flexural tests are generally performed in accordance with the ISO 178 or ASTM D790 standards. Two essential characteristics are measured with the flexural test: the flexural modulus and the flexural strength. In fact, this test combines compressive, tensile and shear stresses.

With regard to flexural strength, the flexural test provides values that are higher than those obtained by a tensile test. This phenomenon can be explained by a combination of several effects:

- A "stratified" structure (see Figure 1)
- The existence of residual internal compressive stresses in the skin, and tensile stresses at the center of the specimen resulting from the injection molding process
- As the result of the distribution of the stresses, a greater plasticizing effect than in a tensile test

Table 2 provides the values measured on various Ixef® PARA compounds.

Figure 10 shows the flexural strength and flexural modulus values of the Ixef® 1022 grade as a function of the temperature.

Figure 10: Flexural Properties of Ixef® 1022 (DAM) as a Function of Temperature

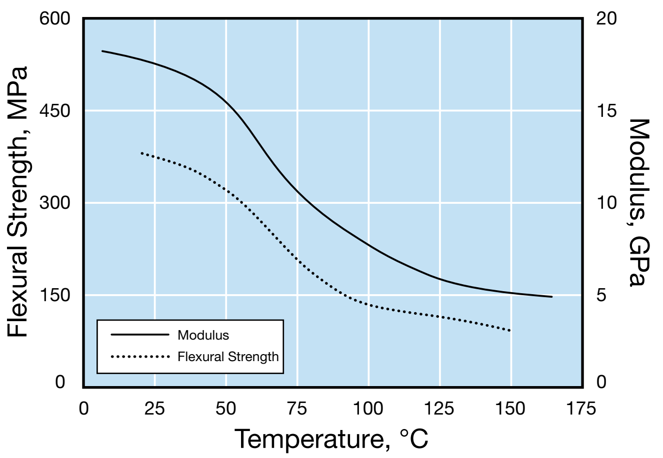


Table 2: Flexural Properties of Ixef® PARA Grades (DAM) (ISO 178)

Grade	σ_R (MPa)	E (GPa)
Ixef® 1002	285	11.5
Ixef® 1022	380	19.0
Ixef® 1032	400	24.0
Ixef® 1521	340	20.0
Ixef® 1524	330	18.5
Ixef® 1622	360	17.0
Ixef® 2011	240	17.0
Ixef® 2030	220	19.0
Ixef® 2060	270	18.0

Impact Properties

The impact tests define the deformation and breaking energies of a material or a structure when they are subject to high-speed stresses.

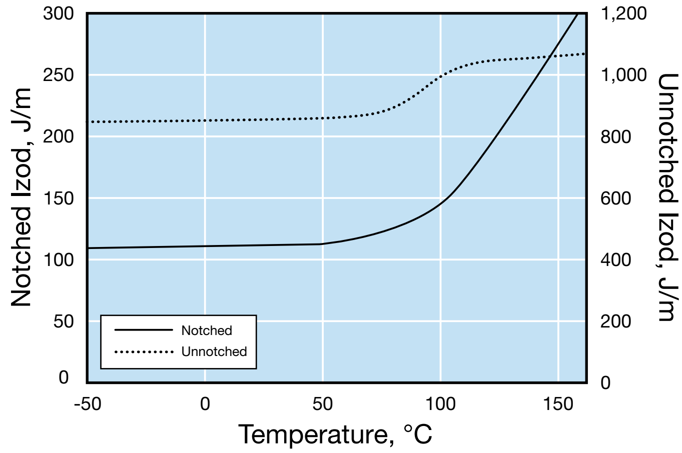
In the case of an Izod impact, the mass undergoes a pendular movement at a defined speed. The specimen (notched or unnotched) is fixed at one end at the base of the pendulum stroke.

The Izod strength, which reflects the impact resistance, is the relationship between the energy absorbed by the specimen and the projected surface area of the rupture plane. The Izod impact resistance (notched or unnotched specimen) at 20°C (68°F) of the Ixef® PARA compounds is presented in Table 3.

Figure 11 shows the influence of temperature on the impact resistance of the Ixef® 1022 compound. We find that this property remains virtually constant below the glass transition point. Above this temperature, the impact resistance increases because of the viscous state of the amorphous regions.

Table 3: Impact Resistance of Ixef® PARA Grades (DAM) (ISO 180)		
Grade	**Notched Specimens (J/m)**	**Unnotched Specimens (J/m)**
Ixef® 1002	70	460
Ixef® 1022	110	850
Ixef® 1032	120	900
Ixef® 1521	95	700
Ixef® 1524	112	–
Ixef® 1622	120	1,100
Ixef® 2011	15	530
Ixef® 2030	50	265

Figure 11: Izod Impact Strength of Ixef® 1022 (DAM) as a Function of Temperature



The Izod test apparatus is easy to construct and quite inexpensive; it allows one to evaluate approximately the deformation and break energies.

Its main drawbacks are:

- The exact trajectory is not known (variation of the speed of impact during the loading period)
- Complex stresses combining simultaneous flexural and shearing actions
- The not-insignificant importance of the geometry of the sample and boundary conditions (support conditions).

The technique of evaluating impact behavior by instrumental tests of the Instrumented Falling Weight type offers the same type of advantages and disadvantages.

Nevertheless, this method can be considered as being closer to normal use conditions of the materials.

During the test, a dart of a given geometry and size falls onto the center of a flat test plate of material fixed in a support.

The energy of the dart is adjusted by the height of the fall and the mass of the dart in order to approximately represent 10 times the rupture energy of the sample.

The maximum force during impact, the deformation at break and the resilience are given for various Ixef® PARA grades in Table 4.

Table 4: Instrumented Falling Weight (Thickness 2 mm) (ASTM D3763)

Grade	Maximum Impact Force (N)		Deformation at Break (mm)		Resilience (J/mm)	
	Dry	After Water Pick-up[(1)]	Dry	After Water Pick-up[(1)]	Dry	After Water Pick-up[(1)]
Ixef® 1002	955	–	3.0	–	0.80	–
Ixef® 1032	1,126	1,200	2.6	3.0	0.76	0.96
Ixef® 1622	1,020	979	4.6	6.2	1.39	1.92
PA 6,6 30% GF	790	–	4.4	–	0.94	–

[(1)] 65% R.H.

Long-Term Mechanical Properties

Tensile Creep

The “creep” phenomenon refers to the evolution of the deformation of a material under a constant load. This evolution is the result of the visco-elastic nature of thermoplastic materials.

Reinforcement with glass fibers reduces this deformation but cannot eliminate it completely.

By their very nature, creep tests generally take a very long time. Nevertheless, it is important to be able to take into account modifications of a material’s mechanical properties over time within reasonable periods. To do this, one generally relies upon modelling based on short-term tests. Such models are created on the basis of tensile tests (stress-deformation) performed at different stress speeds, as well as short-term creep tests (up to 100 hours).

This model makes it possible to evaluate the stress-strain behavior in the range of very low deformation speeds and then to generate long-term creep curves (deformation/time) for various levels of stress.

Figures 12, 13 and 14 give the simulation results for Ixef® 1022 and 1032 at 50°C and 120°C (122°F and 248°F) for several different stress levels.

Figure 12: Tensile Creep of Ixef® 1022 with 2 mm Thickness at 50°C (122°F)

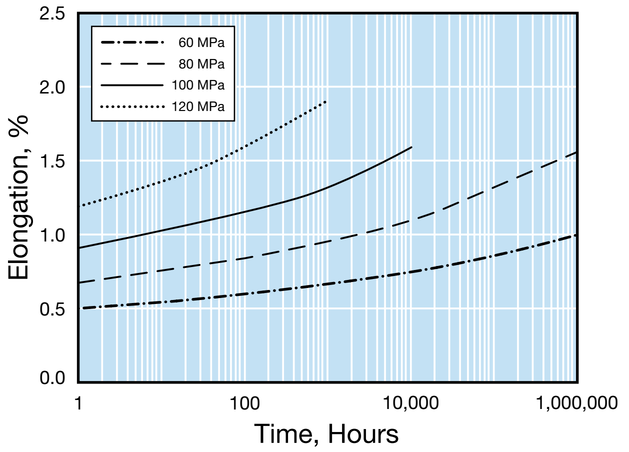


Figure 13: Tensile Creep of Ixef® 1022 with 2 mm Thickness at 120°C (248°F)

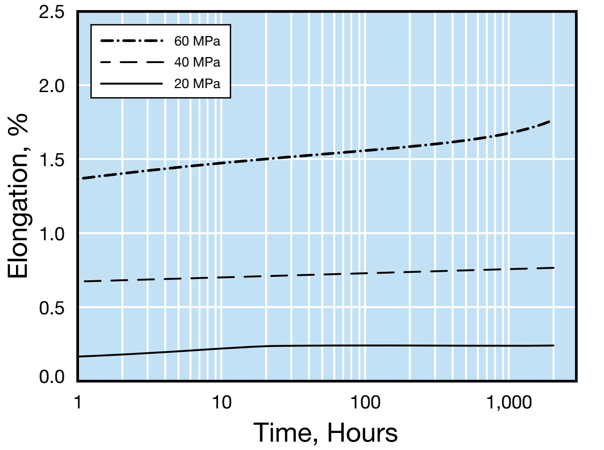


Figure 14: Tensile Creep of Ixef® 1032 with 2 mm Thickness at 50°C (122°F)

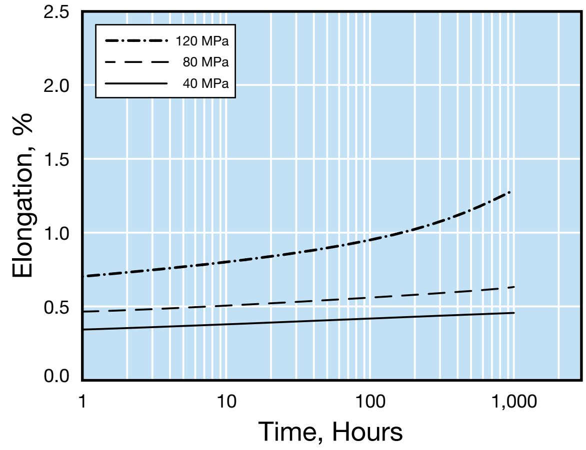
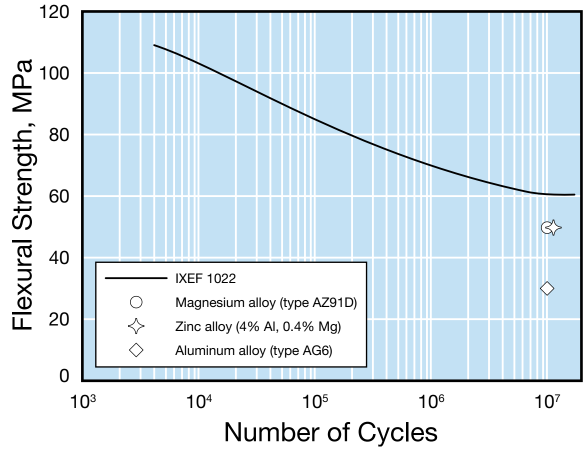


Figure 15: Flexural Strength at 23°C (73°F) for Undulating Loading (Thickness 2 mm)



Fatigue

Just like metals under long-term dynamic stresses, thermoplastic materials (whether reinforced or not) will undergo the phenomenon of fatigue when the amplitude of the stress is sufficient.

