Christian Hopmann
Helmut Greif
Leo Wolters

Training in Plastics Technology

3rd Edition

HANSER

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Preface to the Third Edition

We are pleased that you have decided to study this book, which is available in both print and e-book formats.

The basis of the book was created almost 50 years ago as part of a research project lasting several years with the aim of finding and developing suitable methods of knowledge transfer for plastics technology. In 1976, a first German edition was published under the title *Lernprogramm Technologie der Kunststoffe* ("Training Program Technology of Plastics"), which was developed by the Institute of Plastics Processing (IKV) at RWTH Aachen University in cooperation with the Institute of Educational Science at RWTH Aachen University.

The editors were Prof. Georg Menges (Head of the Institute of Plastics Processing at RWTH Aachen University), Prof. Johannes Zielinski (Director of the Institute for Educational Science at RWTH Aachen University) and Ulrich Porath, a research engineer at the IKV.

The preface to the first edition in 1976 started with the statement:

"It is impossible to imagine our daily lives without plastics. We take this material in our hands as a matter of course without having dealt with it in any detail …"

Today, 47 years later, this statement is more valid than ever, as plastic materials have opened application ranges in almost all areas of life and will continue to do so in the future.

This comprehensively revised, new English edition of the text- and workbook still pursues the same goal of introducing the reader to the world of plastics and imparting the essential basics about the material and its machining and processing. It has been revised professionally, technically, and pedagogically, and further lessons on new topics have been added.

The book is a collaborative effort. The authors wish to thank all those who have contributed to its success – especially the companies and institutions that have provided ample visual material or information.

At this point, we would like to express our sincere thanks to all those who have contributed to the revisions of the different editions: Dr. Johann Thim, Hans Kaufmann, Prof. Walter Michaeli as well as Franz-Josef Vossebürger.

We hope you enjoy learning and working with this new edition.

Christian Hopmann

Helmut M. Greif

Leo Wolters

We highly appreciate any suggestions for improvements (office@ikv.rwth-aachen.de).

Editor's Preface to the Second Edition

This short volume is intended as a text and workbook for technicians employed in the plastics industry. The original German language edition was prepared at the behest of the government of the Federal Republic of Germany, the German Federal Association of Employers in the Chemical Industry and the German Chemical Workers Union. The book was put together and written at the Institut für Kunststoffverarbeitung (IKV) (Institute for Plastics Processing) at the Technical University of Aachen by Prof. Walter Michaeli with Helmut Greif, Hans Kaufmann and Franz-Josef Vossebürger.

Germany has long realized the necessity of organized post-high school teaching of trades to aspiring technicians. It is envisaged as the modem equivalent of the medieval apprenticeship program. Plastics processing is recognized as one of the modem trades deserving this treatment. The German program is described in some detail in Appendix 1.[1] It is one of known success as witnessed by the success of Germany's many manufacturing firms. The skill of their well-trained technicians is proverbial.

In the United States, there has been increased interest in recent years in the post-high school training of technicians. However, little attention has been given to the system long established in Germany which could serve as a model.

It is hoped that this book will find use in educational programs for technicians taught both within industry and in schools/programs dedicated to this purpose.

James L. White

Institute of Polymer Engineering

University of Akron

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[1] This refers to Lesson 21 in the 3rd edition.

The Authors

Professor Dr.-Ing. Christian Hopmann

Prof. Christian Hopmann holds the Chair for Plastics Processing and is director of the IKV – Institute for Plastics Processing in Industry and Craft at RWTH Aachen University in Germany. He is also co-founder of the AZL – Aachen Center for Lightweight Production and Vice Dean of the faculty for Mechanical Engineering of RWTH Aachen University. His interests lie in fundamental and applied research in plastics technology with a particular focus on digitization and simulation, lightweight technologies, and the circular economy. Hopmann is the principal investigator and member of the steering committee of the Federal Cluster of Excellence "Internet of Production". He initiated the Polymer Innovation Center 4.0, which addresses the domain specific realization and implementation of digitization in the plastics industry, with a particular focus on SME.

Hopmann received the Innovation Award of the Federal German state of North Rhine-Westphalia in 2014. He was appointed visiting professor at the Beijing University of Chemical Technology, Beijing/China in 2017 and fellow of the Society of Plastics Engineers (SPE), CT/USA, in 2019. Hopmann has served as international representative of the Polymer Processing Society (PPS) since 2021 and has been a member of the board of directors and the scientific advisory board as well as chairman of the board of the material engineering division of the VDI – The Association of German Engineers – since 2022.

