ALUMINUM ALLOY CASTINGS

Properties, Processes, and Applications

J. Gilbert Kaufman
Elwin L. Rooy

AMERICAN FOUNDRY SOCIETY
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ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

First printing, December 2004

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Prepared under the direction of the ASM International Technical Books Committee (2003-2004), Yip-Wah Chung, FASM, Chair.

ASM International staff who worked on this project include Scott Henry, Senior Manager of Product and Service Development; Charles Moosbrugger, Technical Editor; Bonnie Sanders, Manager of Production; Carol Polakowski, Production Supervisor; and Pattie Pace, Production Coordinator.

Library of Congress Cataloging-in-Publication Data

Kaufman, J. G. (John Gilbert), 1931-
Aluminum alloy castings properties, processes and applications/J. Gilbert Kaufman, Elwin L. Rooy.
p. cm.
Includes bibliographical references and index.
ISBN 0-87170-803-5
1. Aluminum alloys—Mechanical properties. 2. Aluminum castings. I. Rooy, Elwin L. II. title.

TA480.A6K33 2004
620.1'86—dc22

2004052923

ISBN: 0-87170-803-5
SAN: 204-7586

ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

Printed in the United States of America

Preface

This book is intended to provide a comprehensive summary of the physical and mechanical properties of most types of aluminum alloy castings. It includes discussion of the factors that affect those properties, including composition, casting process, microstructure, soundness, heat treatment, and densification. Extensive previously unpublished technical data including aging response, growth, fatigue, and high- and low-temperature performance have been consolidated with existing and updated materials property characterizations to provide a single authoritative source for most performance evaluation and design needs.

The consideration of casting process technologies is intentionally limited to typical capabilities and to their influence on property performance. Many excellent references are available for more detailed information and guidance on production methods and on important aspects of melting, melt processing, solidification, and structure control. Interested readers are referred to the publications of the American Foundry Society (AFS), the North American Die Casting Association (NADCA), and the Non-Ferrous Founders' Society (NFFS). Many of these publications are included in the reference lists at the end of each chapter.

It is also beyond the scope of this book to provide more than generalized economics of aluminum casting production.

The authors gratefully acknowledge the support and assistance of several organizations and individuals in developing this volume. Alcoa, Inc. generously provided extensive previously unpublished production and property data from their archives, adding significantly to the industry's shared knowledge base. We wish, especially, to thank R.R. Sawtell and R.J. Bucci of Alcoa for their cooperation in arranging the release of this material. We are pleased that the American Foundry Society has been credited as co-publisher of this book. The AFS Aluminum Division Review Committee provided substantive and constructive suggestions; the members of the committee are listed in these pages. In addition, Laura Moreno and Joseph S. Santner of AFS provided content from AFS publications and arranged for the necessary permissions to reproduce information as needed. We would also like to thank Joseph C. Benedyk of the Illinois Institute of Technology for his helpful comments, and John C. Hebeisen of Bodycote for his assistance in providing the results of recent studies in hot isostatic processing. The North American Die Casting Association and the Non-Ferrous Founders' Society also gave us permission to cite, with appropriate references, information from their publications. We also acknowledge the support and assistance of the Aluminum Association, Inc., notably, permission to include information from their publications covering aluminum casting alloys.

J. Gilbert Kaufman
Elwin L. Rooy

About the Authors

J.G. (Gil) Kaufman has a background of almost fifty years in the aluminum and materials information industries and remains an active consultant in both areas. In 1997, he retired as vice president, technology, for the Aluminum Association, Inc., headquartered in Washington, D.C., and is currently president of his consulting company, Kaufman Associates. Earlier in his career, he spent twenty-six years with the Aluminum Company of America and five with ARCO Metals, where he was vice president, R&D. He also served as president and CEO of the National Materials Property Data Network, establishing a worldwide online network of more than twenty-five materials databases. Mr. Kaufman is a Fellow and Honorary Member of ASTM, and a Fellow and Life Member of ASM International. He has published more than 125 articles, including four books, on aluminum alloys and materials data systems.