Any calculation of a structural part subject to dynamic stresses must take the fatigue limit of the material into account.

The fatigue tests under alternating or undulating stress make it possible to determine the Wöhler curve of the material. The Wöhler curve represents the variation of the maximum stress amplitude as a function of the number of cycles at a given frequency.

Figure 15 presents the Wöhler diagram (undulating flexural fatigue test) for the Ixef® 1022 compound compared to metals (test conditions: frequency 25 Hz, three-point flexural test at 23°C / 73°F).

Physical Properties

Density

The density ρ (g/cm^3) of Ixef® PARA compounds vary by grade, depending primarily on the amount of glass fibers and mineral filler.

The density values of the main Ixef® PARA grades, measured at ambient temperature and atmospheric pressure, are given in Table 5.

The density and thus the specific volume (1/ρ) vary as a function of the temperature. The specific volume of Ixef® 1022 as a function of temperature and pressure is given in Figure 16.

Figure 16: Specific Volume of Ixef® 1022 as a Function of Temperature and Pressure

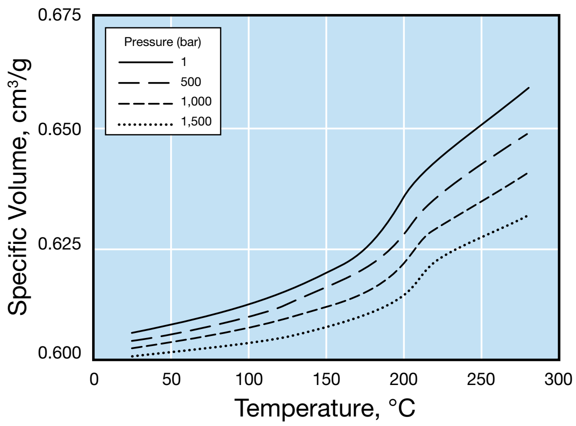


Table 5: Density of Ixef® PARA Compounds (ISO 1183)

Grade	Density (g/cm^3)
Ixef® 1002	1.43
Ixef® 1022	1.64
Ixef® 1032	1.77
Ixef® 1521	1.75
Ixef® 1524	1.68
Ixef® 1622	1.60
Ixef® 2011	1.59
Ixef® 2030	1.74
Ixef® 2060	1.70

Coefficient of Linear Thermal Expansion

Like all non-isotropic composite materials, the thermal expansion coefficient of Ixef® PARA compounds depends on the orientation of the reinforcing fibers.

The coefficients of linear thermal expansion measured at 23°C (73°F) in the longitudinal direction (α_L) and the transversal direction (α_T) of the material flow for the Ixef® 1022 grade are 1.5 x 10^{-5} K^{-1} and 4.6 x 10^{-5} K^{-1}, respectively.

The thermal expansion coefficients in the flow direction α_L of Ixef® PARA compounds are similar to those for steels.

In addition, α_L varies extremely little with the temperature in the range of -30°C to 100°C (-22°F to 212°F). This offers an important advantage when using metal inserts as it prevents the development of exaggerated thermal stresses.

Table 6: Coefficients of Linear Thermal Expansion in the Flow Direction for Ixef® PARA Grades (ISO 11359)

Grade	Coefficient of Thermal Expansion (α_L) (10^{-5} K^{-1})
Ixef® 1002	1.8
Ixef® 1022	1.5
Ixef® 1032	1.4
Ixef® 1521	1.7
Ixef® 1524	–
Ixef® 1622	>1.5
Ixef® 2011	1.8
Ixef® 2030	1.8
Ixef® 2060	>1.7

Figure 17: Coefficients of Linear Thermal Expansion for Ixef® 1022

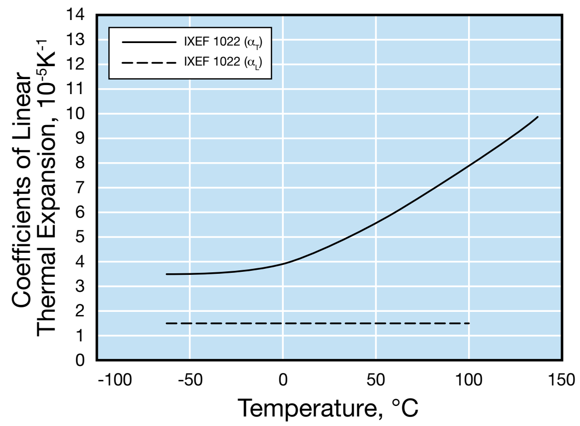


Figure 18: Coefficients of Linear Thermal Expansion for Ixef® 1622

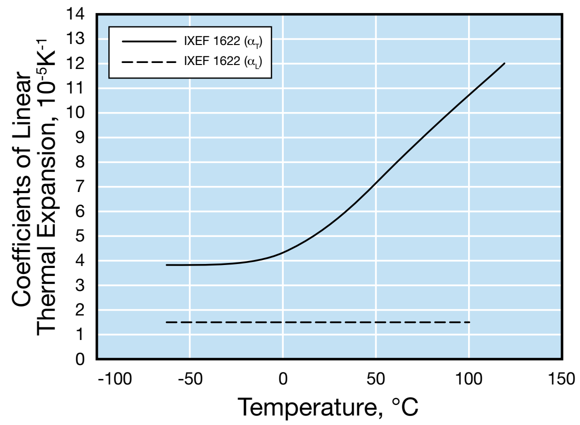
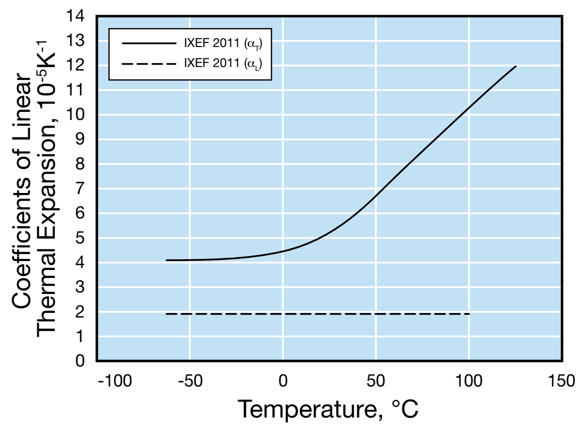


Figure 19: Coefficients of Linear Thermal Expansion for Ixef® 2011



Hardness

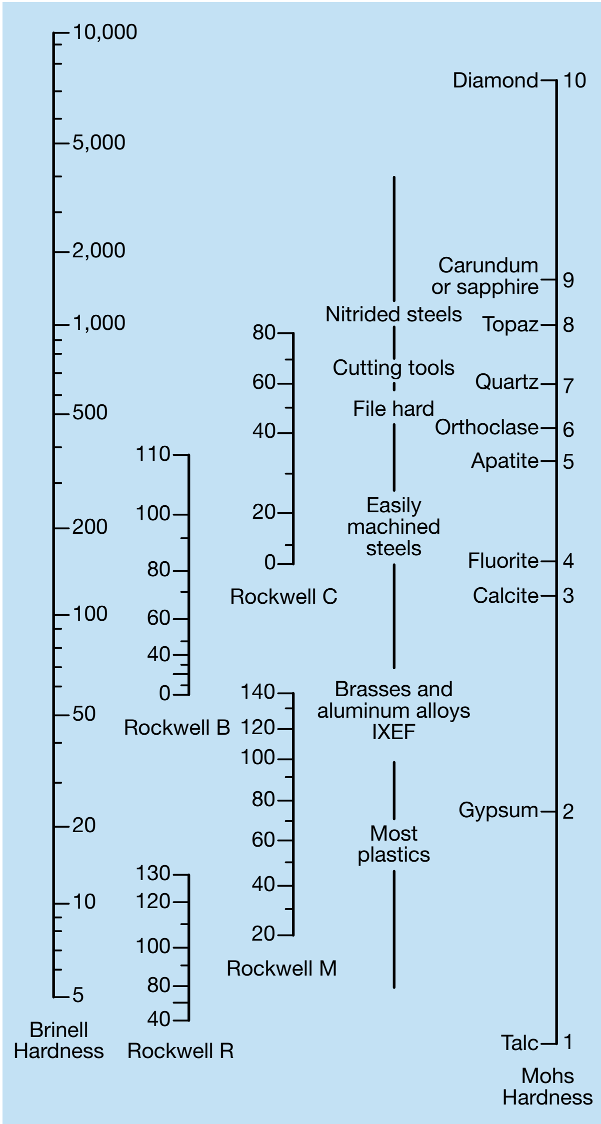
The hardness values for Ixef® 1022 obtained by the most commonly used test methods are given in Table 7.

The relationships between the various hardness scales are given in Table 8.

Table 7: Hardness of Ixef® 1022

Test	Standard	Values
Ball Hardness	ISO 2039/1	HRC 145
Rockwell Hardness	ISO 2039/2	M 110
Shore Hardness	ISO 868	D 90

Table 8: Relations Between Hardness Scales



Friction and Abrasion

Friction Coefficient

A value indicative of the dynamic friction coefficient Ixef® 1022/steel XC 45 was measured by test under the following conditions:

- Speed: 10 m/min
- Pressure: 1.15 MPa
- Initial temperature: 23°C (73°F)

The dynamic friction coefficient is calculated according to the following equation:

$$\mu = \frac{F}{N}$$

with:
μ = Friction coefficient
F = Measured friction load, in Newtons
N = Normal force applied to the block, in Newtons

The dynamic friction coefficients of the Ixef® 1002 and Ixef® 1022 grades are given in Table 9.