Dr. Dipl.-Ing. Helmut Greif M. A.

Until 2016, Dr. Helmut Greif was Managing Director of the Aachen Society for Innovation and Technology Transfer (AGIT). He studied mechanical engineering, with a focus on construction technology, at the Aachen University of Applied Sciences, and sociology/political science/education at RWTH Aachen University, where he also received his interdisciplinary doctorate under Prof. Hörning (sociology) and Prof. Michaeli (mechanical engineering). After working in industry and business as a factory planner (company: agiplan) and then as managing director of a training and qualification institution (Dr. Reinhold Hagen Foundation), he was head of the HPI (Heinz Piest Institute) at the University of Hanover in the faculty of mechanical engineering before moving to AGIT in Aachen in 2007.

Dipl.-Ing. Leo Wolters

Leo Wolters was Managing Director of the Training and Further Education Department at the Institute for Plastics Processing (IKV) in Industry and Craft at RWTH Aachen University from 1995 to 2021. He studied mechanical engineering at the Cologne University of Applied Sciences, majoring in production engineering. Since September 1984, he has been engaged in technology transfer and training and further education in the field of plastics processing at the IKV in Aachen and has been actively involved in numerous national and international committees as well as standards committees.

■ Translation

Dr.-Ing. Marion Hopmann

Marion Hopmann studied mechanical engineering with particular focus on plastics processing at RWTH Aachen University. She received her doctoral degree at the Institute for Plastics Processing (IKV) in Industry and Craft at RWTH Aachen University with a thesis on additive manufacturing. After a career in the automotive industry at Ford Motor Company and Visteon she gave lectures on injection molding at FH Aachen University of Applied Sciences in Jülich and is currently working as consultant.

Notes

How to Use this Book

Introduction

This text and workbook provide an introduction to the world of plastics. The use of the plural “plastics” instead of the singular “plastic” indicates that we are dealing with a variety of different materials that can differ significantly in processibility or in their response to the influence of heat. Nevertheless, they are all classified as plastics as they are all synthetically produced, meaning newly composed, and thus do not occur in this form in nature.

Lessons

“Training in Plastics Technology” is divided into educational units that can be described as lessons, with each lesson covering a distinct subject area. The lessons, approximately equal in length, are designed so that they can be arranged by each student in a meaningful educational sequence.

Key Questions

The key questions at the beginning of each lesson are intended to help the student approach the subject matter with certain questions in mind. The answers to these questions will become clear after the student has worked through the lesson.

Prerequisite Knowledge

It is not necessary to study the lessons in any sequence. Information is provided in each lesson that indicates which lessons or content are important for understanding the lesson at hand.

Subject Area

The lessons can each be assigned to superordinate subject areas. Each lesson starts with a note indicating the subject area to which it belongs.

Performance Review

The review questions at the end of each chapter serve to verify the acquired knowledge. The correct answer must be selected from the list of answers provided and entered in the space provided in the text. The answers can be checked from the solutions at the end of the book. If the selected answer is incorrect, the corresponding topic should be worked through again.

Example: "Optical Data Carrier" (CD, CD-ROM, DVD, Blu-ray Disc)

To increase the understanding of plastics and improve thinking in contexts, a molded part made of plastic has been chosen to serve as an example, and will be referred to in many of the lessons in the book. This product is used to show why, for example, a particular plastic is ideal for manufacturing "optical data carriers", such as a CD, and to ask whether this plastic can be recycled.

Additional Information

Literature, glossary, professions, and abbreviations: The appendixes provide supplementary material on plastics for the interested reader. The selected bibliography can help with finding information on further technical literature. The glossary is intended to contribute to a standardized understanding of the terms used, and it can serve as a kind of short encyclopedia. The information on the job description of "Process Technician for Plastics and Rubber Engineering" and "Materials Tester Focus: Plastics" offers an opportunity to find out more about the tasks of these German plastics professions and their different specializations as well as about further training opportunities and promotion prospects in this area. A list of abbreviations, both general and plastics-specific, is provided to facilitate an understanding of the technical content. The most important physical values and their formula symbols are also provided.