Elwin Rooy retired after thirty-five years with the Aluminum Company of America, where he was corporate manager of metallurgy and quality assurance, to form a consulting firm specializing in aluminum process and product technologies, quality systems, and industry relations. He has been active in committees of the Aluminum Association, American Foundry Society, American Die Casting Institute, The Institute of Scrap Recycling Industries, Society of Die Casting Engineers, ASM International, and TMS. He has served as chairman of the TMS Aluminum Committee, chairman of the AFS Light and Reactive Metals Division, director and chairman of the Northeast Ohio chapter of AFS, regional director of the Foundry Education Foundation, and charter member of the Drexel/WPI Advanced Casting Research Laboratory. Mr. Rooy's honors include the AFS award for Scientific Merit, The TMS/AIME Distinguished Service Award, the M.C. Flemings Award for contributions in the field of solidification, and the Arthur Vining Davis Award for technical achievement. He has served on the editorial boards of the *Journal of Metals* and *Advanced Materials & Processes*, published more than thirty articles and papers, edited *Light Metals 1991*, and authored or coauthored articles in the *ASM Handbook* series.

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Preview for: *Aluminum Alloy Castings: Properties, Processes, and Applications*, by J. Gilbert Kaufman and Elwin L. Rooy, ASM International, 2004
Full digital book available at https://doi.org/10.31399/asm.tb.aacppa.9781627083355

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CHAPTER 1

Introduction

1.1 Background and Scope

It is the objective of this book to comprehensively summarize material properties and engineering data for aluminum alloy castings and to address the need for a single reference that covers production, quality assurance, properties, and applications of aluminum alloy castings.

Unlike most sources, the content addresses not only conventional sand and permanent mold castings, but also pressure die castings and many of the variations of all three that have developed over the years.

The physical and mechanical properties of aluminum castings may be altered through:

- *Alloying composition:* The composition of alloys determines the potential for achieving specific physical and mechanical properties. Alloy content is designed to produce characteristics that include castability as well as desired performance capabilities. The interaction of alloying elements is recognized in promoting desired microstructural phases and solid-solution effects for the development of these properties.
- *Cooling rate during and after solidification:* The conditions under which solidification takes place determine the structural features that affect the physical and mechanical properties of an alloy.
- *Casting process:* There are a large number of casting processes, and each imposes different rates of heat extraction, solidification rates, and means of compensating for solidification-related microstructural and macrostructural tendencies.
- *Solidification:* Engineered castings are susceptible to internal and superficial defects. The complex geometries of shaped castings, fluid dynamics, and solidification mechanics combine to present unique and difficult challenges to the objective of dense, discontinuity-free parts. Internal porosity can result from shrinkage and hydrogen porosity, as well as from visually detectable defects such as misruns, cracks, moisture reactions, folds, and tears. Nonmetallic inclusions affect mechanical properties and nucleate hydrogen pore formation. Pore volume fraction and the geometry and distribution of internal voids reduce tensile properties, fatigue strength, toughness, and ductility, while surface defects strongly influence mechanical and fatigue performance.
- *Heat treatment:* Mechanical properties can be altered by postsolidification thermal treatment, including annealing, solution heat treatment, and precipitation aging.
- *Postsolidification densification:* Hot isostatic processing (HIP) of castings can result in improved levels of internal soundness, higher tensile properties, ductility, and fatigue performance.

These factors and their effects are considered in Chapters 2 through 7, and a comprehensive summary of the mechanical and physical properties of aluminum alloy castings is provided in Chapter 8.

1.2 History

Castings were the first important market for aluminum, following the commercialization of the Hall-Heroult electrolytic reduction process. At first, applications were limited to curiosities such as house numbers, hand mirrors, combs, brushes, tie clasps, cuff links, hat pins, and decorative lamp housings that emphasized the light weight, silvery finish, and novelty of the new metal. Cast aluminum cookware was a welcome alternative to cast iron and brass pots, pans, and kettles. The cost of aluminum steadily declined, and by the end of the 19th century important engineering applications became economically viable.

Aluminum in cast as well as wrought forms was a metal for its time. Three emerging markets coincided with the appearance of aluminum as a material alternative:

- Electrification demanded not only low-density, corrosion-resistant, high-conductivity wire and cable for which aluminum was well-suited, but also transmission towers and cast installation hardware.
- Automotive pioneers sought innovative materials and product forms to differentiate the performance and appearance of their products.
- When the Wright Brothers succeeded in powered flight, engine and other parts in cast aluminum represented the beginning of a close collaboration with what would become the aviation and aerospace industries.

