NYLON PLASTICS

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SERIES PREFACE

The Society of Plastics Engineers is dedicated to the promotion of scientific and engineering knowledge of plastics and to the initiation and continuation of educational activities for the plastics industry.

An example of this dedication is the sponsorship of this and other technical books about plastics. These books are commissioned, directed, and reviewed by the Society's Technical Volumes Committee. Members of this committee are selected for their outstanding technical competence; among them are prominent authors, educators, and scientists in the plastics field.

In addition, the Society publishes *Plastics Engineering, Polymer Engineering and Science (PE&S),* proceedings of its Annual, National and Regional Technical Conferences *(ANTEC, NATEC, RETEC)* and other selected publications. Additional information can be obtained by writing to the Society of Plastics Engineers, Inc., 656 West Putnam Avenue, Greenwich, Connecticut 06830.

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PREFACE

The word "nylon" immediately brings to mind the world's first synthetic fiber, and many books exist that deal with nylon and related fiber technology. Nylon also was, however, the first engineering thermoplastic, that is, a material that can be readily processed as a melt via injection molding or extrusion to yield products having the strength, toughness, rigidity, and durability demanded of mechanical parts. Plastics applications for nylons have become extensive and are the result of a broadening technology marked by the appearance of new compositions, new synthetic procedures, and new fabricating methods. A need has existed for a text concerned with nylons from the plastics point of view. This book is directed toward that need.

The book follows a roughly chronological sequence from monomer synthesis to polymerization, characterization, processing, properties, and applications. Emphasis is placed on subjects of special concern to the plastics industry, such as thermal degradation and melt flow, but these topics as well as the discussions of polymer characterization, physical structure, transition phenomena, and others will also be helpful to many people outside the plastics industry.

In covering an industry from raw material to ultimate use, we have called upon the talents of many people of diverse technical skills and owe them many thanks. This book would not have been possible without the support of the Plastics Department, E. I. du Pont de Nemours and Co., Inc., and in particular many members of the Commercial Resins Division. Virtually all the manufacturers of nylon polymers for the plastics industry in the United States have generously provided information on their products and so permitted discussion of a very broad spectrum of nylons. To them all we extend our sincere thanks.

MELVIN I. KOHAN

Wilmington, Delaware
June 18, 1973

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CONVERSION OF UNITS

Units are given as far as practicable in both the English and metric systems. Conversion factors are provided where appropriate. The symbols employed are those recommended by the American Chemical Society in *Handbook for Authors,* 1967, pp 97-99. Commonly encountered metric units are used rather than those proposed by the International Organization for Standardization as in ISO Recommendation R1000, Ed. 1, 1969. The table below permits interconversion of the English, common metric, and ISO units for the quantities most likely to be of concern.

	To convert from	To	Multiply by
Length	in.	cm	2.54
	cm	in.	0.394
Mass	lb	kg	0.454
	kg	lb	2.20
Force	lb (wt)	dyn (= 1 g cm sec^{-2})	4.45×10^{-6}
	dyn	N (= 1 kg m sec^{-2})*	10^{-5}
	lb (wt)	N*	0.445
	N*	lb (wt)	2.25
	kg (wt)	N*	9.81
	N*	kg (wt)	0.102
Density	lb ft^{-3}	g cm^{-3}	0.0160
	g cm^{-3}	lb ft^{-3}	62.4
	g cm^{-3}	kg m^{-3} *	10^{3}
Pressure, stress, or modulus	lb (wt) $in.^{-2}$	dyn cm^{-2}	6.89×10^{4}
	dyn cm^{-2}	lb (wt) $in.^{-2}$	1.45×10^{-5}
	lb (wt) $in.^{-2}$	kg (wt) cm^{-2}	0.0703
	kg (wt) cm^{-2}	lb (wt) $in.^{-2}$	14.2
	dyn cm^{-2}	N m^{-2} *	10^{-1}
	kg (wt) cm^{-2}	N m^{-2} *	9.81×10^{4}

