

Advances in Metallic Alloys
A series edited by **J.N. Fridlyander** and **D.G. Eskin**

Physical Metallurgy of Direct Chill Casting of Aluminum Alloys

DMITRY G. ESKIN

 **CRC Press**
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of Direct Chill Casting
of Aluminum Alloys

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A series edited by **J.N. Fridlyander**, *All-Russian Institute of Aviation Materials, Moscow, Russia* and **D.G. Eskin**, *Netherlands Institute for Metals Research, Delft, The Netherlands*

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List of Symbols and Abbreviations

| | |
|--------------------|---|
| 1D | one-dimensional |
| 2D | two-dimensional |
| 3D | three-dimensional |
| A | a constant |
| Bi | Biot number |
| C_0 | nominal alloy composition |
| C_E | eutectic composition |
| $C_L; C^L$ | solute concentration in the liquid at the solid/liquid interface |
| C_{limit} | limit solubility of a solute in aluminum |
| $C_S; C^S$ | solute concentration in the solid at the solid/liquid interface |
| C_{SS}^L | solute concentration in the supersaturated liquid at the solid/liquid interface |
| D | billet diameter |
| D_{gr} | grain size |
| D_S | diffusion coefficient of a solute in the solid phase |
| E | Young's modulus |
| Eq, eq | equilibrium |
| F_z | separation force |
| G | shear modulus |
| G | thermal gradient, temperature gradient |
| H | depth of the sump |
| K | partition coefficient |
| K | permeability |
| L | liquidus isotherm |
| L_m | vertical dimension of the mushy zone |
| N | amount (density) of particles in the melt |
| N_i | principal quantum number of the i electron shell (A_i for aluminum) |
| NEq, neq | nonequilibrium |
| P | undercooling parameter |
| Pe | Peclet number |
| Q | flow rate |
| Q | growth restriction factor |
| Q_w | water flow rate |
| R | billet radius; regression coefficient |
| S | solidus isotherm |
| S_e | interfacial area concentration of the grain envelope |
| S_v | specific surface area of the solid phase |
| T | temperature |
| T_{coh} | coherency temperature |
| T_m | melting temperature |

| | |
|--------------------------|---|
| T_{surf} | surface temperature |
| T^{th} | temperature of thermal contraction onset (rigidity) |
| \dot{T} | cooling rate |
| V_c | cooling rate |
| V_{cast} | casting speed |
| V_{growth} | interfacial growth velocity |
| V_L | volume of liquid |
| V_s | solidification rate (linear velocity of the solidification front) |
| V_{shr} | shrinkage-flow velocity |
| V | volume element |
| a_{cr} | critical defect size |
| b | liquid film thickness; coefficient |
| c | specific heat |
| c | tortuosity constant of dendrite network |
| d | (secondary) dendrite arm spacing |
| f | fraction of nucleating particles |
| f_e | feeding rate |
| f_e | volume fraction of grain envelope |
| f_l | liquid fraction |
| f_r | shrinkage (contraction) rate |
| f_s | solid fraction |
| g | gravity acceleration |
| h | melt level |
| k_D | permeability coefficient |
| k_{KC} | Kozeny–Carman constant |
| m | microstructure parameter |
| m | liquidus slope |
| n | coarsening exponent, material parameter, coefficient |
| n_a | number of atoms in a stable nucleus |
| n_i | number of electrons on the i level (A_i for aluminum) |
| p_r | reserve of plasticity |
| P_s | effective feeding pressure |
| q | heat transfer coefficient |
| q/A | heat flux through surface A |
| t | running (solidification) time |
| t_f | local solidification time |
| t_R | time available for stress relief |
| t_v | vulnerable time period |
| v | average (superficial) flow velocity |
| $\dot{\epsilon}$ | thermal strain rate |
| ΔH_f | enthalpy (latent heat) of fusion |
| ΔH_v | enthalpy (latent heat) of evaporation |
| Δl_{exp} | pre-shrinkage expansion |
| ΔP | pressure drop |
| ΔP_{cr} | critical pressure drop |
| ΔP_{mech} | pressure drop due to the deformation-induced fluid flow |