Notes

Abbreviations and Symbols

Physical Quantities

Formula Symbol	Explanation	Unit
A	Area	m^2
a	Center-to-center distance	m
α	Thread angle (Greek: “alpha”)	°
Å	Ångström (1 Å= 10^{-10} m)	m
b	Channel width	m
D	Screw diameter	m
d	Core diameter	m
e	Land width	m
E-modulus	Young’s modulus (modulus of elasticity)	MPa
ε	Strain (Greek: “epsilon”)	%
F	Force	N
$\dot{\gamma}$	Shear rate (Greek: “gamma dot”)	1/s
h	Flight depth	m
η	Viscosity (Greek: “eta”)	Pa s
i	Number of flights	n (number)
J	Joule	W s = N m
λ	Heat conductivity (Greek: “lambda”)	W/m K
L/D	Screw length/screw diameter ratio	1
M	Torque	N m
Mt	Million tons	
P	Power	W
φ	Screw pitch angle (Greek: “phi”)	°
$\dot{Q}$	Volumetric flow rate	m^3/s
Q	Heat quantity	J
$qm = \dot{m}$	Mass flow	kg/s
R	Resistance	Ω (Ohm)

Formula Symbol	Explanation	Unit
s_k	Screw clearance	m
σ	Tensile strength (Greek: "sigma")	N/m² or Pa
t	Screw pitch	
t	Ton (metric) or tonne	1000 kg
T	Temperature	°C
T	Trillion (10^9)	
τ	Shear stress (Greek: "tau")	N/m²
T_f	Flow temperature range (FT)	°C
T_g	Glass transition or softening temperature range (GT or ST)	°C
T_c	Crystalline melting temperature range (CM)	°C
v	Velocity	m/s

Plastics

Abbreviation	Explanation
ABS	Acrylonitrile butadiene styrene copolymers (amorphous copolymers)
BR	Polybutadiene (general purpose rubber; butadiene rubber)
C	Carbon (Latin: "carbonium")
CAMPUS	Computer Aided Material Preselection by Uniform Standards
CFRP	Carbon fiber reinforced plastic (carbon fiber composite material (CF) with a polymer matrix)
Cl	Chlorine
CMR	Crystalline melting temperature range (also T_c)
CR	Polychloroprene (specialty type of rubber)
DT	Decomposition temperature
EP	Epoxy resins
EVOH	Ethylene/vinyl alcohol copolymer
EX	Extrusion
F	Fluorine
FIT	Fluid injection technology
FRP	Fiber reinforced polymers
FT	Flow temperature range (also T_f)
GIT	Gas injection molding, also gas-assisted injection molding
GKV	*Gesamtverband Kunststoffverarbeitende Industrie* (German Association of Plastics Converters)
GMT	Glass mat reinforced thermoplastics
GRP	Glass fiber reinforced plastics – composite materials made of glass fibers (GF) and a polymer matrix

Abbreviation	Explanation
H	Hydrogen (Latin: "Hydrogenium")
IKV	*Institut für Kunststoffverarbeitung* (Institute for Plastics Processing)
IM	Injection Molding
MFR	Melt flow rate, is replaced by melt volume rate (MVR)
MVR	Melt volume rate, colloquially also MVI (melt volume index)
N	Nitrogen (Latin: "nitrogenium")
NR	Natural Rubber
O	Oxygen (Latin: "oxygenium")
PA	Polyamide (semicrystalline thermoplastic)
PC	Polycarbonate (amorphous thermoplastic)
PE	Polyethylene (semicrystalline thermoplastic)
PE-HD	High-density polyethylene
PE-LD	Low-density polyethylene
PEEK	Polyether ether ketone (semicrystalline thermoplastic, heat-resistant)
PES	Polyether sulfone (amorphous thermoplastic)
PET	Polyethylene terephthalate (semicrystalline thermoplastic)
PF	Phenol formaldehyde
PMMA	Polymethyl methacrylate (amorphous thermoplastic)
POM	Polyoxymethylene (semicrystalline thermoplastic), also called polyacetal
PP	Polypropylene (semicrystalline thermoplastic)
PPI	Plastics processing industry
PS	Polystyrene (amorphous/semicrystalline thermoplastic)
PUR	Polyurethane (elastomer)
PVC	Polyvinyl chloride (amorphous thermoplastic)
RIM	Reaction injection molding
SBR	Styrene butadiene rubber
SMC	Sheet molding compound
ST	Softening temperature range (also T_g = glass transition temperature range)
ST	Softening temperature
UP	Unsaturated polyester resin
WIT	Water-assisted injection molding