Nevertheless, the results can vary depending on the measurement technique used. The data are only intended to allow a comparison among the various Ixef® PARA grades and other materials.

Table 9: Dynamic Friction Coefficients (μ) of Ixef® PARA Compounds and Other Materials

Grade	μ
Ixef® 1002	0.36 to 0.45
Ixef® 1022	0.40 to 0.53
PA 6 30% GF	0.32 to 0.42
POM 25% GF	0.49 to 0.61

Abrasion Resistance

The abrasion resistance values obtained with the TABER abrasion meter for the Ixef® 1022 compound are:

- CALIBRASE CS17 abrasive wheel, load 1 kg, loss: 16 mg/1000 revolutions
- CALIBRASE H22 abrasive wheel, load 1 kg, loss: 53mg/1000 revolutions

Tests done under real conditions will give more accurate information.

Electrical Properties and Fire Behavior

Electrical Properties

Ixef® PARA compounds are increasingly used in the electrical and electronic sectors, notably for control mechanisms inside circuit breakers. This use is justified by the material's good electrical insulating properties, combined with a high dielectric strength in a wide range of temperatures and over very long periods. A description of various electrical tests is offered below. The results of these tests can be found in Tables 10, 11 and 12.

Volume Resistivity

Volume resistivity is evaluated by measuring the electrical resistance of a sample sheet. It represents the relationship between voltage and current, the voltage between electrodes being fixed (IEC 60093/167).

Dielectric Strength

The dielectric strength, expressed in kV/mm, is determined by the electrical voltage at which a specimen subjected to a progressively increasing alternative voltage is perforated. This yields information about the behavior of the material when exposed to brief stresses of high electrical voltage and thus describes its insulating ability (IEC 60243).

Dielectric Constant and Dielectric Loss Angle

Two major characteristics are used to define the behavior of a dielectric material in an alternating electrical field:

- The dielectric constant σ, or permittivity (IEC 60250), is a measure of the capacity of the material to accumulate electrical charges when placed inside the field
- The dielectric loss angle ($\tan \delta$) (IEC 60250) is the result of a shift of the electrical polarization in relation to the electrical field, which induces a loss of energy transformed into heat

Comparative Tracking Index

The comparative tracking index (CTI - IEC 60112) characterizes the resistance to the creation of a conductive path of an insulating material to an electrical stress in a humid environment.

The CTI index is the maximum voltage in volts at which one can drop, between two electrodes applied to the surface of the material, 50 drops of an electrolyte (NH_4ClO, 1% – 1 drop every 30 seconds) without forming a conducting track.

Table 10: Electrical Properties of Ixef® PARA Grades Reinforced with Glass Fibers

Properties	Standards	Units	Ixef® 1002	Ixef® 1022	Ixef® 1032	Ixef® 1622
Volume Resistivity	IEC 600 93/167	Ω.cm	2×10^{15}	2×10^{15}	2×10^{15}	2×10^{15}
Dielectric Strength	IEC 60 243	kV/mm	30	31	24	1
Dielectric Constant (110 Hz)	IEC 60 250		3.9	4.6	4.5	4.4
Dielectric Loss Angle (110 Hz)	IEC 60 250		0.010	0.017	0.009	0.007
Comparative Tracking Index	IEC 60 112	V	400	570	600	570

Table 11: Electrical Properties of Fire-Resistant Ixef® PARA Grades

Properties	Standards	Units	Ixef® 1521	Ixef® 1524
Volume Resistivity	IEC 600 93/167	Ω.cm	2×10^{15}	2×10^{15}
Dielectric Strength	IEC 60 243	kV/mm	26	–
Dielectric Constant (110 Hz)	IEC 60 250		4.1	–
Dielectric Loss Angle (110 Hz)	IEC 60 250		0.012	–
Comparative Tracking Index	IEC 60 112	V	400	600

Table 12: Electrical Properties of Mineral Reinforced Ixef® PARA Grades

Properties	Standards	Units	Ixef® 2011	Ixef® 2030
Volume Resistivity	IEC 600 93/167	Ω.cm	2×10^{15}	2×10^{15}
Dielectric Strength	IEC 60 243	kV/mm	24	35
Dielectric Constant (110 Hz)	IEC 60 250		4.3	4.8
Dielectric Loss Angle (110 Hz)	IEC 60 250		0.009	0.025
Comparative Tracking Index	IEC 60 112	V	520	600

Underwriters Laboratories and IEC 60 216

The Underwriters Laboratories (UL) organization has tested the following properties on the major Ixef® PARA compounds:

Relative Thermal Index (RTI)

The relative thermal index (RTI) reflects the retention of certain properties (mechanical without impact, mechanical with impact, electrical) of a material after thermal aging. It represents the temperature at which the compound will still retain 50% of its initial property value compared to a reference material. This temperature is extrapolated on the basis of tests of shorter duration.

The thermal index “65°C (149°F)” is given by default to a polyamide-type material not tested by the Underwriters Laboratories.

UL 94

There are 4 different UL classifications described in this manual for characterizing the self-extinguishing properties of a material based on the UL 94 test standards. The UL 94 HB category is applied to materials that burn in a horizontal position. The UL 94 V-2, V-1 and V-0 classifications describe the degree of self-extinguishing ability in a vertical position, by increasing order of severity.

Hot Wire Ignition Test (HWI)

This test, characterizing the flammability of the material, indicates the time in seconds necessary to ignite a specimen around which is coiled a wire dissipating a defined power. This test yields information on the resistance of a material at abnormally high temperatures caused, for example, by an electrical defect. It can be compared with the Glow Wire Test (see page 18).

Table 13: Thermal Stability of Ixef® 1521 Following the Standard IEC 60 216

Exposure Time	Temperature Evaluated	Index T° with IEC 216
5,000 Hours	146	TI 5 kh/146
20,000 Hours	126	TI 20 kh/126

High Current Arc Ignition (HAI)

This measure indicates the number of electrical arcs which could be applied at a given rate to the surface of the material before it ignites. To reflect the practical conditions, the arcs used are low voltage but high current.

High Voltage-Arc Tracking Rate (HVTR)

This test, important for components used in circuits over 15 W, yields information on the speed, in mm/minute at which a tracking current develops on the surface of the material under given conditions.

High-Voltage/Low Intensity Arc Resistance

The time in seconds required for a leakage path to form across the surface of the material when it is subjected to an intermittent high-voltage, low current arc (ASTM D495).

Comparative Tracking Index (CTI)

See page 14.

Thermal Stability Following IEC 60 216

This test, completed on thermally isolated materials, is used to determine the length of time, at a given temperature, for which the flexural strength at rupture of a material is reduced to half of its initial value (half-life).

Using the appropriate statistical methods, these values can give information on the long-term behavior of the material at other temperatures. The UL values of various Ixef® PARA compounds are included in Table 14.

A certified external laboratory has completed these tests on the Ixef® 1521 flame-retardant grade, on 4-mm thick samples. The results are included in Table 13.

Table 14: UL Classification of the Main Ixef® PARA Compounds (2012)

Material	Color	Min. Thick, mm	UL 94 Flame Class	HWI	HAI	RTI, °C Electric	RTI, °C Mechanical Impact	RTI, °C Mechanical Strength	HVTR	D495	CTI
Ixef® 1022	All	1.5	HB	0	0	130	105	105	–	–	–
		3.0	HB	0	0	130	105	120	0	5	1
Ixef® 1027	All	1.5	HB	1	1	140	115	115	–	–	–
		3.0	HB	0	1	140	125	125	0	6	1
Ixef® 1521	All	1.5	V-0	0	0	130	105	105	–	–	–
		3.0	V-0	0	0	130	105	120	3	6	1
Ixef® 1524	All	0.40	V-0	1	2	65	65	65	0	5	0
		0.75	V-0	0	2	65	65	65	–	–	–
		1.5	V-0	0	1	65	65	65	–	–	–
		3.0	V-0	0	1	65	65	65	–	–	–

Note: The 5 short-term electrical properties and their associated values are also available on the Internet: http://www.ul.com/database, Customer: Solvay

Fire Classification

This section summarizes the "fire" characteristics of the flame-retardant Ixef® PARA grades (Ixef® 1521 and 1524).

Limiting Oxygen Index

The limiting oxygen index (LOI) is a measure of the flammability of a specimen placed in an enclosed area flooded by a mixture of gaseous oxygen/nitrogen in controlled proportions. Combustion is ignited by a pilot flame in contact with the upper end of the specimen. The greater the concentration of O_2 in the gaseous mixture that is required in order to keep the specimen burning, the better the material's flame retardancy.

Table 15 gives the LOI values for several Ixef® PARA grades.

Glow Wire Test

The glow wire test is performed to simulate the thermal stresses produced by heat sources such as overloaded resistance in an electrical circuit. An electrically heated wire (whose temperature is known) is placed in contact with a vertical plate of the material during a 30-second period.

- IEC 60995-2-12 GWFT or GWFI: Glow-wire flammability temperature (GWFT or GWFI) is the highest temperature at which the flaming or glowing of the test specimen extinguishes within 30 seconds.
- IEC 60995-2-13 GWIT: Glow-wire ignitability temperature (GWIT) is 25°C (77°F) hotter than the maximum temperature that does not cause ignition. Ignition is defined as a flame that persists for longer than 5 seconds.

Table 15: Limiting Oxygen Index

Grade	Limiting Oxygen Index (%)
Ixef® 1022	25
Ixef® 1032	25
Ixef® 1521	31.5
Ixef® 1524	37
Ixef® 1622	25

SNCF-RATP Standards

The Société Nationale des Chemins de Fer (SNCF - the French national rail company) classifies the materials used in its passenger wagons by their reaction to fire (classification M and I) and by the characteristics of the fumes released (classification F).

According to measurements performed by Belgium's Institut Scientifique de Service Public, Ixef® 1521 is classified M3 (according to the FD P 92 507 standard). Ixef® 1521 is classified I3 (according to the NF F 16-101 standard), and F3 (according to the GTM 000 standard). Ixef® 1524 is classified I3 (according to the NF F 16-101 standard), and F2 (according to the GTM 000 standard).

Aeronautics

The compounds Ixef® 1521 and 1524 have been tested by independent laboratories and have attained the classification conforming to the following standards.