The large number of applications for which aluminum competed in these and other markets required the development of specialized compositions and material conditions to satisfy specific engineering requirements. The characterization of physical and mechanical properties and the results of performance testing were the basis for continuous new alloy developments and refinements in composition control. The development of permanent mold and pressure die casting as alternatives to sand casting encouraged the development of new alloys suited not just to application requirements but also to the casting process. Continuing technological improvements in alloy, casting, and recycling technology have improved the competitiveness and enhanced the growth of aluminum castings markets.

1.3 Advantages and Limitations of Aluminum Castings

Aluminum castings are produced in a range of alloys demonstrating wide versatility in the characteristics than can be achieved. More than 100 compositions are registered with the Aluminum Association, and more than 300 alloys are in international use. Properties displayed by these alloys, without considering the expanded capabilities of metal-matrix and other composite structures, include:

Tensile strength, ksi (MPa)	10–72 (70–505)
Yield strength, ksi (MPa)	3–65 (20–455)
Elongation, %	<1–30
Hardness, HB	30–150
Electrical conductivity, %IACS	18–60
Thermal conductivity, Btu · in./h · ft^2 · °F at 77 °F (W/m · K at 25 °C)	660–1155 (85–175)
Fatigue limit, ksi (MPa)	8–21 (55–145)
Coefficient of linear thermal expansion at 68–212 °F (20–100 °C)	9.8–13.7 × 10^{-6}/°F (17.6–24.7) × 10^{-6}/°C)
Shear strength, ksi (MPa)	6–46 (42–325)
Modulus of elasticity, 10^6 psi (GPa)	9.5–11.2 (65–80)
Specific gravity	2.57–2.95

An ability to produce near-net-shape parts with dimensional accuracy, controlled surface finish, complex geometries including internal passages, and properties consistent with specified engineering requirements represents significant manufacturing advantages (Fig. 1.1, 1.2):

- In many cases, multicomponent welded or joined assemblies can be replaced with a single cast part.
- Machining requirements are reduced.
- Aluminum castings display controlled variations in as-cast finish.
- Contrasts between as-cast and machined finishes can be highlighted to create pleasing cosmetic effects.
- Capital requirements are typically less than for wrought products.
- Tooling can range from simple patterns to complex tool steel dies depending on product requirements and production volume.
- Metallurgically or mechanically bonded bimetal parts can be routinely cast.
- Aluminum parts are routinely cast by every known process, offering a broad range of volume, productivity, quality, mechanization, and specialized capabilities.
- Most aluminum casting alloys display solidification characteristics compatible with foundry requirements for the production of quality parts.