| | |
|----------------------------------|--|
| ΔP_{sh} | pressure drop due to the solidification shrinkage |
| ΔS_f | volumetric entropy of fusion |
| ΔT_0 | solidification range |
| ΔT_{br} | brittle temperature range |
| ΔT_c | constitutional undercooling |
| ΔT_n | undercooling required for nucleation |
| Γ | Gibbs–Thompson coefficient |
| Ξ | solubility supersaturation |
| Ω | grain-refining criterion |
| α | angle between the tangent to the coherency isotherm and the horizon; coefficient |
| α_n | angle between the billet axis and the normal to the solidification front |
| α' | Fourier number |
| β | volumetric shrinkage; coefficient |
| β_d | intradendritic permeability |
| β_l | extradendritic permeability |
| β_T | volumetric thermal expansion coefficient |
| ε | total solidification shrinkage; strain; deformation |
| ε_{app} | actual (apparent) strain |
| $\varepsilon_{\text{free}}$ | free thermal contraction strain |
| ε_{int} | internal strain |
| ε_p | elongation to failure |
| ε_{th} | linear thermal contraction |
| φ | porosity |
| γ | surface tension; effective fracture surface energy |
| λ | thermal conductivity |
| λ_1 | primary dendrite arm spacing |
| λ_2 | secondary dendrite arm spacing |
| μ | dynamic viscosity of the liquid |
| ν | Poisson's ratio |
| θ | dihedral angle |
| ρ | density |
| σ_{fr} | fracture stress |
| σ_{ls} | solid/liquid interfacial energy |
| ψ | shape factor |
| $\psi(f_s)$ | function discriminating the mechanical behavior of a semi-solid sample |
| ζ_{cr} | critical feeding rate |
| $\Delta\varepsilon_{\text{res}}$ | reserve of technological strain (plasticity) |
| CET | columnar-to-equiaxed transition |
| DAS | dendrite arm spacing |
| DC casting | direct chill casting |
| El | tensile elongation |
| EMC | electromagnetic casting |
| EPMA | electron probe microanalysis |

| | |
|------|--|
| FEM | finite element method |
| GR | grain refined |
| HCS | hot cracking susceptibility |
| LTEC | linear thermal expansion coefficient |
| NES | nonequilibrium solidus |
| NGR | not grain refined |
| PFT | pseudo front tracking model |
| SC | similarity criterion |
| SEM | scanning electron microscope |
| SPV | maximum volumetric flow rate per unit volume (feeding term) |
| SRG | rate of volumetric solidification shrinkage |
| TCC | thermal contraction coefficient |
| UTS | ultimate tensile strength |

Preface

Direct chill (DC) casting is not a new technology; it has been known for more than 70 years. Despite important developments in this casting technique over the years, the core features have remained the same, and the prototypes invented in the 1930s are still evident in modern DC casting machines. For more than 60 years, this casting technology has been the primary means for producing extrusion billets and rolling ingots from a wide range of aluminum wrought alloys. There is no other technology on the horizon that could replace DC casting. This book is not about the technology of casting, though some principles and milestones are discussed in Chapter 1.

The principles of solidification and structure formation are very important for understanding the quality and performance of billets and ingots produced by DC casting. This book is not about the fundamentals of solidification, but Chapter 2 gives all necessary information for understanding the formation of structure and defects during casting of aluminum alloys.

Today most efforts in the field of solidification and practical casting are concentrated on computer modeling and process simulation. Physicists and mathematicians are replacing materials scientists at the forefront of research. This book is not about modeling and simulation, but the results obtained using these methods are widely used throughout the book as tools for interpreting experimental results and for studying the physical mechanisms involved.

At this point, the reader might ask: What is this book about? The answer is in the book title: the book is about physical metallurgy of DC casting. This means that the formations of structure, properties, and defects in the as-cast material are considered in close correlation with the physical phenomena that are involved in the solidification and with the process parameters. There is a serious lack of such information in the Western literature.

The formation of structure in relation to the peculiarities of heat and mass flow during DC casting is the main subject of Chapter 3, while the formation of major defects—macrosegregation and hot cracking—is the topic of Chapters 4 and 5. Throughout the book, the formation of structure and defects is considered in relation to the main process parameters: casting speed, melt temperature, water-flow rate, and grain refinement.

In this book, I have tried to present a logical system of structure and defect formation based on the specific features of the DC casting process. The basis of this system is, on the one hand, melt flow and heat flow (cooling) in different parts of the solidifying domain and, on the other hand, kinetics of solidification and the solidification path of the alloy. The complexity of the mechanisms involved in the structure and defect formation is the main problem that frequently hinders clear understanding of the experimentally observed patterns. In this book, I try to single out these mechanisms and

demonstrate that the seemingly controversial results reported in the literature are, in fact, caused by different ratios of the same mechanisms.