- Ixef® 1521 conforms to std. FAR 25.853 (b) mod 2532
- Ixef® 1521 and 1524 are conformed to std. FAR 25.853 (d) std. ABD 0031

Table 16: Resistance to Glow Wire

Properties	Test Method	Units	Thickness, mm	Ixef® 1521	Ixef® 1524
Glow-Wire Flammability (GWFI)	IEC 60695-2-12	°C	0.4		960
			0.75		960
			0.8	960	
			1.5	960	960
			3.0	960	960
Glow-Wire Ignition (GWIT)	IEC 60695-2-13	°C	0.4		775
			0.75		800
			0.8	900	
			1.5	930	825
			3.0	900	850

Chemical Resistance

Water Resistance

The resin used in all Ixef® PARA compounds, contains amide functions. As with all polyamides (nylons), water acts as a plasticizer forming reversible complexes with the amide functions.

The speed (kinetics) with which Ixef® PARA compounds absorb water (C(t) - concentration of absorbed water as a function of time) depends on several parameters:

- D: diffusion coefficient (which depends on the temperature). See Table 17.
- C_S: water concentration at equilibrium under the conditions being considered, i.e. the relative humidity (RH). The value of C_S as a function of the RH rate is given in Figure 20.
- S, V: surface area and volume of the specimen

The kinetics of water absorption can be described mathematically by Fick's Law:

$$\frac{C(t)}{C_s} = 2 \cdot \frac{S}{V} \cdot \sqrt{\frac{D.t}{\pi}}$$

The chart in Figure 21 graphically represents this relationship.

Table 17: Diffusion Coefficient of Water in Various Engineering Compounds

	Diffusion Coefficient (10^{-6} cm^2/h)		
Temperature (°C)	**Ixef® 1022(1)**	**PA 6,6 GF**	**PA 6 GF**
20	1	7.2	14.4
40	5.2	–	–
60	28	–	–
90	210	–	–
100	370	–	–

(1) Note: the coefficient of Ixef® increases very slightly with the level of reinforcement.

Figure 20: Water Content of Ixef® 1022, 1032 and 1622 at Equilibrium as a Function of Relative Humidity

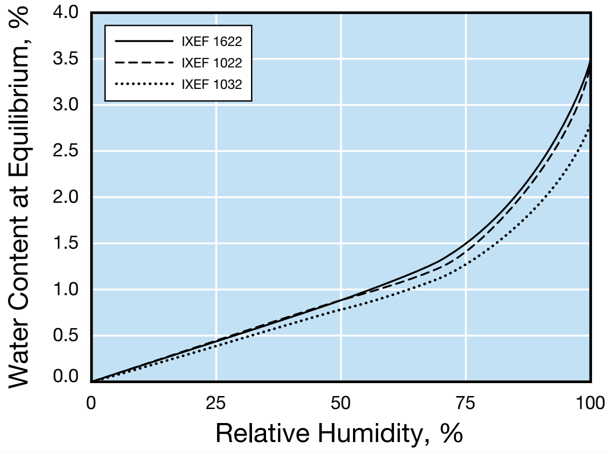
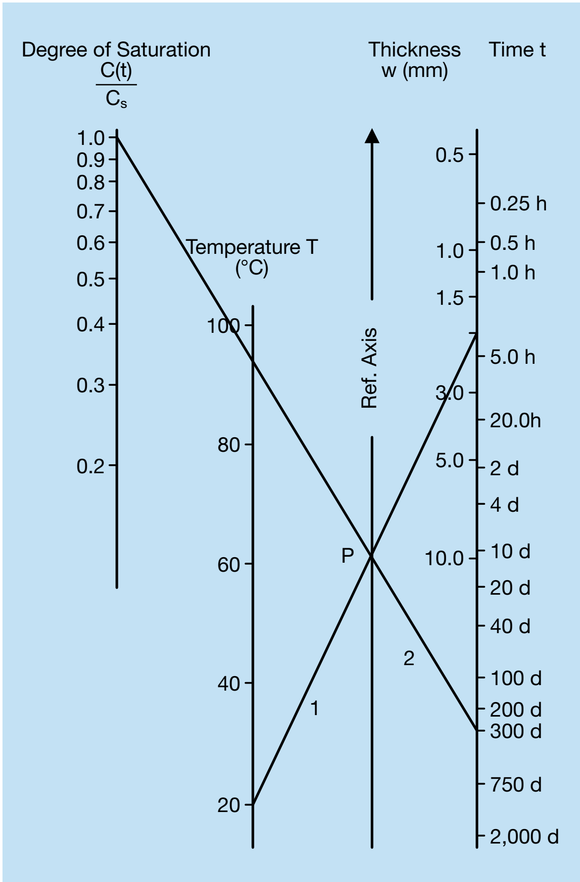


Figure 21: Ixef® 1022 - FICK's Chart for Determining the State of Parts in Contact with Water or Water Vapor



There are several important consequences of this water absorption which must be taken into account:

- A reduction of mechanical properties due to plasticizing (Figures 22, 23 and 24).
- A dimensional change due to the swelling caused by water absorption (Figure 25). This can be aggravated by the presence of glycol- or methanol-type additives.
- A decrease in the glass transition temperature (Table 18). This can lower the creep resistance of the Ixef® PARA compounds and can also cause a post-crystallization of the resin injected into a mold whose temperature was below 120°C (248°F). This will cause deformation of the part.

It is thus very important to carefully test, under the actual use conditions, every Ixef® PARA part which will be in continuous contact with water, in order to verify the absence of problems.

Table 18: Glass Transition Temperature for Ixef® 1022

	Glass Transition Temperature (T_g) (°C)		
Product	**Beginning**	**Middle**	**End**
Ixef® 1022 Dry	50	85	110
Ixef® 1022 Saturated With Water	7	25	80

Figure 22: Izod Impact Strength of Ixef® 1022 and 1622 as a Function of Water Content

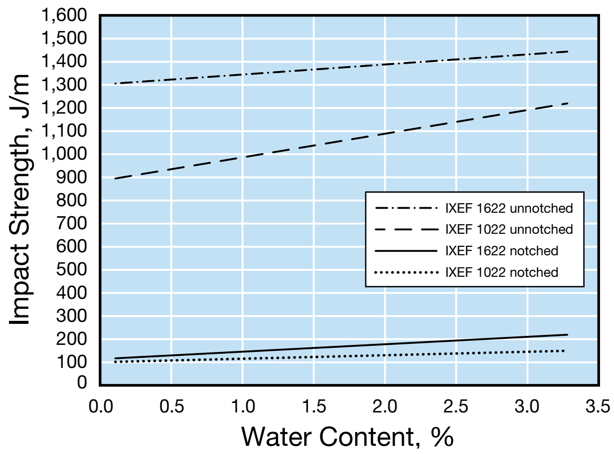


Figure 23: Tensile Strength at Equilibrium of Ixef® 1022, 1032 and 1622 as a Function of Relative Humidity

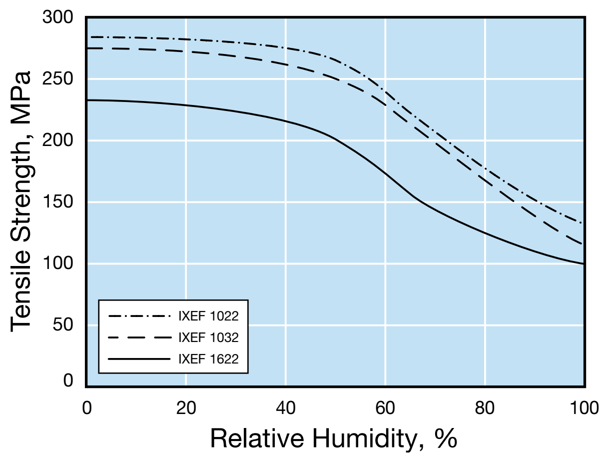


Figure 24: Tensile Modulus at Equilibrium of Ixef® 1022, 1032 and 1622 as a Function of Relative Humidity

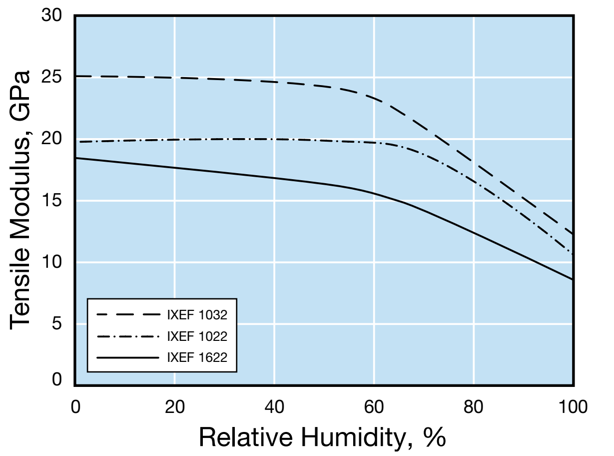


Figure 26: Chemical Resistance of Ixef® 1022 to a Gasoline-Ethanol Mixture at 40°C (104°F): Flexural Strength

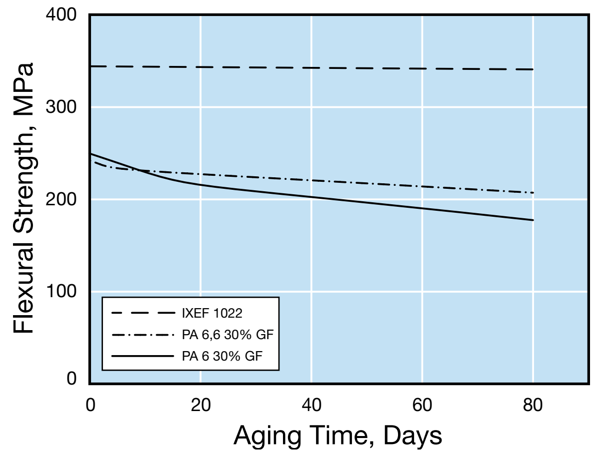
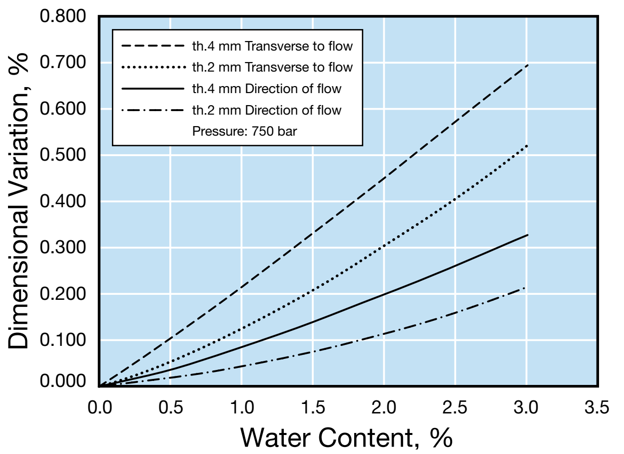


Figure 25: Dimensional Variation of a 40x40x2 mm Specimen and a 40x40x4 mm Specimen of Ixef® 1032 as a Function of Water Content



Resistance to Automotive Fluids

In general, Ixef® PARA compounds display good resistance to the various fluids encountered in the automotive industry. Thanks in part to this good resistance, Ixef® PARA compounds have found many uses in the automotive market:

- Rocker box covers (Ixef® 1022)
- Fuel pump bodies (Ixef® 1022)
- Door handles (Ixef® 1022 and 1025)
- Headlamp components (Ixef® 2011)
- External rear-view mirror support (Ixef® 2030)
- Clutch cylinders (1027)

Resistance to Gasoline

The variations in the flexural properties and in the weight of specimens made of Ixef® 1022 polyarylamide, polyamide PA 6,6 30% GF and PA 6 30% GF submerged in a mixture of gasoline and ethanol at 40°C (104°F) are given in figures 26, 27 and 28. The proportions of the mixture are 80% gasoline, 20% ethanol by weight.