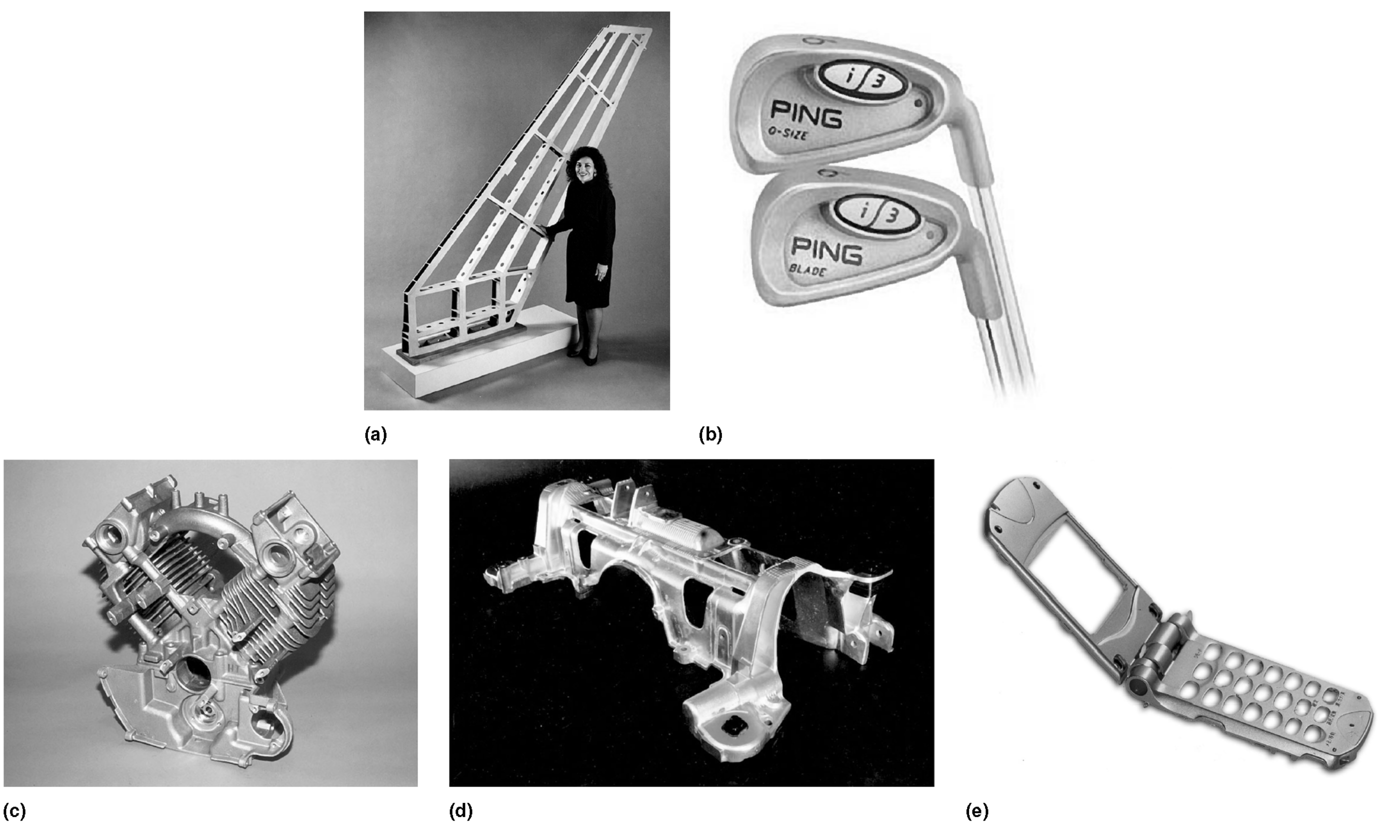

Fig. 1.1 Casting applications include innovative and complex designs serving the needs of diverse industries. (a) Aircraft stabilizer. (b) Golf irons. (c) Crankcase for small engine. (d) Cross member for a minivan. (e) Cellular phone casing. Source: Ref 1

- Many aluminum casting alloys display excellent fluidity for casting thin sections and fine detail.
- Aluminum casting alloys melt at relatively low temperatures.
- Aluminum casting processes can be highly automated.

Many limitations do apply. Very thin sections may not be castable. There are practical limitations in size for specific casting processes. The solidification behavior of some alloys precludes casting in difficult engineered configurations or in specific casting processes. The casting process is simpler and less capital intense than processes for producing forgings, extrusions, and rolled products. However, solidification in complex geometrical shapes, as with other fabrication options, can result in surface discontinuities and internal microstructure features with varying degrees of quality that affect properties and performance.

Aluminum alloy castings can display the tensile properties of most forgings, extrusions, and rolled plate. Because wrought products are normally characterized by finely recrystallized grain structures with specific anisotropy and highly textured microstructural features, ductility in longitudinal directions is typically greater than in castings that contain coarser grain structures. Conversely, the typically uniaxial grain structure and absence of anisotropy in cast structures do not present design engineers with the challenges associated with transverse property limitations.

1.4 Major Trends Influencing Increased Use of Aluminum Castings

1.4.1 Technology

The importance of improved energy efficiency in recent decades reflects the effects of increased gasoline and oil costs to the consumer and graduated government-mandated fuel-efficiency standards for automobile and truck manufacturers. Environmental concerns, global competitiveness, and raw-material concerns reinforce the incentives to reduce fuel consumption while preserving product performance and cost objectives.