This book is inspired by and based on results that have been obtained in the last 8 years from the extensive scientific program on solidification and casting of the Netherlands Institute for Metals Research. The scientific foundation for understanding DC casting was established long before that, by extraordinary scientists and visionaries such as W. Roth, W. Patterson, V. Kondic, S.M. Voronov, V.I. Dobatkin, and V.A. Livanov. Among these names, Roth, Dobatkin, and Livanov should be distinguished as three individuals who successfully combined the practical development of DC casting technology with fundamental studies. Dobatkin and Livanov have also written monographs (V.I. Dobatkin, *Direct Chill Casting and Casting Properties of Alloy*, 1948; *Ingots of Aluminum Alloys*, 1960; V.I. Livanov et al., *Direct Chill Casting of Aluminum Alloys*, 1977) that were published in the former Soviet Union and remain to date the only scientific books on DC casting. I frequently refer to these books because they are still very valuable in many respects. Two other important books provide a background for scientific understanding of structure and defect formation during solidification: *Solidification Processing* by M.C. Flemings (1974) and *Hot Tearing of Non-Ferrous Metals and Alloys* by I.I. Novikov (1966).

The current book is based on the important achievements of previous generations of scientists. We realize that we are building on an already existing foundation, and that we can only move forward if we have taken into account what has been achieved before us. Chapters 1, 4, and 5 include historic overviews of technologies, theories, and hypotheses that demonstrate the brilliant heritage we can utilize in our work.

The original data that are presented in this book result from a team effort. I would like to acknowledge the contribution of post-doctoral researchers Dr. Q. Du and Dr. R. Nadella and Ph.D. students Suyitno, J. Zuidema, A. Stangeland, V. Savran, A. Turchin, and D. Ruvalcaba, who actively participated in the solidification research. Our joint papers are extensively cited in the book. Technical assistance in setting up and performing experiments was provided by J.J. Jansen and J.J.H. van Etten, whose help and expertise are gratefully acknowledged.

I am a metals scientist who graduated from the distinguished Department of Metals Science of the Moscow Institute of Steel and Alloys. I am greatly indebted to my teachers, Professor V.S. Zolotovskiy and Professor I.I. Novikov, for the knowledge they imparted to me and for the passion and critical approach to the research they fostered in me. DC casting has been a familiar subject for me since childhood. My father, Professor G.I. Eskin, is a well-known scientist in solidification processing who worked with the renowned Professor V.I. Dobatkin for many years. It was, however, not until 1999 when I became involved in solidification science. Two professors gave me this opportunity: Professor S. Radelaar, then the scientific director and general manager of the Netherlands Institute for Metals Research, who hired me as a senior researcher and always supported me, and Professor L. Katgerman,

who heads the light-metals processing research at Delft University of Technology. I would like to express my profound gratitude to Professor Katgerman, who gave me many opportunities, supported me in my work, and shared with me his vast expertise. Many of the results presented in this book were obtained within the framework of the research program of the Netherlands Institute for Metals Research (www.nimr.nl), and I would like to thank Dr. S. Hoekstra for the opportunity to carry on our solidification research. Constant help and support from Corus Aluminium are also gratefully acknowledged.

Over the years I have met many individuals involved in solidification research all over the world who have impressed me with their knowledge, attitude, and experience, including Professors A. Mo, L. Arnberg, M. Rappaz, C. Beckermann, and Drs. R. Mathiesen, Ø. Nielsen, R. Kieft, W. Boender, A.L. Dons, G.-U. Grün, J. Grandfield, and J.-M. Drezet.

And finally, I would like to thank my father and mother for their love and encouragement. Special thanks go to my wife, Natasha, who courageously and critically read the drafts of this book.

I hope that this book will fill the gap in the literature on solidification processing and provide new insight and perspective for DC casting research. The book is written for a wide audience that includes scientists, engineers, postgraduate and graduate students, and hopefully can be easily understood by readers without a special background in the subject.

Dmitry G. Eskin

Author

Dmitry G. Eskin, Ph.D., received his M.Sc. and Ph.D. in physical metallurgy in 1985 and 1988, respectively, from the Moscow Institute of Steel and Alloys (Technical University). He worked at the Baikov Institute of Metallurgy (Russian Academy of Sciences) until 1999, researching precipitation hardening, alloy development, and phase composition of aluminum alloys. Since 1999, he has worked at the Netherlands Institute for Metals Research in Delft, the Netherlands. As a senior scientist and fellow, Dr. Eskin is involved in an extensive research program on solidification phenomena in light alloys, including industrial applications. The focus of this research is the interconnection among solidification parameters, as-cast structure, and casting defects. A well-known specialist in the field of aluminum alloys, Dr. Eskin has published more than 90 scientific papers and co-authored three monographs.

1

Direct Chill Casting: Development of the Technology

Direct chill casting of aluminum alloys, commonly known as DC casting, is an example of a technology that appeared just in time to serve the needs of the industry. Before discussing the history of DC casting, we will briefly consider the history of aluminum.