Figure 27: Chemical Resistance of Ixef® 1022 to a Gasoline-Ethanol Mixture at 40°C (104°F): Flexural Modulus

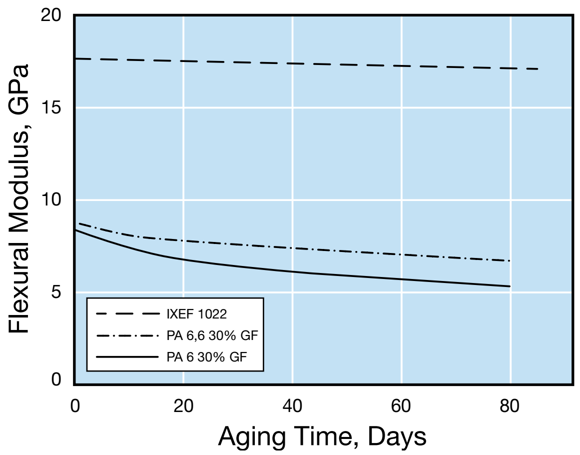


Figure 28: Chemical Resistance of Ixef® 1022 to a Gasoline-Ethanol Mixture at 40°C (104°F): Weight Increase

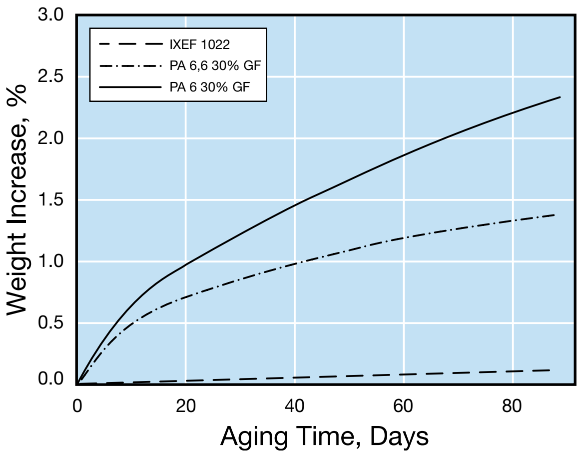


Figure 29: Chemical Resistance of Ixef® 1002 to a Motor Oil at 120°C (248°F): Tensile Properties

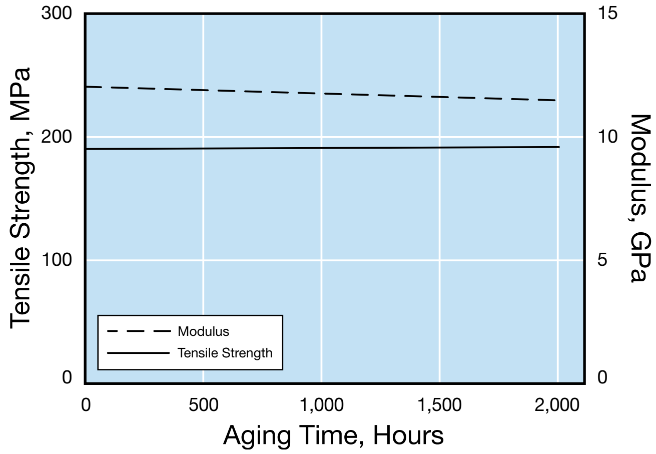
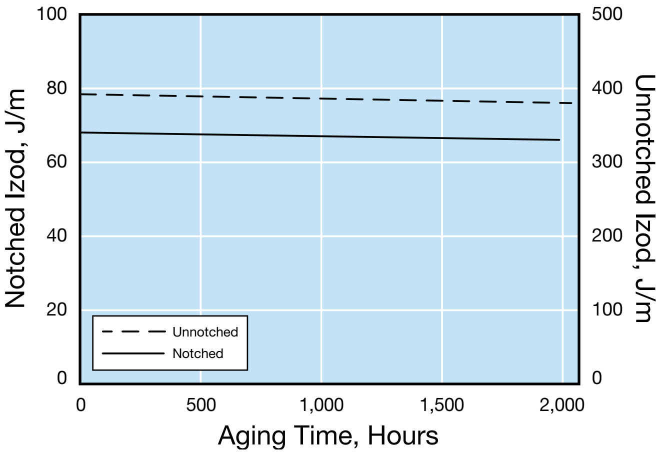


Figure 30: Chemical Resistance of Ixef® 1002 to a Motor Oil at 120°C (248°F): Izod Impact Strength



Resistance to Motor Oils

The variations in mechanical properties and in the weight of specimens made of Ixef® 1002 submerged in motor oil at 120°C (248°F) are shown in Figures 29 and 30.

Oil characteristics: SAE 10W30.

Various Reagents

Table 18 compares the behavior of Ixef® 1002 with that of several other thermoplastics after contact with various liquids.

In general, Ixef® PARA compounds display good resistance to chemical reagents. However the amide function in the resin matrix makes them sensitive to certain chemicals.

It is very rapidly degraded by:

- Powerful oxidants (O_3, Cl_2, ...)
- Highly concentrated mineral acids (H_2SO_4, HNO_3, ...)

It is degraded at ambient temperature by:

- Diluted mineral acids
- Acetic acid and formic acid

It is degraded at high temperature by:

- Strong bases (KOH, NaOH, ...)
- Most organic acids
- Formaldehyde

By contrast, according to laboratory tests performed at 60°C (140°F) (or at boiling temperature if below 60°C (140°F)), Ixef® PARA is not affected by aliphatic hydrocarbons (white spirit, kerosene), aromatic hydrocarbons (benzene, toluene), ketones, esters, ethers, weak bases, aldehydes (except for formaldehyde) or alcohols (except for the light alcohols which plasticize polyamides like water does).

Comment:

The indications of resistance to chemical reagents and to solvents included in this section are helpful for recommending (or advising against) use of the glass fiber-reinforced Ixef® PARA compounds. When using a part made of Ixef® PARA in the presence of chemical agents, it is always necessary to verify the stability of the part in contact with these agents under the anticipated use conditions (including stress).

Table 19: Chemical Resistance of Various Thermoplastics After Aging for 30 Days at 23°C (73°F) in Different Chemicals

Reagents/Polymers	Ixef® 1002	PA 6 GF	PA 11 GF	PBTP GF	PC GF	OPP GF
NH_4Cl, Saturated Solution	–	–	0	+	0	0
Na_2CO_3, Saturated Solution	+	–	0	+	0	0
$CaCl_2$, Saturated Solution	0	0	+	+	0	0
Methanol	–	–	–	+	–	–
Propanol	+	–	–	+	+	0
Benzyl Alcohol	+	0	0	+	–	0
Toluene	+	+	0	+		
Formaldehyde	0	–	–	+	+	0
Methylene Chloride	+	–	–	–		
Perchloroethylene	+	+	–	+	–	
Acetone	+	+	–	0	–	–
Methyl Ethylene	+	+	–	0		0
Benzene	+	+	–	+		
Trichloroethylene	+	0	–	–		
Methyl Acetate	+	0	–	+	–	
Tetrahydrofuran	+	+	–	0		
Olive Oil (at 40°C/104°F)	+					
Brake Fluid	+	+	+	+	–	0
Gasoline + CH_3CH_2OH (80/20)	+	–	–	+		
Gasoline + CH_3CH_2OH (90/10)	+	–	–	+		
Super Gasoline	+	0	+	+	0	–

Selection Criterion:
+: variation of weight below 1%, and variation of breaking strength less than 10%.
0: only one of the two criteria met.
–: neither of the 2 criteria met.

Thermal Aging

Aging at high temperatures in an inert atmosphere (e.g. in motor oil) does not significantly alter the properties of Ixef® PARA compounds (at least for periods lasting several months). By contrast, aging at high temperature in air results in a surface oxidation and a loss of properties over time.

During this aging, there appears in succession:

- A surface oxidation several microns deep, leading to yellowing and micro-cracking
- Core oxidation, the rate of which is limited by the diffusion of oxygen, leading to a reduction of flexural strength and elongation
- Ultimately, destruction of the oxidized specimen throughout its thickness.
- The thickness of the wall plays a fundamental role in the loss of mechanical properties, since it determines the concentration of the oxygen at the core of the part.

The thermal aging of Ixef® 1022 is expressed in Figure 31 by the time required for the tensile strength and tensile impact values to fall to 50% of their initial values (DAM), plotted as a function of the test temperature.

The laboratory results obtained by aging different Ixef® PARA grades at high temperature in a ventilated oven are summarized in Figure 32.

