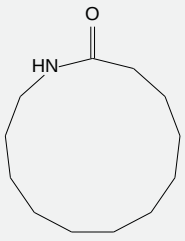
PA-12 polyamide-12

PARAMETER	UNIT	VALUE	REFERENCES
GENERAL			
Common name	-	polyamide-12, nylon-12, poly(imino-1-oxodecamethylene), polydodecanolactam	
IUPAC name	-	poly[imino(1-oxododecane-1,12-diyl)]	
CAS name	-	poly[imino(1-oxo-1,12-dodecanediyl)]	
Acronym	-	PA-12	
CAS number	-	24937-16-4	
HISTORY			
Person to discover	-	Schaaf, S; Griehl, W	Schaaf, S; Griehl, W, US Patent 3,564,599, Inventa AG, Feb. 16, 1971.
Date	-	1971	
SYNTHESIS			
Monomer(s) structure	-	 lauryl lactam	
Monomer(s) CAS number(s)	-	947-04-6	
Monomer(s) molecular weight(s)	dalton, g/mol, amu	197.32	
Monomer(s) expected purity(ies)	%	99.9 min	
Monomer ratio	-	100%	
CH_2/CONH ratio		11	
Method of synthesis	-	hydrolytic polycondensation of dodecanolactam at 300-330ºC in the presence of phosphoric acid	
Catalyst	-	phosphoric acid	
Number average molecular weight, M_n	dalton, g/mol, amu	23,400-44,100	Robert, E C; Bruessau, R; Dubois, J; Jacques, B; Meijerink, N; Nguye, T Q; Niehaus, D E; Tobisch, W A, Pure Appl. Chem., 76, 11, 2009-25, 2004.
Mass average molecular weight, M_w	dalton, g/mol, amu	42,400-144,300	Robert, E C; Bruessau, R; Dubois, J; Jacques, B; Meijerink, N; Nguye, T Q; Niehaus, D E; Tobisch, W A, Pure Appl. Chem., 76, 11, 2009-25, 2004.
Polydispersity, M_w/M_n	-	1.54-3.5	Robert, E C; Bruessau, R; Dubois, J; Jacques, B; Meijerink, N; Nguye, T Q; Niehaus, D E; Tobisch, W A, Pure Appl. Chem., 76, 11, 2009-25, 2004.
Molar volume at 298K	cm^3 mol^{-1}	171 (crystalline); 199.3 (amorphous)	
Van der Waals volume	cm^3 mol^{-1}	115.3 (crystalline); 125.1 (amorphous)	

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PARAMETER	UNIT	VALUE	REFERENCES
STRUCTURE			
Crystallinity	%	30-52; 18.3-29.1 (non-isothermal crystallization); 45 (dry); 28 (wet)	McFerran, N L A; Armstrong, C G; McNally, T, J. Appl. Polym. Sci., 110, 1043-58, 2008; Urman, K; Otaigbe, J, Antec, 2063-66, 2004.
Crystalline structure	-		Gogolewski, S; Czerniawska, K; Gasiorek. M, Coll. Polym. Sci,. 258, 1130, 1980.
Cell type (lattice)	-	pseudohexagonal; monoclinic hexagonal; triclinic	Gogolewski, S; Czerniawska, K; Gasiorek. M, Coll. Polym. Sci,. 258, 1130, 1980; McFerran, N L A; Armstrong, C G; McNally, T, J. Appl. Polym. Sci., 110, 1043-58, 2008.
Cell dimensions	nm	a:b:c=0.479:3.19:0.958; a:b:c=0.958:3.19:0.479; a:b:c=0.91:0.53:3.18	Gogolewski, S; Czerniawska, K; Gasiorek. M, Coll. Polym. Sci,. 258, 1130, 1980; McFerran, N L A; Armstrong, C G; McNally, T, J. Appl. Polym. Sci., 110, 1043-58, 2008; Dosiere, M, Polymer, 34, 15, 3160-67, 1993.
Unit cell angles	degree	β=120; α=γ=90, β=120	Gogolewski, S; Czerniawska, K; Gasiorek. M, Coll. Polym. Sci,. 258, 1130, 1980.
Number of chains per unit cell	-	4	Gogolewski, S; Czerniawska, K; Gasiorek. M, Coll. Polym. Sci,. 258, 1130, 1980.
Crystallite size	nm	10.3-12.6	Rajesh, J J; Bijwe, J, Wear, 661-68, 2005.
Spacing between crystallites	nm	0.42-0.479	
Polymorphs	-	α; γ (the most stable, monoclinic)	
Avrami constants, k/n	-	n=2.05-2.55; n=2.3-2.9 (non-isothermal crystallization)	McFerran, N L A; Armstrong, C G; McNally, T, J. Appl. Polym. Sci., 110, 1043-58, 2008.
Activation energy for crystallization	kJ mol^{-1}	345.5	
COMMERCIAL POLYMERS			
Some manufacturers	-	EMS, Arkema, Evonik	
Trade names	-	Grilamid, Rilsan, Vestosint	
PHYSICAL PROPERTIES			
Density at 20°C	g cm^{-3}	1.01-1.03; 1.11 (crystalline)	
Refractive index, 20°C	-	1.52-1.53	
Melting temperature, DSC	°C	174-185	
Activation energy of thermal degradation	kJ mol^{-1}	2208	Herrera, M; Matuschek, G; Kettrup, A, Chemosphere, 42, 601-7, 2001.
Fusion heat	J g^{-1}	58	Jun g, H S; Choi, M C; Chang, Y-W; Kang, P-H; Hong, S C, Eur. Polym. J., 66, 367-75, 2015.
Thermal expansion coefficient, 23-80°C	10^{-4} $°C^{-1}$	1.1-1.61; 0.2-1 (15-65% glass fiber, dry)	Bai, J; Goodridge, R D; Hague, R J M; Song, M; Okamoto, M, Polym. Testing, 36, 95-100, 2014.
Thermal conductivity, 10-100°C	W m^{-1} K^{-1}	0.24	
Glass transition temperature	°C	55 (dry); 45 (equilibrated at 50% RH)	
Specific heat capacity	J K^{-1} kg^{-1}	2,000-2,900	
Heat of fusion	kJ kg^{-1}	65-70	