	To convert from	To	Multiply by
Energy	ft-lb (wt)	kg (wt) - cm	13.8
	kg (wt)-cm	ft-lb (wt)	0.0723
	kg (wt)-cm	J (= 1 N-m)*	0.0981
Impact strength	ft-lb (wt) $in.^{-1}$	cm-kg (wt) cm^{-1}	5.45
	cm-kg (wt) cm^{-1}	ft-lb (wt) $in.^{-1}$	0.183
	ft-lb (wt) $in.^{-1}$	J m^{-1} *	53.3
	ft-lb (wt) $in.^{-2}$	cm-kg (wt) cm^{-2}	2.14
	cm-kg (wt) cm^{-2}	ft-lb (wt) $in.^{-2}$	0.466
Viscosity	lb (wt) sec $in.^{-2}$	poise (= 1 dyn sec cm^{-2})	6.89×10^{4}
	poise	lb (wt) sec $in.^{-2}$	1.45×10^{-5}
	poise	N sec m^{-2} *	10^{-1}

** = ISO unit*

NYLON PLASTICS

CHAPTER 1

Introduction

M. I. KOHAN

HISTORY

Synthetic materials have developed on a truly grand scale since the 1920s. They graduated from the ranks of substitutes for natural products to preferred materials with unique performance capabilities. Their annual volume grew from less than fifty million pounds to over twenty billion pounds. Many people contributed to this remarkable achievement, but among the most prominent was Wallace Hume Carothers, who began his now classic studies on condensation polymerization in 1928 at the behest of the Du Pont Company. Condensation polymerization links molecules together via a reaction that involves the loss of a small molecule. Carothers' work led to the preparation, in 1935, of a truly high-molecular-weight polyamide from hexamethylenediamine and adipic acid:

$$\underset{\text{hexamethylenediamine}}{H_2NCH_2CH_2CH_2CH_2CH_2CH_2NH_2} + \underset{\text{adipic acid}}{HOOCCH_2CH_2CH_2CH_2COOH} \xrightarrow{-H_2O} \cdots HN(CH_2)_4NHCO(CH_2)_4COHN(CH_2)_6NHCO(CH_2)_4CO \cdots$$

The development of a wholly man-made fiber from this new, proteinlike material was announced to the public on October 27, 1938. The name nylon was

coined by Du Pont for this kind of polymer, one which included the carbonamide group –CONH– as a recurring unit of the main chain and which could be drawn into fibers. Two years later the first commercial plant for the production of nylon fiber was in operation at Seaford, Delaware.

The first nylon product to be marketed in 1938 was not a yarn but a continuous, large-diameter filament used as a bristle for toothbrushes. Like the fiber, it depends for its utility on the enhancement of properties realized by stretching the initial filament several fold, but large-diameter monofilament is normally considered a plastic rather than fiber application (see Table 1-1). This, then, was the origin of nylon, the synthetic-fiber industry, and a new concept in plastics. This very brief comment on the birth of nylon does justice neither to Carothers' research nor the fiber development; the interested reader is directed to the collected papers of Carothers (1) and to E. K. Bolton's review on the development of nylon (2).

Nylon was a new concept in plastics for several reasons; for one, it was the first crystalline plastic. Its crystallinity meant a sharp transition from solid to melt, unlike polystyrene or poly(methyl methacrylate); it also meant a much higher service temperature than previously known thermoplastics. Further, nylon provided a combination of toughness, rigidity, and lubrication-free performance which led to mechanical uses such as bearings and gears, applications heretofore denied to plastics. Nylon acquired the reputation of a quality material by showing that a thermoplastic could be tough as well as stiff and could do some jobs better than metals, which had previously defined standards of performance. This performance capability gave nylon the label "an engineering thermoplastic."

Nylon molding powder was first offered for sale by Du Pont in 1941. Beginning in 1954 with the introduction by the Allied Chemical Co. of extracted polycaprolactam, new to the American but not the European market, the number of United States manufacturers gradually grew. A tabulation of current United States suppliers and trade names is given in the Appendix.

The susceptibility of nylon to modification was clear from the outset. Different acids and amines could be reacted to provide a variety of nylons and nylon copolymers. Structural limitations on reactivity existed, but the polycondensation method of synthesis was an extension of classical organic chemistry more generally applicable and amenable to manipulation than the chain mechanisms by which other plastics such as styrene, ethylene, and methyl methacrylate were polymerized. In 1948 Du Pont's line of nylon molding and extrusion compounds included six products and twelve colors. In the next twenty years the Du Pont line alone increased by an order of magnitude in both the number of formulations and the number of standard and service colors. It is not surprising that a 1964 article cited diversity as the key to nylon and suggested that a nylon might actually be designed to meet the specific needs of an application if it were big enough (3).