Figure 31: Half-Life of Tensile Specimens (3.2 mm) Made of Ixef® 1022 in Accordance with the UL 746B Method

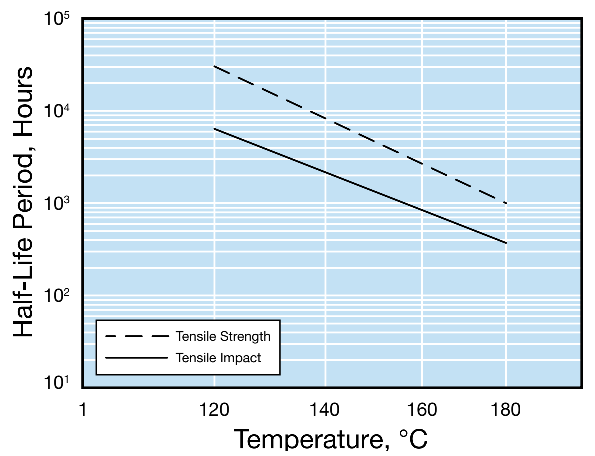
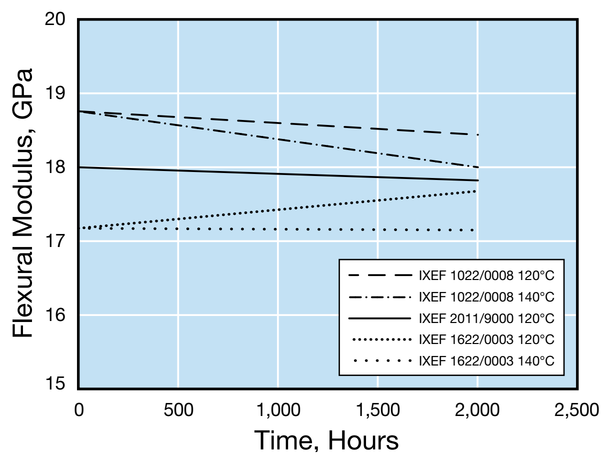


Figure 32: Thermal Aging in a Ventilated Oven at 120°C and 140°C (248°F and 284°F): Flexural Modulus Evolution



Natural Aging

Specimens were exposed at the Hiratsuka Test Station over a 4 year period (average temperature 23°C (73°C), average precipitation 130 mm/month, solar radiation of 500 kJ/year/cm^2).

The results obtained on 3.2-mm thick specimens show:

- A reduction of flexural strength of around 30%, corresponding essentially to reversible plasticizing by water (Figure 33)
- Unchanged modulus
- An increase of roughness due to surface photo-oxidation

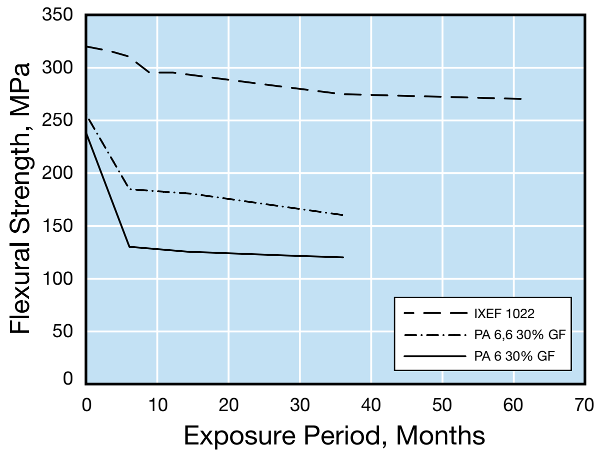
The surface of a part made of Ixef® PARA is composed of a layer of pure polymer around one µm thick. This layer makes it possible to obtain a very high gloss finish. If photo-oxidation occurs, an alteration of this layer can cause increased surface roughness (eg. from surface rugosity of Ra = 0.15 µm to Ra = 0.2 µm). Oxidation, affecting a minute quantity of matter, thus leads to a change in surface appearance (gloss and color) without significantly affecting the mechanical properties of the material.

In choosing the surface appearance of parts subject to U.V. radiation, it is therefore useful to avoid excessively low roughnesses which will be sharply affected by even very superficial photo-oxidation.

Certain Ixef® PARA grades have been developed to increase their resistance to the photo-oxidation phenomenon.

The variation of surface rugosity in these grades under UV is notably improved.

Figure 33: Natural Aging: Flexural Strength



Accelerated Aging

In order to evaluate the effects of aging within reasonable delay, the tests for accelerated aging were carried out on Ixef® PARA samples using the test method DIN 53387/1.

The change in properties of the products after 2,000 hours of exposure are shown in Table 20.

Table 20: Accelerated Aging - Flexural Properties of Ixef® PARA Grades after 2,000 Hours of Exposure (DIN 53387/1)

Grades	Residual Modulus (% Initial Value)	Residual Strength (% Initial Value)	Residual Elongation at Break (% Initial Value)
Ixef® 1022	97	90	94
Ixef® 1622	96	93	95

Food and Water Contact Approvals

Ixef® PARA resin is well-suited for applications involving contact with cold water. 50% glass-filled Ixef® 1022 is approved for food contact meeting European standard 10/2011/EC for both black (Ixef® 1022/9006) and natural (Ixef® 1022/0006). Ixef® 1022 also meets the following European water approval standards:

Table 21: European Water Approval Standards

Standard	Grade
French positive list (FPL)	Ixef® 1022/0006 (natural)
	Ixef® 1022/0008 (natural)
KTW (cold water only)	Ixef® 1022/0006 (natural)
	Ixef® 1022/9006 (black)
ACS	Ixef® 1022/9006 (black)

Other Certifications

Microbial Cultures

The German BAM organization (Bundesanstalt für Materialforschung und-prüfung) tested Ixef® 1521 according to the MIL-STD- 810 method (American Military Standard) using the following fungi: chaetomium globosum, penicillium funiculosum and aspergillus flavous, niger and versicolor. No signs of microbial growth were observed.

Automotive Certifications

Ixef® PARA compounds are used in various automotive applications by several car manufacturers (PSA, GM, VW, Fiat, Renault, Daimler Chrysler, Ford, BMW, ...). Some of these manufacturers have approved several Ixef® PARA compounds and given them a code which is listed in their plastic materials approval handbooks.

The following list gives the codes of these Ixef® PARA grades:

OPEL: Ixef® 1022/9007 QK 000686
Ixef® 1002 QK 000689

FIAT: Ixef® 1022/0003 PA-A 220.100
Ixef® 2010/X914 PA-A 130.35
Ixef® 2030/X003 PA-A 220.50

BMW: Ixef® 1002 PAA-GF 30
Ixef® 1022 PAA-GF 50
Ixef® 1032 PAA-GF 60
} BMW N 601 00.0

ISO 9002

The resin used in Ixef® PARA compounds is polymerized in a ISO 9002 certified facility. (Certificate 92038C, 4th May 2001, delivered by AIB-VINÇOTTE (B)).

Part Design

Estimation of Stresses

The design of thermoplastic parts must take several factors into account:

- The mechanical stress on the part.
- The environment (thermal, chemical, etc.) which the part must withstand.
- The electrical and flame retardancy requirements of the part.
- The form of the part. The form can influence the dimensional stability, the molding cycle time and the level of stress in the part.
- Shrinkage of parts after molding. This is very important in designing the mold.
- Assembly techniques.
- Decoration techniques.

External loads produce stresses in a part. These stresses may cause the part to break or result in too high a deformation, depending on the form and the material chosen.

The stresses (σ) and the deformations (ε) can be estimated from the mechanical equations based on Hooke's Law and the modulus of the material (E):

$$\sigma = E.\varepsilon$$

It is impossible here to describe all possible modes of deformation, so we have chosen to concentrate on tensile and flexural loadings. For other types of stress, or for complicated parts, Solvay's technical service department can help you.

Tensile Stress

Tensile stresses can be estimated using the following equation:

$$\sigma_T = \frac{F_T}{A}$$

where:

σ_T = tensile stress (MPa)
F_T = tensile force (N)
A = cross-sectional area (mm^2)

Flexural Stress in Beam

The flexural stress in a beam can be estimated with the following equation:

$$\sigma_f = \frac{M_f \cdot C}{I}$$

where:

σ_f = flexural stress (MPa)
M_f = flexural moment (N.mm)
C = distance from the neutral axis to the outer fiber (mm)
I = moment of inertia (mm^4)

These factors depend on the form of the beam (C and I), the position of the load (M_f) and the mode of attachment (M_f).

Figure 34 gives the moments of inertia (I) and the distance from the neutral axis to the outer fiber (C) for beams of different sections.

Figure 35 gives the flexural stress (σ_{max}) and the maximum deflection (Y_{max}) for different types of attachment and loading.

Of course, there are other types of loading and attachment. The interested reader should refer to books on the strength of materials (e.g. Formulas for Stress and Strain, Roark and Young, McGraw-Hill Publishers).

Figure 34: Moments of Inertia Around the Axis of Symmetry of Different Geometric Forms

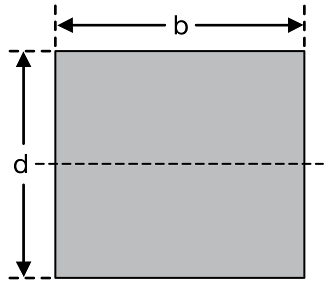
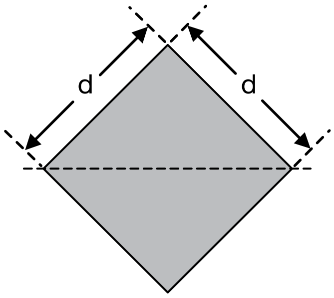
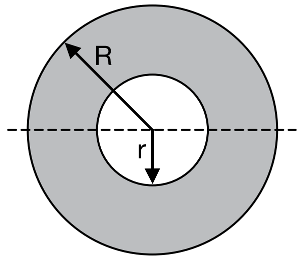
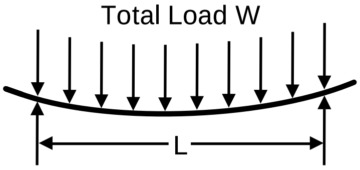
Rectangular Form	Diamond Form	Circular Form *(for a solid cylinder r=0)*
		
$I = \frac{bd^3}{12}$ $\quad C = \frac{d}{2}$	$I = \frac{d^4}{12}$ $\quad C = 0.707d$	$I = \frac{\pi(R^4 - r^4)}{12}$ $\quad C = \frac{R}{2}$

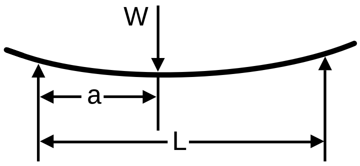
Figure 35: Maximum Stress (X_{max}) and Deflection (Y_{max}) as a Function of the Type of Load