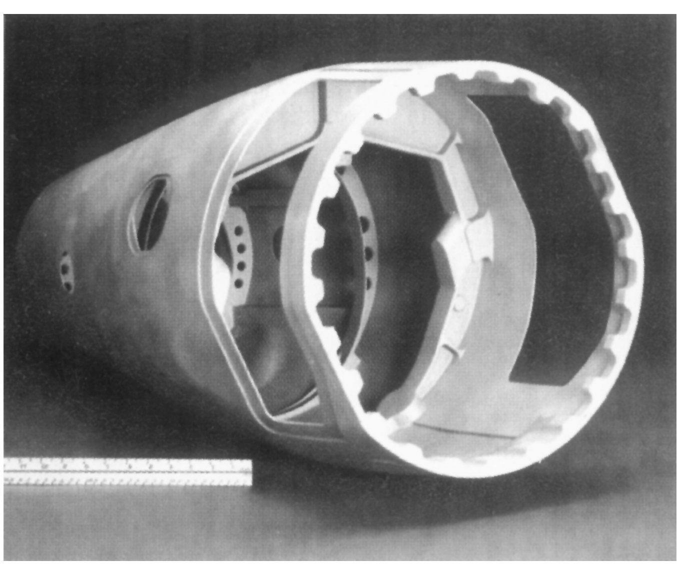

Fig. 1.2 One-piece cast missile tail cone. A cost-effective and reliable alternative to what had been a multicomponent assembly

The most cost-effective means of addressing these challenges has been the substitution of lightweight materials in existing and projected automotive designs. The U.S. automotive industry in collaboration with suppliers and the U.S. Department of Energy formed coalitions, including USAMP, which focused on materials characterization, and USCAR, which focused on materials development and process capabilities. Their objective has been to facilitate the transition to lighter-weight materials and more fuel-efficient performance without sacrifice in safety and with minimal impact on cost

The emphasis placed on improved efficiency in energy-consuming applications has resulted in a steady increase in the production and use of aluminum castings. The recent pattern of growth in aluminum casting shipments in the United States, including projections through the year 2005 is (Ref 2):

Year	Casting shipments in the United States	
	10^6 lb	10^6 kg
1994	2880	1306
1995	2990	1356
1996	3260	1479
1997	3380	1533
1998	3490	1583
1999	3550	1610
2000	3640	1651
2001	3800	1724
2202	4100	1860
2003	4500	2041
2004	4900	2223
2005	5160	2341

Cast aluminum has been used or demonstrated successfully for many decades in power-train applications including engine blocks, cylinder heads, pistons, transmission cases, and oil pans. In the first wave of light-weighting, aluminum was extensively adopted for these parts. For maximum impact on fuel efficiency, this expansion in the role of cast aluminum necessitated substitutions in more critical structural parts requiring the qualification of new component designs, materials, and production methods. These applications include traditionally cast iron, malleable iron, nodular iron and steel cross members, suspension and control arms, brackets, brake valves, rotors, and calipers. The commercialization of aluminum-intense automobile designs can result in 20 lb less engine emissions over the life of an automobile for each pound of iron or steel replaced by lower-density aluminum with correspondingly significant reductions in fuel consumption (Ref 3). New aluminum-intensive automotive construction concepts include cast fittings or nodes for extruded stringers in monocoque assemblies and the development of energy-absorbing thin-wall cast space frames. Figures 1.3 through 1.6 summarize the results of a study performed for the Aluminum Association showing the growth in cast aluminum as well as total aluminum products in North American light vehicle production.

