G. W. Ehrenstein · G. Erhard

Designing with Plastics

A Report on the State of the Art

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With 83 illustrations and 5 tables

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Hanser Publishers, Munich Vienna New York

Distributed in the United States of America by
Macmillan Publishing Co., Inc., New York
and in Canada by
Collier Macmillan Canada, Ltd., Toronto

Professor Dr.-Ing. Gottfried Wilhelm Ehrenstein
Director of the Institute for Materials Technology, University Kassel, Germany

Dr.-Ing. Gunter Erhard
Head of the Department for Part and Tool Construction within the Applied Technology Division of BASF AG, Ludwigshafen, Germany, Teaching faculty member at the University Karlsruhe

Distributed in USA by
Scientific and Technical Books
Macmillan Publishing Co., Inc.
866 Third Avenue, New York, N. Y. 10022

Distributed in Canada by
Collier Macmillan Canada Distribution Center,
539 Collier Macmillan Drive, Cambridge, Ontario

Distributed in all other countries by
Carl Hanser Verlag
Kolbergstr. 22
D-8000 München 80

CIP-Kurztitelaufnahme der Deutschen Bibliothek

Ehrenstein, Gottfried W.:
Designing with plastics: a report on the state of the art / G. W. Ehrenstein; G. Erhard.
– Munich; Vienna; New York: Hanser;
New York: Macmillan; Toronto: Collier
Macmillan, 1984.
Einheitssacht.: Konstruieren mit Polymerwerkstoffen (engl.)
ISBN 3-446-14080-8

NE: Erhard, Gunter:

Macmillan Publishing Co., Inc., New York

Printed in Germany by Courier Druckhaus, Ingolstadt

Preface

Originally this progress report was planned and given in order as a situation survey about the subject of design with polymer materials.

Before working out this report important companies and competent engineers in the field of highly loaded polymer parts were consulted. We soon had to recognize that such complex subject would exeed the frame of a paper and violating our own restriction in volume the report grew to the present extent. According to a suggestion of Dr. Glenz this work was edited as a book which we do believe will be the best form to give hints to scientist and design engineers as well as to enable students to review the latest knowledge about the design with polymer materials.

Kassel/Ludwigshafen, February 1984

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1. Introduction

Figure 1.1 shows the development and importance of polymeric materials. It reveals that from 1950 to today, the production of raw steel has roughly trebled, whilst the production of polymers has, in total, increased at least thirty-fold. If rubber and fibers are left out of consideration, the increase is even forty-fold. Since most calculation parameters are dependent on geometry, it is more logical to consider amounts produced in terms of volume than in terms of weight. Presented in terms of volume, it is found that the curves for raw steel and for polymers intersect in 1978.

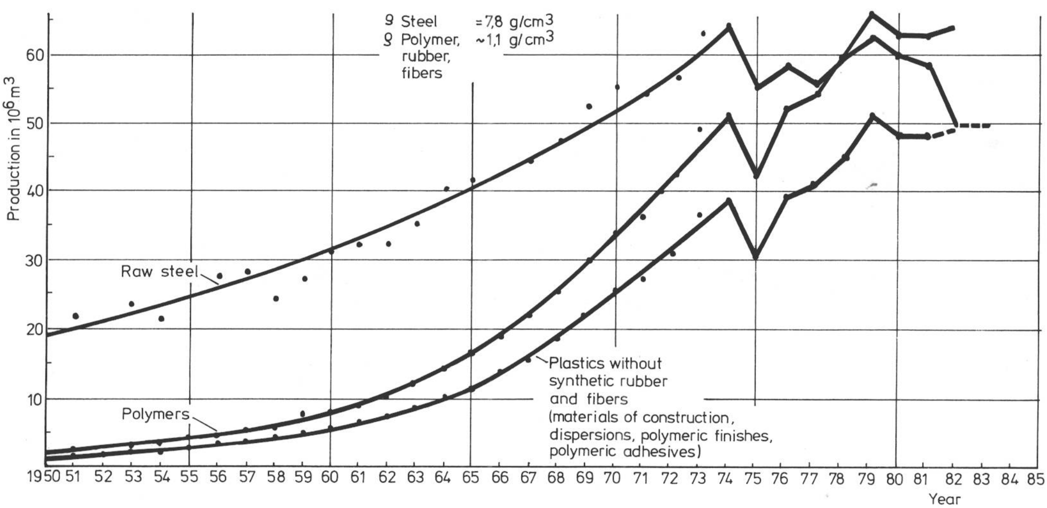

Figure 1.1: Production of crude steel and synthetic polymers in the Western world

The fact that the higher-quality polymeric materials, which conform to demanding technical requirements, show comparatively greater growth than those which can be considered as commodities is attributable to the following facts:

- The much more complicated deformation characteristics of the viscoelastic materials of construction, which do not directly permit computation and design by conventional equations well-proven for metals, are becoming increasingly understood.
- Experience with this very much more recent group of materials of construction is growing.
- With the increase in knowledge and experience in proven applications, confidence in these materials is increasing.