General Terms

Abbreviation	Explanation
AI	Artificial intelligence
Al	Aluminum
APR	Accident Prevention Regulations (see also VBG)

Abbreviation	Explanation
ASI	Austrian Standards International
AT (AUT)	Austria (.at)
BBiG	*Berufsbildungsgesetz* – (German) vocational training act
BEM	Boundary element method
BG	*Berufsgenossenschaft* – (German) occupational insurance association
BGR	*Berufsgenossenschaftliche Regeln* – (German) occupational insurance association rules
BGV	*Berufsgenossenschaftliche Vorschriften* – (German) regulations of the trade association
BIBB	*Bundesinstitut für Berufsbildung* – (German) Federal Institute for Vocational Training
Blu-ray disc	HD-DVD = High-Density Digital Versatile Disc
CAD	Computer aided design
CAE	Computer aided engineering
CAM	Computer aided manufacturing
CAQ	Computer aided quality
CD	Compact disc
CH (CHE)	Switzerland (.ch)
CIM	Computer integrated manufacturing
CIP	Continuous improvement process
CNC	Computerized numerical control
DE (DEU)	Germany (.de)
DGQ	*Deutsche Gesellschaft für Qualität* – German society for quality
DGUV	*Deutsche Gesetzliche Unfallversicherung* – German social accident insurance
DIN	*Deutsches Institut für Normung* – German equivalent of American National Standards Institute ANSI
DSD	*Duales System Deutschland* – Dual System Germany
DVD	Digital Versatile Disc
EC	Is replaced by EU – European Union
ECS	European Committee for Standardization
EDP	Electronic data processing
EMG	European machine guidelines
EMS	Environmental management system
EN	European Norm
EU	European Union (see also EC)
FEM	Finite elements method
FVM	Finite volume method
GC	German constitution

Abbreviation	Explanation
HD	High density
IMS	Integrated management systems (see also QM, EMS)
IR	Infrared
ISO	International Standard Organization
JIS	Just in sequence
JIT	Just in time
KrWG	*Kreislaufwirtschaftsgesetz* – German circular economy law
LCA	Life cycle assessment
LD	Low density
LIL	Lower intervention limit (see also UIL)
log	Logarithmic (not linear)
LP	Long-playing record
MT	Machine tool
OHS	Occupational health and safety
ÖN	*Österreichische Norm* – Austrian Norm
OS	Operations scheduling
OSHA	Occupational Safety and Health Act
PCDA	Plan-check-do-act
PGE	Planetary gear extruder
QA	Quality assurance (see also IMS)
QM	Quality management (see also IMS)
QMS	Quality management system
QRK	Quality control chart
SF	Substitute fuels
SME	Small and medium-sized enterprises
SN	Swiss Norm
SNV	Swiss Standards Association
SPC	Statistical process control
TQM	Total quality management
UIL	Upper intervention limit (see also LIL)
UV	Ultraviolet
VBG	Regulation of the Trade Association (see also APR)
VDA	Association of the German Automotive Industry
VerpackG	German Packaging Act from 2019 (replaces the German VerpackV)
VerpackV	German Packaging Act from 1998, new regulation 2014)
WIP	Waste incineration plant

Academic Degrees

Abbreviation	Explanation
Dipl.-Ing.	Diplom-Ingenieur (old term in Germany for M. Eng. or M. Sc.)
B. Eng.	Bachelor of Engineering
B. Sc.	Bachelor of Science
M. Eng.	Master of Engineering
M. Sc.	Master of Science

Introduction

Plastic – An Artificial Material?

Key Questions

Where do we encounter plastics in everyday life?

How long have we been using plastics?

What is a compact disc (CD) made of?

Contents

Plastics – Part of Our Everyday Life

Plastics – Versatile Materials

Plastics – Young Materials

Plastics – Part of Our Everyday Life

In our environment, plastics have become perfectly acceptable as a matter of course in everyday use. People don't think about why these products are made of plastic when they use freezer bags or cell phones.

plastics ...