The most significant barrier to the acceptance of cast aluminum in these and many other structural applications has been its reputation for variability. Overcoming this barrier required the demonstration of integrity and reliability derived from the evolu-

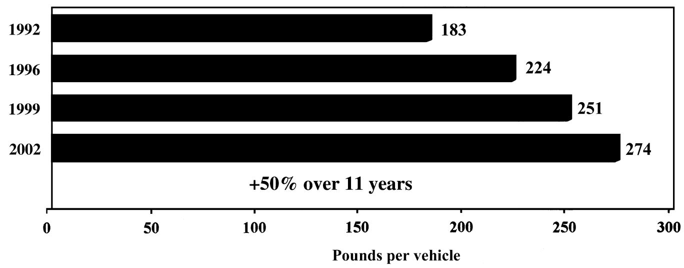

Fig. 1.3 North American light vehicle change in aluminum content, 1991 to 2002

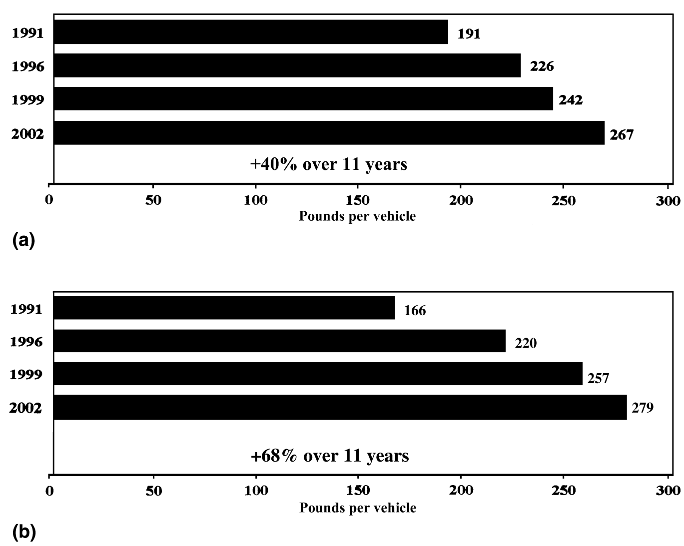

Fig. 1.4 North American light vehicle change in aluminum content, 1991 to 2002. (a) Passenger cars. (b) Trucks

tion of manufacturing processes and effective process controls. To be economic, casting results must be consistent and predictable without reliance on extensive inspection and nondestructive evaluation.

Each step in these developments has been the product of close collaboration between aluminum casting suppliers and the automotive industry. Not only are specific engineering criteria to be met for each new component, process designs and controls must reliably demonstrate capability and consistent product quality in the high volumes that are required. New casting processes, alloys, composite compositions, thermal treatments, process control methodologies, and the sensors and controls they require have contributed to an accelerated evolution of technologies that has been facilitated by research and development programs, many of which were sponsored by USCAR and USAMP in cooperation with national laboratories, colleges, and universities and with supplier industries.

Aluminum castings will play an important future role when inevitable electric, hybrid, or fuel-cell technologies are developed to combine materials, design, and construction methods for maximum efficiency.

Technological progress achieved in automotive programs affects all phases of aluminum foundry operations and all casting applications. Technology is also being broadly advanced by the activities of the U.S. Department of Energy that has identified metal casting as one of nine important "Industries of the Future." Benefits have been the development of a technology roadmap (Ref 4) that includes many of the challenges and technical barriers facing the aluminum castings industry and the funding of research and development programs in casting, aluminum, sensors, automation, and industrial materials of the future to meet or overcome them.

The product of these efforts has been greater versatility and improved capability in consistently and economically meeting even the most severe engineering challenges in automotive and other industries. Understanding the material and process changes that are

Aluminum product form	1999 lb/vehicle	Percent of total	2002 lb/vehicle	Percent of total	Percent change 1999 vs 2002
Die castings	95.76	38.2%	101.42	37.1%	+5.9% or 5.66 lb
Permanent mold castings	92.43	36.9%	100.58	36.8%	+8.8% or 8.15 lb
Flat rolled products	27.24	10.9%	29.39	10.7%	+7.9% or 2.15 lb
Extruded and drawn products	16.83	6.7%	18.49	6.8%	+9.9% or 1.66 lb
Forgings and impacts	6.34	2.5%	6.10	2.2%	–3.8% or –0.24 lb
Sand, lost foam, squeeze, and semisolid castings	11.94	4.8%	17.52	6.4%	+46.7% or 5.58 lb
Total	**250.54**	**100%**	**273.50**	**100%**	**+9.2% or 22.96 lb**