What remains to be dealt with is a gap in the training of university engineering students. This is because the new group of polymeric materials is frequently dealt with by metallurgists in technological departments. Undoubtedly, a consequence of this situation is that today most applications are being developed by practical men working empirically - men who in many cases have had no opportunity at all of receiving adequate instruction in this new group of materials, and who therefore have to base their work on experience alone.

It follows that the potential of polymeric materials is not yet fully exhausted.

2. New materials of construction – new material systems

In the last decade there has been no development of completely new polymeric materials for industrial design applications. Those which come closest to being describable as new materials are the particularly heat-resistant thermoplastics and thermoplastic elastomers, which have been brought to a fully marketable stage. On the other hand, more detailed research of material properties has had the effect that, firstly, existing materials of construction are being used with greater awareness of the properties of the material and, secondly, these materials have been improved through deliberate modification, so that they conform to special requirements.

Examples of such developments include carbon fiber-reinforced nylons (PA 66-CF), glass mat-reinforced thermoplastics (GMT), unsaturated polyester resin mats (SMC) with oriented glass fibers, and special polymer mixtures for components subjected to friction.

2.1 Carbon fiber-reinforced thermoplastics

On combining thermoplastics with carbon fibers, there are certain differences found compared to glass fiber reinforcement, because of the particular physical properties of the carbon fibers. They include the markedly higher modulus of elasticity, the lower specific gravity, the lower coefficient of thermal expansion, the higher electrical and thermal conductivity and, last but not least, the intrinsic black color. The difference in the modulus of elasticity of the reinforcing fiber and of the matrix is greater in the case of carbon fibers than in the case of glass fibers. Hence, a lower fiber content suffices to give a worthwhile reinforcing and stiffening effect. The carbon fiber content is preferably about 14 - 21 % by volume, corresponding to 20 - 30 % by weight.

Table 2.1 Mechanical and thermal properties of reinforced nylon 66 (carbon fibers, glass fibers and hybrid)

Property	Test method (DIN)	Unit	20 % by weight (13.5 % by volume) of carbon fibers	25 % by weight (12.4 % by volume) of glass fibers	40 % by weight (23.2 % by volume) of glass fibers	20 % by weight of carbon fibers 20 % by weight of glass fibers
Density	53,479	g/cm^3	1.23	1.30	1.46	1.40
Flexural strength	53,452	N/mm^2	280	240	315	325
Tensile strength	53,455	N/mm^2	198	170	222	227
Modulus of elasticity (in tension)	53,457	N/mm^2	15,200	8,000	14,700	23,000
Impact strength a_n	53,453	kJ/m^2	21	48	53	29
Fracture work W_{50}	53,433-1	Nm	0.28	0.90	0.66	0.26
Heat distortion point, ISO R 75	53,461	^oC	258	260	262	260
Coefficient of linear expansion	VDE 0304	$1/k.10^{-5}$	2.0	2.5	2.2	2.1

Carbon fiber-reinforced nylons

Carbon fiber-reinforced nylon is a high-performance material of construction, exhibiting a substantial specific rigidity. The most important mechanical and thermal properties are shown, in comparison to glass fiber-reinforced nylons, in Table 2.1. In making this comparison, attention must also be drawn to the enormous advances achieved in recent years in improving the quality of nylons reinforced with chopped glass fibers (Figure 2.1.)

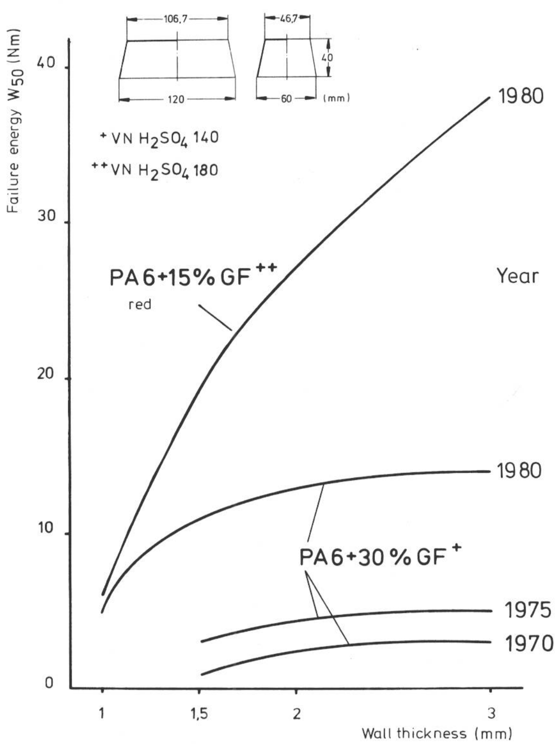

Figure 2.1: Improvement in the mechanical energy absorption of glass fiber-reinforced nylon in recent years, according to Dorst W_{50} is the product of the falling mass, gravitational acceleration and fall height, at which 50 % of the test specimens sustain damage