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PARAMETER	UNIT	VALUE	REFERENCES
Maximum service temperature	°C	140-150; 150-160 (15-65% glass fiber, dry); 180 (blend with EPDM)	Jun g, H S; Choi, M C; Chang, Y-W; Kang, P-H; Hong, S C, Eur. Polym. J., 66, 367-75, 2015.
Long term service temperature	°C	85-110; 90-120 (15-65% glass fiber, dry)	
Heat deflection temperature at 0.45 MPa	°C	110-130	
Heat deflection temperature at 1.8 MPa	°C	45-50; 150-160 (15-65% glass fiber, dry)	
Vicat temperature VST/A/50	°C	170	
Vicat temperature VST/B/50	°C	140	
Hansen solubility parameters, δ_D, δ_P, δ_H	$MPa^{0.5}$	18.5, 8.1, 9.1	
Interaction radius		6.3	
Hildebrand solubility parameter	$MPa^{0.5}$	calc.=19.0; exp.=22.2	
Surface tension	$mN\ m^{-1}$	calc.=35.8	
Dielectric constant at 100 Hz/1 MHz	-	-/3.00 (at 50% RH)	
Relative permittivity at 100 Hz	-	3.8	
Relative permittivity at 1 MHz	-	3.8 (dry), 6.7 (wet)	
Dissipation factor at 1 MHz	E-4	500 (dry); 170 (wet)	
Volume resistivity	ohm-m	1E11 to 1E12 (conditioned)	
Surface resistivity	ohm	1E13 (at 50% RH)	
Electric strength K20/P50, d=0.60.8 mm	$kV\ mm^{-1}$	27-34 (dry); 32 (conditioned); 35-45 (15-65% glass fiber, dry)	
Comparative tracking index, CTI, test liquid A	-	600 (conditioned); 600 (15-65% glass fiber, dry)	
Contact angle of water, 20°C	degree	72.4; 77/56.2 (asc/rec)	
Surface free energy	$mJ\ m^{-2}$	39.3	
MECHANICAL & RHEOLOGICAL PROPERTIES			
Tensile strength	MPa	50-70 (dry); 45-50 (conditioned); 80-190 (15-65% glass fiber, dry); 70-170 (15-65% glass fiber, conditioned)	
Tensile modulus	MPa	1,400-1,600 (dry); 1,100 (conditioned); 3,500-20,000 (15-65% glass fiber, dry); 3,000-18,500 (15-65% glass fiber, conditioned)	
Tensile stress at yield	MPa	41-46	
Tensile creep modulus, 1000 h, elongation 0.5 max	MPa	45 (dry); 40-45 (conditioned)	
Elongation	%	>50 (dry); >50 (conditioned); 3-8 (15-65% glass fiber, dry); 3-10 (15-65% glass fiber, conditioned)	
Tensile yield strain	%	5-6 (dry); 12-15 (conditioned)	
Flexural modulus	MPa	360-1,260	
Young's modulus	MPa	460-1,900	
Charpy impact strength, unnotched, 23°C	$kJ\ m^{-2}$	NB (dry); NB (conditioned); 65-100 (15-65% glass fiber, dry); 60-90 (15-65% glass fiber, conditioned)	
Charpy impact strength, unnotched, -30°C	$kJ\ m^{-2}$	NB (dry); NB (conditioned); 65-100 (15-65% glass fiber, dry); 60-90 (15-65% glass fiber, conditioned)	
Charpy impact strength, notched, 23°C	$kJ\ m^{-2}$	6-25 (dry); 6 (conditioned); 12-15 (15-65% glass fiber, dry); 12-15 (15-65% glass fiber, conditioned)	
Charpy impact strength, notched, -30°C	$kJ\ m^{-2}$	4-8 (dry); 5-7 (conditioned); 10 (15-65% glass fiber, dry); 10 (15-65% glass fiber, conditioned)	