Why are more and more drinking bottles being made of plastic instead of glass?

Here, weight plays the most crucial role. The lighter, plastic bottle is stable enough to transport the liquid it contains. It is more energy-efficient to manufacture and saves fuel as well as CO_2 because less weight is being transported. The consumer also benefits from carrying a lighter, plastic bottle.

... are lightweight

Why are power cables coated with plastic and not, for instance, with porcelain or fabric?

Plastic sheathing is more flexible than porcelain and tougher than fabric, yet it insulates the cable just as well, if not better.

... insulate against electric current and can be flexible

Why is a refrigerator interior lined with plastic?

Because plastic is, on one hand, rugged. On the other, it is a poor conductor of heat, and so the low temperatures can be maintained better. Furthermore, the surfaces are easy to clean.

... insulate against heat

The opposite is the case, for example, for the insulation of houses. Here, foamed plastics help to keep the heat in the house for much longer. Heating costs, but also CO_2 emissions, are significantly reduced.

... insulate against cold

Why is a CD made of plastic?

Because the plastic polycarbonate (PC) is as translucent as glass. At the same time, it is much lighter than glass and not as fragile.

... are low-cost materials

Of course, we must also consider the price in all these examples. Using plastics is often the more cost-effective technical solution, especially for mass-produced articles. Why this is so, and which problems are often overlooked in this context (e. g. waste disposal), we will examine later.

Plastics – Multifunctional Materials

wood
natural rubber

Before plastics became known, only nature provided lightweight materials. Wood is easy to process and is strong and flexible. It can also be permanently shaped by special processes. Natural rubber, a raw material for synthetic rubber, is elastic and stretchable.

natural materials

All technical problems cannot be solved with the properties of natural materials, however. This triggered a search for new materials possessing the required properties. Not until the twentieth century did chemists learn enough about the molecular structure of natural materials (e. g., natural rubber) to be able to produce these materials artificially. The heat-insulating neoprene (for wetsuits), which came to market in 1930 and was produced from rubber, was the first major application of this new group of materials.

Lego bricks

Another example illustrating the diversity of plastics is the “Lego bricks” that were launched in 1958. Initially they were made from cellulose acetate and later from ABS. The high quality of this well-known plastic product is apparent from the fact that even after 50 years, the precision fit is still fully guaranteed.

ideal properties

The properties of plastics produced today are often far superior to those of natural materials. For the most diverse purposes, we now have materials whose properties are ideally customized to the intended application.

material properties

It is impossible to determine the purpose for which a plastic article is best suited by observing its external appearance. We also need to know something about the internal structure of the material. It gives us information about density, conductivity, permeability, or solubility, for example. In other words, it tells us the “material-specific properties”.

Plastics – Young Materials

plastics model
Nobel Prize

The systematic conversion of natural substances into the materials known today as “plastics” began in the 19th century. However, they did not attain commercial significance until the 1930s, when Prof. Hermann Staudinger developed his model picture of the structure of plastics. A German chemist, Staudinger (1881 to 1965) received the Nobel Prize for this research in 1953.

The global boom in the plastics industry began after World War II. Coal was initially used as the basic material, and it was not until the mid-fifties that the switch was made to petroleum. The advantage of this change was that the previously worthless refining fractions that occurred as separation products in the process of cracking crude oil could be put to effective use. The rapid increase in plastics production experienced a moderate setback during the 1973 oil crisis. Nevertheless, the materials have recorded above-average, dynamic growth up to the present day.

petroleum

World production of plastics shows a continuous growth rate of 3 to 5% per year (see Figure 1).