However, as with all fiber-reinforced thermoplastics, the properties determinded on injection-molded test specimens are only with certain reservations representative of the material characteristics in the component. This is because the generally slender shape of the samples results in a preferential orientation of the fibers during production of the samples, thereby emphasizing the properties in the lengthwise direction of the fibers, especially when it comes to mechanical data /1/. Moreover, combination with carbon fibers results in more advantageous frictional characteristics and wear resistance /2, 3/. Though carbon fibers are harder than glass fibers, this does not have as adverse an effect under frictional load as might have been expected. In fact, in frictional pairings with glass fiber-reinforced polymers, it is generally the other component of the pair which shows a greater tendency to wear.

The greater dimensional stability resulting from the lower coefficient of expansion of the carbon fibers and from the better heat conductivity of the composite have an advantageous effect, especially in the case of components exposed to relatively severe heat conditions. However, in selecting the material of construc-

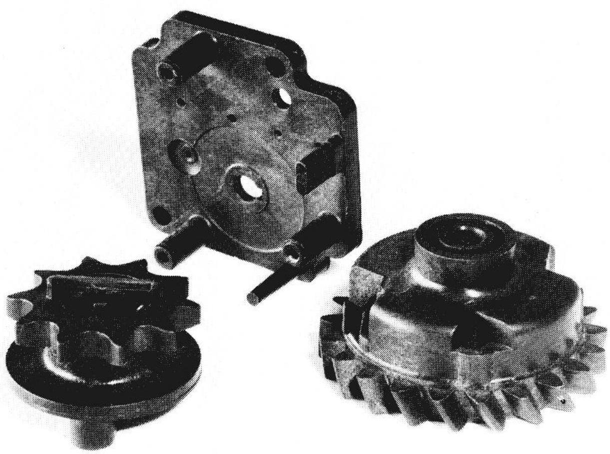

Figure 2.2: Machine components made from carbon fiber-reinforced nylon 66
(Works photograph: Sigri, Meitingen)

tion, the substantially higher cost attributable to the more expensive reinforcing material must be taken into account. Even the fact that the density is about one-third lower comes nowhere near offsetting the higher cost of the material.

Examples of applications of carbon fiber-reinforced nylons include, in particular, very rigid components which undergo rapid movements, as well as machinery components which are exposed to friction, in particular components of bearings and gear wheels exposed to severe mechanical load under difficult tribological conditions (Figure 2.2).

Hitherto, carbon fiber-reinforced nylons have not found anything like the wide range of applications of carbon fiber-reinforced epoxy resins, glass fiber-reinforced thermoplastics, nor is it expected that they will do so in the future.

The reinforcement of other thermoplastics with carbon fibers evidently offers less in the way of advantages.

2.2 Glass mat-reinforced thermoplastics (GMT)

It has long been a development aim to provide what many automotive bodywork producers dream about - namely a plastic counterpart of sheet metal, from which large-surface components can be produced - of comparable strength and rigidity to sheet steel, corrosion-resistant and light in weight, and yet rapidly and easily moldable like deep-drawing sheet metal. The hope is that the development of glass mat-reinforced thermoplastics has brought this objective one step nearer /4, 5/.

Glass mat-reinforced thermoplastics are produced as semi-finished goods, namely in sheet form, from thermoplastics (polyethylene, polypropylene and nylon) with long, generally continuous, glass fibers as the reinforcement. Due to the random distribution of the fibers in the plane of the sheet, isotropic properties are achieved. The material either has good flow or greater extensi-

Table 2.2
Comparison of types of GMT semi-finished goods /4,5,6/

Reshaping	Flow pressing
Introduction into mold:	
must overlap mold single layer	smaller blanks multi-layer
Advantages:	
no problems in introducing into the mold; easily automated; moldings quasi-isotropic; no weld lines; wooden mold or epoxy resin mold adequate for short runs; lamination possible	no waste; finished articles with complex geometry can be produced (ribs, thickenings); no wear of mold edges
Disadvantages:	
wear of mold edges; 5-15 % scrap (utilizable); limited ability to produce ribs and thickenings	exact positioning of the blanks is needed; automatic insertion into mold is expensive; anisotropy due to flow orientation; weak points due to welds; metal mold needed because of the high pressure required; lamination difficult