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PARAMETER	UNIT	VALUE	REFERENCES
Izod impact strength, unnotched, 23°C	J m^{-1}	160	
Crack growth velocity	x 10^{-6} m s^{-1}	913-962	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Fracture energy	x 10^{4} J m^{-2}	3.9-4.43	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Ductility factor	mm	14.21-14.76	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Stress necessary to cause spontaneous fracture	MPa	96.98-98.24	Rajesh, J J; Bijwe, J, Tribology lett., 18, 3, 331-40, 2005.
Abrasion resistance (ASTM D1044)	mg/100 cycles	14	
Shore D hardness	-	61-79	
Ball indention hardness at 358 N/30 S (ISO 2039-1)	MPa	75 (dry); 70 (conditioned)	
Shrinkage	%	0.5-1.1; 0.1-0.7 (15-65% glass fiber, dry)	
Melt volume flow rate (ISO 1133, procedure B), 275°C/5 kg	cm^3/10 min	20-36	
Melt index, 235°C/2.16 kg	g/10 min	52.5	Jun g, H S; Choi, M C; Chang, Y-W; Kang, P-H; Hong, S C, Eur. Polym. J., 66, 367-75, 2015.
Water absorption, equilibrium in water at 23°C	%	1.3-1.5; 0.8-1.1 (15-65% glass fiber, dry)	
Moisture absorption, equilibrium 23°C/50% RH	%	0.4-0.8; 0.4-0.8 (15-65% glass fiber, dry)	
CHEMICAL RESISTANCE			
Acid dilute/concentrated	-	good/poor	
Alcohols	-	poor	
Alkalis	-	good/poor	
Aliphatic hydrocarbons	-	good	
Aromatic hydrocarbons	-	good	
Esters	-	good-fair	
Greases & oils	-	good	
Halogenated hydrocarbons	-	fair-poor	
Ketones	-	good	
Good solvent	-	cresol, formic acid/dichloromethane	
FLAMMABILITY			
Limiting oxygen index	% O_2	21-22.5	
Volatile products of combustion	-	CO_2, CO, ethylene, propylene	Levchik, S V; Costa, L; Camino, G, Polym. Deg. Stab., 36, 31-41, 1992.
UL 94 rating	-	HB; HB (15-65% glass fiber, dry)	
TOXICITY			
NFPA: Health, Flammability, Reactivity rating	-	1/1/0	
Carcinogenic effect	-	not listed by ACGIH, NIOSH, NTP	

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PARAMETER	UNIT	VALUE	REFERENCES
PROCESSING			
Typical processing methods	-	electrospinning, extrusion, injection molding, spinning	
Preprocess drying: temperature/ time/residual moisture	°C/h/%	80/3-5/0.1	
Processing temperature	°C	240-270	
Processing pressure	MPa	0-1 (back)	
Additives used in final products	-	MWCNT, exfoliated graphite, graphene	Karevan, M; Eshraghi, S; Gerhard, R; Das, S; Kalaitzidou, K, Carbon, 64, 122-31, 2013.
Applications	-	automotive (compressed air systems, hydraulic systems, electrical, lighting, cooling and climate control, fuel systems, powertrain chassis), connectors, electrical equipment, film, industry & consumer goods (housewares, hydraulics & pneumatics, mechanical engineering, medical devices, sanitary, water and gas supply, sports & leisure, tools & accessories)	
Outstanding properties	-	low environmental stress cracking, low moisture absorption	
BLENDS			
Suitable polymers	-	EPDM, EPR, HDPE, PA6, PBT, PET, PP, SBM, SEBS	
ANALYSIS			
FTIR (wavenumber-assignment)	cm^{-1}/-	see ref.	Yoshioka, Y; Tashiro, K; Ramesh, C, J. Polym. Sci. B, 41, 1294-1307, 2003.
Raman (wavenumber-assignment)	cm^{-1}/-	amide – 1636; C-C – 1063/1107	Hendra, P J; Maddams, W F; Royaud, I A M; Willis, H A; Zichy, V, Spectrochim. Acta, 64A, 5, 747-56, 1990.
NMR (chemical shifts)	ppm	see ref.	Davis, R D; Jarrett, W L; Mathias, L J, Polymer, 42, 2621-26, 2001.