substituting traditional materials

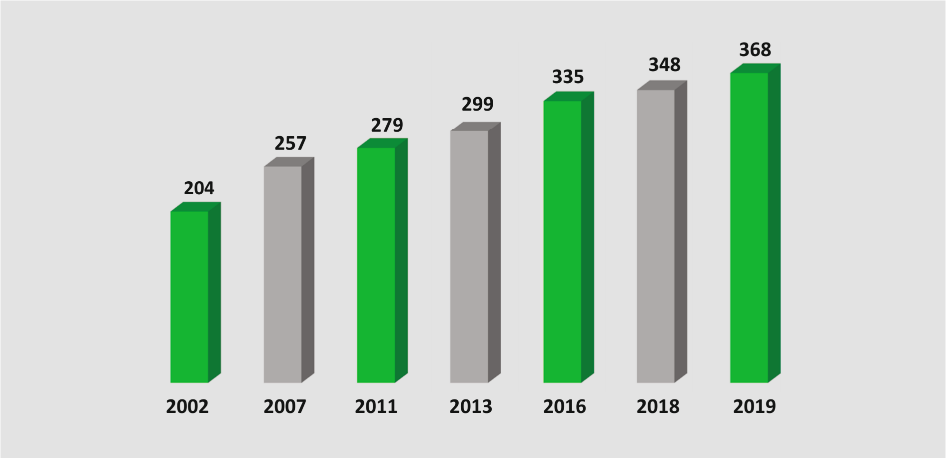

Figure 1 Worldwide production of plastics in millions of tons [based on: Plastics Europe]

However, plastics can only be used with optimal effectiveness when their special characteristics are considered. Particularly when they are substituted for traditional materials such as wood or metal, a design suitable for plastics must be taken into consideration that will allow the plastics to bring their many possibilities to the application. It is important to be familiar with the appropriate processing methods, as well as the corresponding characteristic material values.

Such a plastic-based approach requires a fundamental understanding of the manufacturing and processing methods as well as the material characteristics. This book is intended to provide a first fundamental and comprehensive overview of the subject of plastics. We intend to follow a technical plastic component on its way from the starting material, crude oil, through production, to final disposal through recycling. This part will be a compact disc (CD) or DVD, which should be familiar to everyone. It thus makes an ideal example of modern plastics processing.

compact disc (CD)

Figure 2 shows a CD produced via the injection molding process and its dimensions.

CD

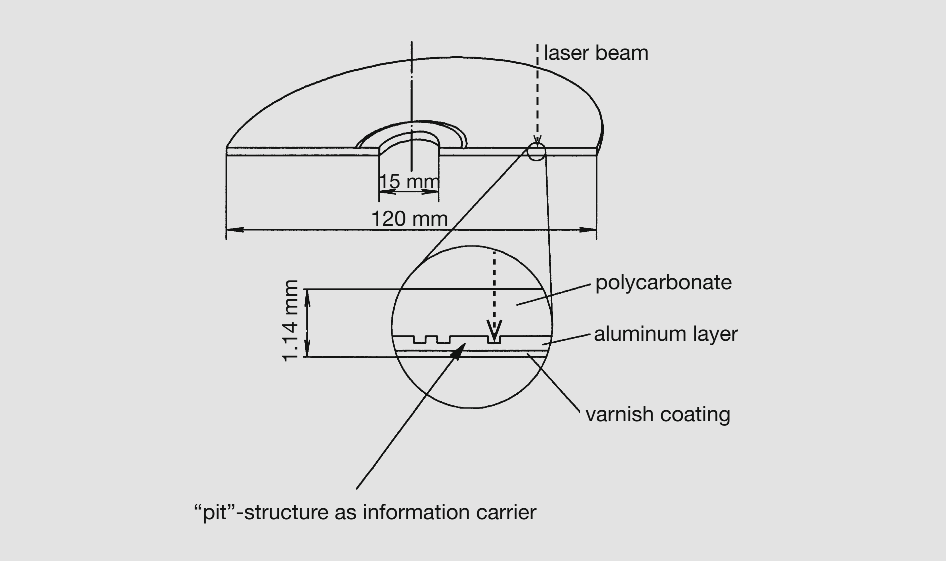

Figure 2 Compact disc (CD) and its dimensions

DVD
Blu-ray (HD-DVD)

The modern siblings of the CD, for example the DVD (Digital Versatile Disc) and the HD-DVD or Blu-ray disc, are not produced using the classic injection molding process. Due to their multilayer structure, significantly thinner discs must be produced. They are injection compression molded and glued together in a further step.

long-playing record (LP)
polyvinyl chloride (PVC)

It is interesting to note in this context that the long-playing record (LP) was a plastic predecessor technology of the CD for high-quality music. The LP came onto the market in 1948. At that time, this new material group of "plastics" contributed decisively to the worldwide success of a recording medium. The LP is made of PVC (polyvinyl chloride), a material that is highly resistant to external influences and is the same material used to produce plastic windows, for example.

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