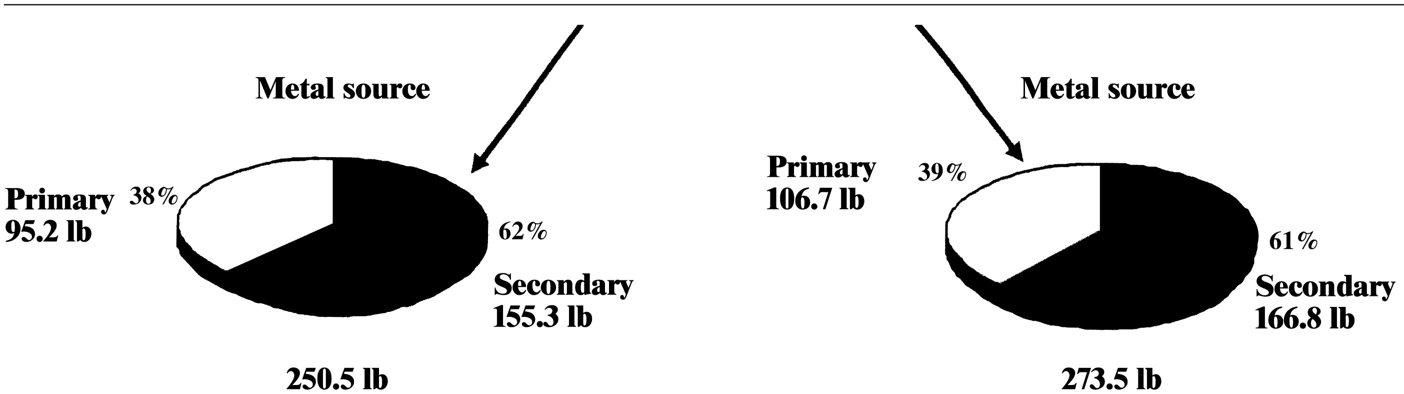

Fig. 1.5 North American light vehicle change in aluminum content by product form and metal source, 1999 to 2002

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taking place to further increase the comfort of design engineers in the use of aluminum castings is essential for defining material advantages for any new application.

1.4.2 *Recycling*

Recycling and its impact in life-cycle studies are increasingly important considerations in materials selection (Ref 5). The manner in which energy efficiency can be directly and indirectly affected is important, but so are environmental and competitive considerations. While the production of aluminum is energy-intensive, it can be efficiently recovered from scrap at 5% of the energy required for reduction. Corrosion resistance preserves metal value, and new technologies are being developed for the segregation of scrap streams by alloy and product form for essentially closed-loop recycling.

Virtually all aluminum forms classified as old scrap (end of cycle) and new scrap (turnings, borings, gates and risers, rejections) are recyclable. With appropriate recycling processes, recoveries typically exceed 90%.

Many casting compositions are compatible with the alloy content of even mixed scrap. The cost of ingot produced from scrap is typically less than that of primary metal. As a consequence, most aluminum alloy castings are produced from recycled metal.

The use of aluminum in energy-consuming applications provides efficiencies with calculable benefits for prolonging product life, conserving raw materials, reducing energy consumption in manufacturing and service, reducing levels of environmental pollution and the costs of environmental control, and lowering material cost through recycling. When factored into cost comparisons with competing materials, the advantage of aluminum in life-cycle analysis can be significant.

1.5 Selecting the Right Aluminum Alloy and Casting Process

The succeeding chapters review the substantial portfolio of aluminum casting alloys available; Chapter 2 illustrates the characteristics that have made certain alloys the first choice for specific applications. Chapters 3 through 7 focus on the process and thermal treatment variables that influence the metallurgical structure of aluminum alloys and, in turn, how the combination of process variables and metallurgical structure influence their properties and performance. Finally, Chapter 8 provides a broad range of physical and mechanical property data, a substantial amount of which has never been published before, certainly not all in a single resource.