Total Load W



$$\sigma_{max} = \frac{WLC}{8I}$$

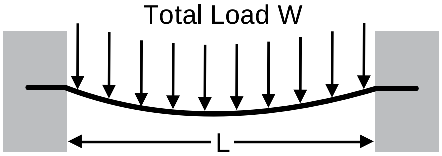
$$Y_{max} = \frac{-5WL^3}{384EI}$$



$$\sigma_{max} = \frac{Wa(L-a)C}{LI}$$

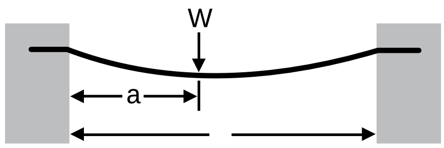
$$Y_{max} = \frac{-Wa}{3EIL}\left(\frac{L^2-a^2}{3}\right)^{3/2}$$

Total Load W



$$\sigma_{max} = \frac{-WLC}{12I}$$

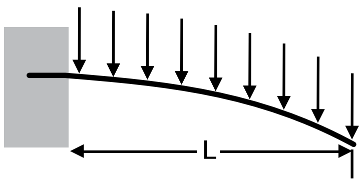
$$Y_{max} = \frac{-WL^3}{384EI}$$



$$\sigma_{max} = \frac{-Wa(L-a)^2C}{L^2I}$$

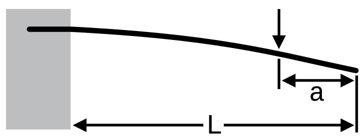
$$Y_{max} = \frac{-2Wa^3}{3EI}\left(\frac{L-a}{L+2a}\right)^2$$

Total Load W



$$\sigma_{max} = \frac{-WLC}{2I}$$

$$Y_{max} = \frac{-WL^3}{3EI}$$



$$\sigma_{max} = \frac{-Wa(L-a)C}{I}$$

$$Y_{max} = \frac{-W}{6EI}(2L^3-3L^2a + a^3)$$

Design of the Part

The design or form of the parts must not only satisfy the functional constraints but also the technological constraints imposed by the injection molding process described below:

- Wall thickness as uniform as possible
- Design of draft angles allowing ejection from the mold
- No sharp angles
- Design of bosses, holes and ribs

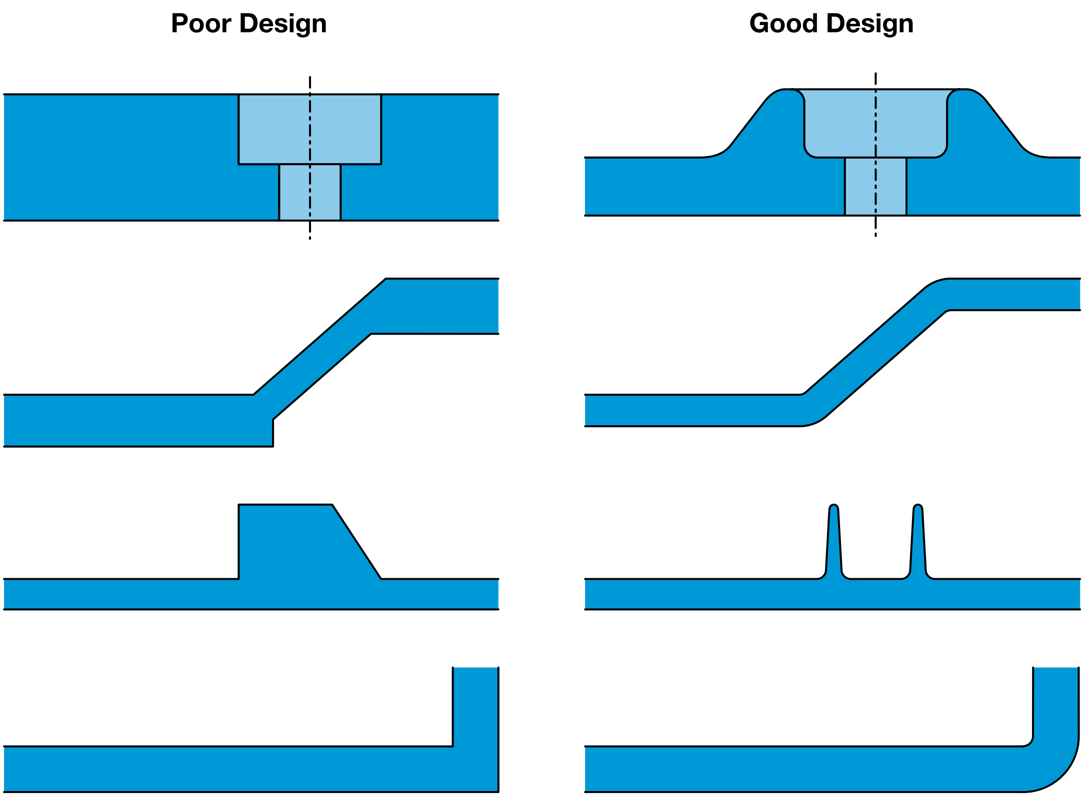
These basic rules, which are not specific to Ixef® PARA compounds (which often tolerate more liberty than most thermoplastics), are discussed in more detail in the following sections.

Wall Thickness

In general, Ixef® PARA compounds permit wall thicknesses between 0.5 mm and 12 mm (0.02 inch and 0.472 inch). Large thickness variations can cause distortion, hesitation and dimensional problems (Figure 36).

Moreover, if w (in mm) is the part wall thickness, the injection molding holding time is of the order of 3 w (in seconds) and the cooling time is of the order of 2.5 w^2 (in seconds, $w \geq 2$ mm). It is thus of interest to reduce the wall thickness by making use of reinforcing ribs.

Figure 36: Examples of How to Achieve a Uniform Wall Thickness



Draft Angles

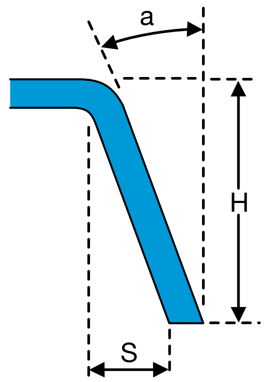
Since Ixef® PARA compounds undergo relatively little shrinkage, a draft angle of 1 to 2 degrees (1.7% to 3.4%) is generally necessary to facilitate ejection of the part from the mold.

Several different cases are described below (Figure 37).

Figure 37: Draft Angles

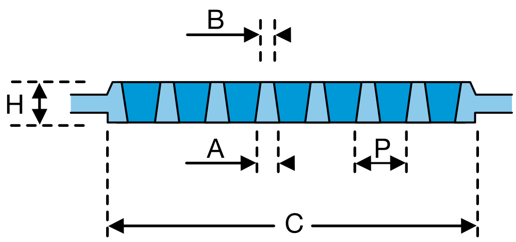
Smooth flat wall:
for H<100mm, a = 3%-3.5%
for H>100mm, a = 1.7%

Textured flat wall:
S/H = 1/5-1/10, a = 10%-18%



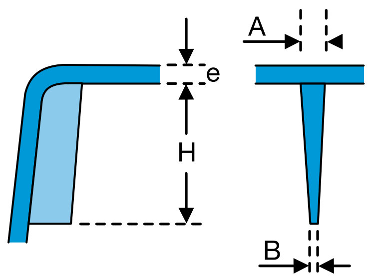
Grill:
(A-B)/(2.H) = 11%-9%

If the pitch (P) of the grill is less than 4mm, use a draft angle of 1/10.
The draft angle can be increased as the dimension (C) of the grill increases.



Vertical ribs:
(reinforced sides)
(A-B)/(2.H) = 0.3%-0.5%

Horizontal ribs:
(reinforced bottom)
(A-B)/(2.H) = 0.7%-1%



Internal Corner Radii

Internal corners with sharp angles or very short radii and notches are one of the main causes of failure under load of parts made in plastic, and notably Ixef® PARA compounds.

It is necessary to calculate the stress concentration created by an internal corner in order to verify that the strength of the material is adequate in this region. The mathematical formula used to estimate the stress concentration factor for different geometries can be obtained from strength of materials handbooks. As an example, Figures 38 and 39 present the stress concentration as a function of the ratio of internal corner radius.

A good rule of thumb consists of choosing an internal corner radius equal to or greater than one-half of the thickness of the part, and at least equal to 0.6 mm (0.024 inch).

Ribs, Bosses and Holes

Ribs

Ribs increase the rigidity (higher moment of inertia) and strength of parts with little increase in weight. By avoiding too large and widely distributed thicknesses, one can thus reduce the weight and the cycle time. The recommended rib dimensions are given in Figure 40.

Because of their low shrinkage, Ixef® PARA compounds minimize the sink marks caused by thick ribs. If sink marks are unacceptable on the opposite wall, they can be masked by a grained texture at the site of the sink mark.

Bosses

Bosses are used to permit the assembly of parts or to reinforce holes. As a general rule, the external diameter of the boss must be double the diameter of the hole to be reinforced, and the wall thickness of the boss may not exceed that of the part. Figure 41 offers several design possibilities.

Holes

The molding of holes does not pose any problems, but it does create a weld line which constitutes a mechanical weak point.

When designing holes, the following basic rules should be observed:

- The distance between the axes of two holes must be at least greater than the sum of their diameters.
- A blind hole whose axis is perpendicular to the flow direction must have a depth less than twice its diameter: beyond this ratio there is a risk of bending the stem during injection.