This wide range of information contained herein is provided as a reference for aluminum alloy casting producers, heat treaters, designers, and users with the intent of aiding them in the selection of the right alloy, temper, and processing needed to achieve the performance required of cast components. The authors believe it is clear that, as suggested above, aluminum casting alloys provide a broad range of capabilities including—when appropriate, process-optimization and quality-control procedures are applied—components suitable for challenging applications where soundness, strength, and toughness are critical. The authors hope it will also be clear that there are great advantages for designers and casting suppliers working closely with their customers on the selection of alloys, tempers, and casting processes capable of meeting manu-

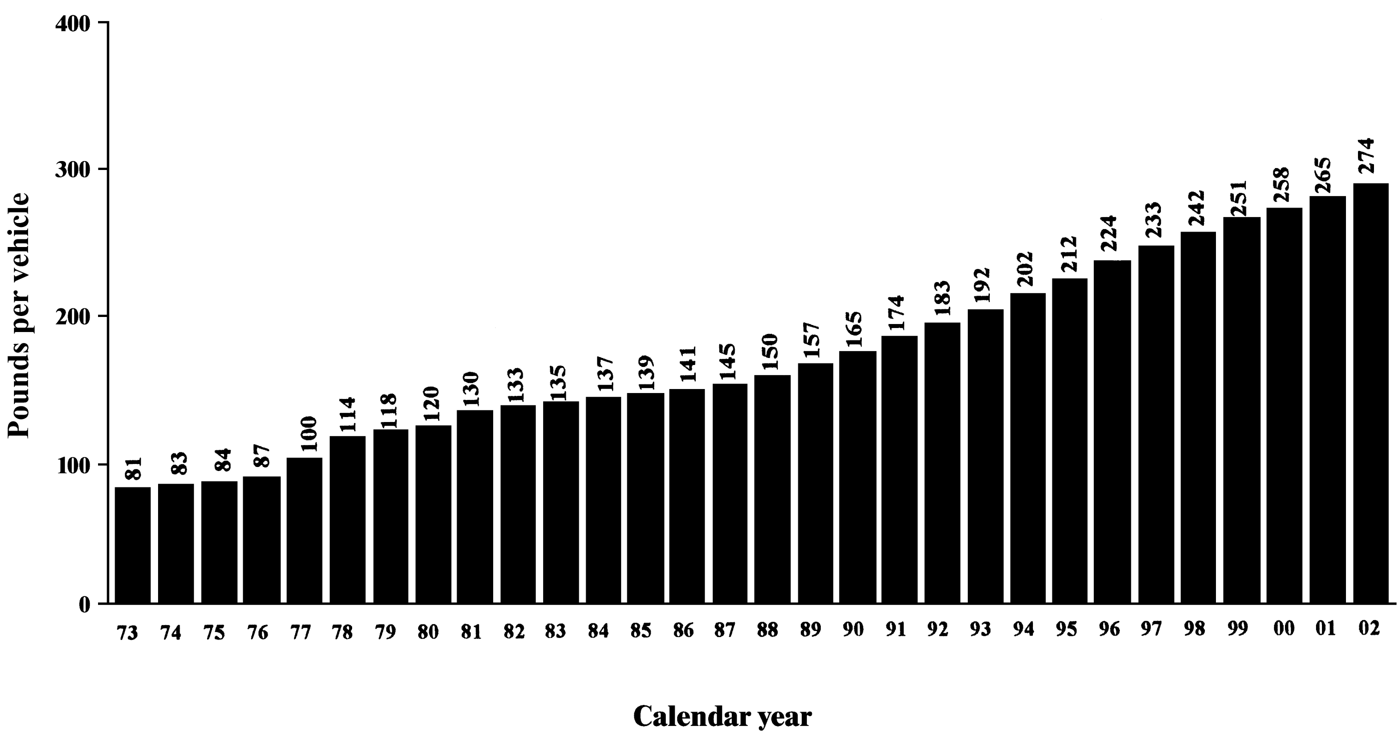

Fig. 1.6 North American light vehicle change in aluminum content, 1973 to 2002

facturing objectives, component performance criteria, and economic targets.

This reference volume is not intended as a guide to producing aluminum alloy castings; for example, it does not cover the details of how to design and build molds, inject the molten alloys, and sequence the finishing process. For more information on such matters, the reader is referred to the excellent aluminum casting industry publications of the American Foundry Society and similar organizations (Ref 1, 6–9) plus those of the Aluminum Association (Ref 10–12). For those interested in a broader overview of the entire aluminum industry, D.G. Altenpohl's volume (Ref 13) is recommended.

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