Figure 38: Internal Corner Radii

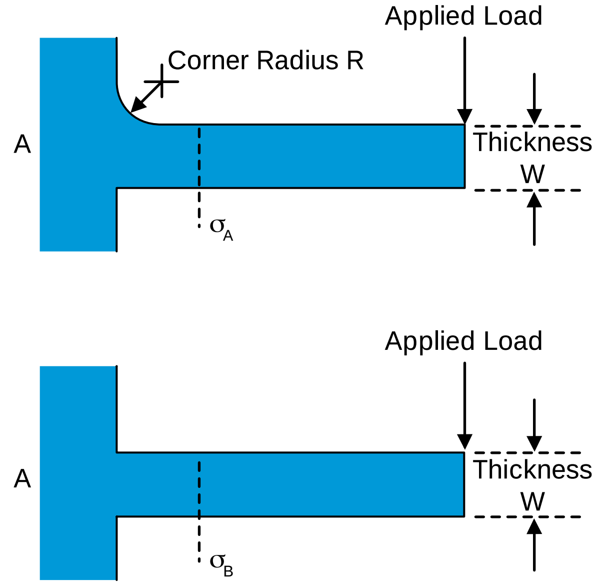
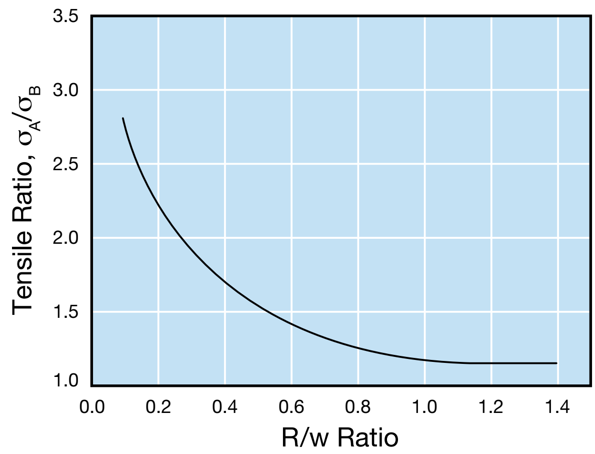
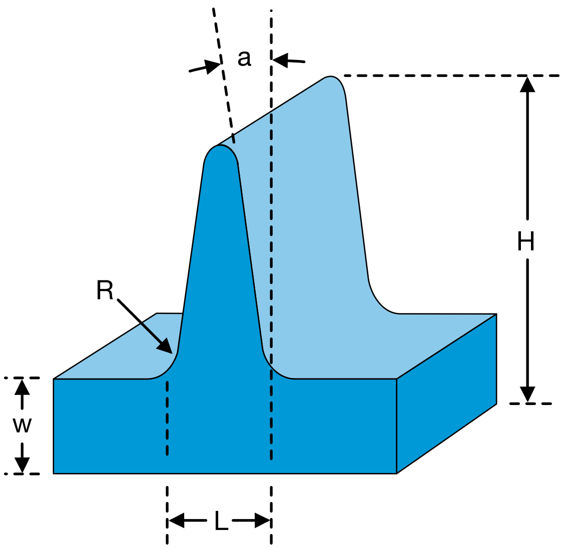


Figure 39: Stress Concentration Due to an Internal Corner



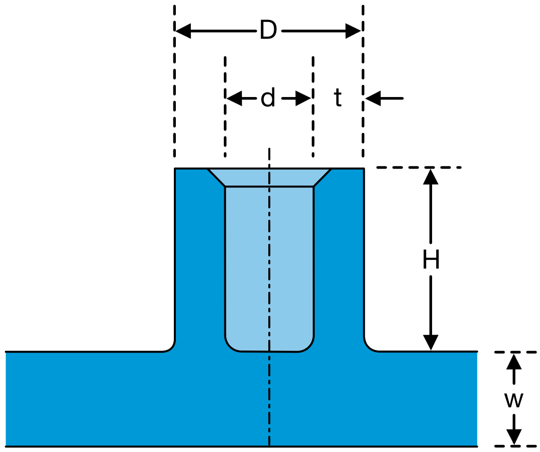
- In the case of aligned holes, one can tolerate a decentrage if the diameter of one of the holes is slightly greater than that of the other.
- An overflow tab can be used in certain cases to improve the mechanical strength of the weld line.

Figure 40: Rib Design



R = w/4
H = 4w
L = 0.4w in order to minimize sink marks
L = 0.6w in order to maximize strength
L = w in case of expanded molding

Figure 41: Boss Design



D = 2d
t = 0.6w
H = 2d to 3d
Edge bevelled at 45°
Radii = 0.8 to 1.5 mm

Table 22: Shrinkage of Ixef® PARA Compounds

Compound	Thinckness (mm)	Holding Pressure (bar)	Shrinkage in Flow Direction (%)	Shrinkage Transverse to Flow (%)
Ixef® 1022	10	750	0.1	0.3
Ixef® 1622	40	750	0.2	0.5
Ixef® 1032	10	750	0.1	0.3
	20	750	0.1	0.3
	40	750	0.2	0.3
Ixef® 1521	10	750	0.1	0.3
	20	750	0.1	0.3
	40	750	0.2	0.5
Ixef® 2011	20	750	0.1	0.4
	40	750	0.3	0.6
Ixef® 2030	10	750	0.1	0.4
	20	750	0.2	0.4
	40	750	0.3	0.5

Shrinkage and Tolerances

Shrinkage

Ixef® PARA compounds are characterized by a low level of shrinkage during molding. Ixef® 1022 for example has an average shrinkage of only 0.3%. Although the dimensions of a mold must always be adjusted depending on the results obtained from the first molding trials, one can use the nominal values contained in Table 22.

The actual skrinkage obtained depends, in addition to the Ixef® PARA grade used, on the geometry of the part (notably its thickness), the position of the gates as well as the packing during cooling. The nominal values in Table 22 were measured on injection-molded parallelepiped-shaped specimens with 20 x 40 surfaces and a thickness of 1, 2 or 4 mm (0.039, 0.079 or 0.158 inch).

At a temperature above the glass transition point, a very slow post-molding crystallization can cause the part to develop sink marks over time. Water pickup, very slow at low temperature, can result in expansion. In practice, one may assume that these two phenomena cancel each other out.

Dimensional Tolerances

The dimensional tolerances or the precision of the parts made with glass fiber-reinforced thermoplastics (the class to which Ixef® PARA belongs) depend on several factors. A partial list includes:

- The form of the part. The presence of different thicknesses or weld lines for example can increase the achievable circularity or flatness tolerances.
- Design of the mold. Wear, too much play between the fixed and the moving parts of the mold, or an improper temperature regulation can cause significant dimensional variations.
- Processing conditions. A variation of the processing conditions over time (temperature of the material or the mold, holding phase, injection rate, etc.) can lead to a dimensional variation.
- Variations among the different batches. To reduce such variation, Ixef® PARA compounds are manufactured and checked in accordance with the ISO 9002 standards.
- Working conditions. Water pickup and post-shrinkage phenomena can also influence the tolerances that can be attained.

Due to these factors, it is difficult to precisely predict the dimensional tolerances for a thermoplastic part. However, it should be noted that Ixef® PARA is used in many applications requiring low tolerances.

For example, on the basis of typical shrinkage variations, it is possible to estimate the tolerances achievable on lengths (e.g. distance between two axes). When the general molding recommendations are observed, we can consider linear tolerances:

$$\Delta l = \pm 0.05\%$$

For typical tolerances for flatness, circularity, etc., please contact Solvay's technical service department.

It is also recommended, when machining mold cavities, to **leave some metal on** in the dimensionally critical zones so as to be able to make the necessary adjustments after the first injection trials.

Comparison with Competitive Materials

Engineering Thermoplastics

Compared to other thermoplastics, Ixef® PARA compounds offer several interesting advantages:

- A very high tensile modulus (up to 24 GPa for some grades, e.g. Ixef® 1032)
- A very good surface finish, even for filler contents of 60% (Ixef® 1032). Due to their excellent surface appearance, the Ixef® 2011 grades (mineral fillers only) are used in the manufacture of headlamps
- Excellent creep resistance
- Easy processing. The spiral length of Ixef® 1022 (50% glass fibers) is close to that of a PA 6,6 filled with 30% glass fibers
- A very low water pickup which does not necessarily require granule drying prior to injection molding.

Table 23 compares the physical and mechanical properties of Ixef® PARA compounds with those of other glass fiber-reinforced compounds (data purely indicative).

Light Alloys

For many applications the mechanical properties of Ixef® PARA compounds are sufficient to replace light alloys (aluminium, magnesium, ZAMAK). Among glass fiber-reinforced thermoplastics, the modulus of the Ixef® PARA grades is probably closest to that of the light alloys.

Compared to light alloys, Ixef® PARA compounds offer several advantages:

- The molding of Ixef® PARA parts does not require subsequent machining.
- The surface finish of Ixef® PARA parts is often better than that of light alloys.
- The maximum stress that an Ixef® 1022 test specimen can withstand in an undulating flexural fatigue test is higher than that of light alloys.

Table 24 compares the mechanical and physical properties of Ixef® 1022 and several grades of light alloys.

Table 23: Comparison of the Mechanical Properties of Various Glass Fiber-Reinforced Thermoplastics

Properties	Units	Ixef® 1022		Ixef® 1032		PA 6,6 50% GF		PA 6 50% GF		PBT 30% GF
Density	g/cm^3	1.64		1.77		1.55		1.55		1.68
Water Absorption (24h @ 20°C/68°F)	%	0.16		0.13		1.2		1.5		25
Water pickup at saturation (23°C/68°F)	%	3.3		2.80		4.0		4.8		0.45
Tensile		**Dry**	**After Water Pick-up[(1)]**	**Dry**	**After Water Pick-up[(1)]**	**Dry**	**After Water Pick-up[(1)]**	**Dry**	**After Water Pick-up[(1)]**	
Maximum Strength	MPa	280	260	280	250	230	180	235	160	135
Modulus	GPa	20	20	24	23	17	13	16	11	11
Elongation	%	1.9	2.2	1.8	2.0	2.5	3.5	3	5.5	2.2
Flexural										
Maximum Strength	MPa	400	–	400	305	–	–	330	260	190
Modulus	GPa	19	–	23.5	18.5	–	–	13	10	11
HDT/A	°C	230		230		250		215		210

(1) 65% R.H.

Table 24: Comparison of Ixef® PARA Compounds and Light Alloys (Data Purely Indicative)

				Cast of Metal Alloys			
				of Al		of Zn	of Mg
Properties	**Units**	**Ixef® 1022**	**Ixef® 1032**	**AG6**	**AS9U3**	**ZAMAK[(1)]**	**AZ91D**
Density	g/cm^3	1.64	1.77	2.7	2.9	6.6	1.83
Melting Temperature	°C	235	235	660	660	390	470
Thermal Conductivity	W/m K	0.4	0.4	110	95	110	51.2
Heat Capacity	J/g K	1.7	1.6	1	1	0.4	–
Maximum Tensile Strength	MPa	280	280	220	200	280	235
E-modulus	GPa	20	23.5	65	72	85	45
Elongation at Yield	%	1.7	1.8	0.2	0.2	0.2	3.0
Cyclical Flexural Strength at 10^7 Cycles	MPa	70	400	~35	~35	~50	~50

(1) At 4% Al, 0.04% Mg

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