Aluminum is a “young” metal whose existence was established only 200 years ago. However, Pliny the Elder mentions a strange, light, and silvery metal in his *Historia Naturalis*, which might indicate that aluminum may have been discovered accidentally and then forgotten almost 2000 years ago:

One day a goldsmith in Rome was allowed to show the Emperor Tiberius a dinner plate of a new metal. The plate was very light, and almost as bright as silver. The goldsmith told the Emperor that he had made the metal from plain clay. He also assured the Emperor that only he, himself, and the Gods knew how to produce this metal from clay. The Emperor became very interested, and as a financial expert he was also a little concerned. The Emperor felt immediately, however, that all his treasures of gold and silver would decline in value if people started to produce this bright metal of clay. Therefore, instead of giving the goldsmith the regard expected, he ordered him to be beheaded.

Modern scientists and inventors were more fortunate and, as a result of their efforts, we now have a variety of aluminum alloys that are used in a wide range of applications.

In 1808 the Englishman H. Davy established the existence of a new metal that he called alumium. This name later was changed to aluminum (U.S.A.) and aluminium (U.K.). It was not until 1825 that minute amounts of pure aluminum were extracted by the Dane N.C. Oersted. Between 1827 and 1845, the German F. Wöhler developed the first process to produce aluminum powder by reacting potassium with anhydrous aluminum chloride. He also determined some physical properties of aluminum, including density, which appeared to be the most remarkable characteristic of the new metal. Jules Verne wrote in his “From the Earth to the Moon” in 1865 about the material of his fictitious space capsule:

This valuable metal possesses the whiteness of silver, the indestructibility of gold, the tenacity of iron, the fusibility of copper, the lightness of glass. It is easily wrought, is very widely distributed, forming the base

of most of the rocks, is three times lighter than iron, and seems to have been created for the express purpose of furnishing us with the material for our projectile.

The era of light metals would have begun if not for one vital problem—the price. Despite some improvement to Wöhler’s process in 1854 by the Frenchman H.E.S.-C. Deville, aluminum remained very expensive, in fact it cost more than platinum and gold. An ingot of aluminum was presented at the Paris World Exhibition in 1855 as a new precious metal. During the next 30 years aluminum remained an exotic, expensive material used in jewelry, royal cutlery, plates, and parade decorations. “Silver from clay” was an unofficial name of the metal. Napoleon III allowed only the most honored guests to eat from aluminum plates; the others were forced to settle for silver and gold ones. In 1889 the British Royal Society presented a set of scales made from gold and aluminum to the Russian scientist D.I. Mendeleev to honor his achievements in chemistry. In 1886, two 22-year-old scientists, Paul-Louis Toussaint Héroult of France and Charles Martin Hall of the United States, independent of each other and in different countries, invented a commercial process of producing pure aluminum by electrolysis of alumina dissolved in molten cryolite. Their process, the Hall–Héroult process, is still used today. In 1888, together with A.E. Hunt, C.M. Hall founded the Pittsburgh Reduction Company, now known as the Aluminum Company of America (ALCOA). By 1914, the cost of a kilogram of aluminum was down from \$40 in 1860 to 40¢, and aluminum was no longer considered a precious metal. The annual production went from 15 tons in 1885 to 65,000 tons in 1913. Simultaneous or almost simultaneous discoveries and inventions occur frequently in the history of aluminum. This is an unmistakable sign of the need for such discoveries and inventions and the research that is under way throughout the industrial world.

Remarkably, Jules Verne foresaw the most promising application for aluminum—airspace vehicles. The first aircraft that took to the air on December 17, 1903 at Kitty Hawk was designed and built by the Wright Brothers. Their biplane was made from wood and fabric and powered by a 12-horsepower, 4-cylinder engine. And yet, even in this first successful attempt to fly with a heavier-than-air machine, aluminum had a vital role as a one-piece cast crankcase of the engine.

One more discovery was needed to fully implement the potential of aluminum in construction. Although castings from aluminum alloys were occasionally used in manufacturing some details, the strength of deformed aluminum was not sufficient for its use as a structural material. The breakthrough came in 1908–1909 when A. Wilm of Germany found that the strength of an Al–Cu alloy would increase after several days of so-called “natural aging” after quenching. He patented the alloy and the technology of its heat treatment as “duralumin.” Now aluminum alloys could acquire the mechanical properties that would make them suitable for use in structures. The true era of aluminum had begun. It is interesting to note that the nature of hardening zones that cause room-temperature aging was discovered in

1938 simultaneously and independently by A. Guinier in France and G.D. Preston in Great Britain.

Not surprisingly, the demand for wrought aluminum alloys came from the aircraft industry, fueled by World War I and later by increased requirements for speedy delivery of mail. The first all-metal (mainly duralumin) airplanes were built by the German designer H. Junkers in 1915–1916. Junkers started from steel (J1) and then shifted to duralumin in the J7 and J9. The fuselage was made from plane and corrugated sheets. In 1919 Junkers together with O. Reuter designed the first all-metal passenger plane, the F13 (J13). This design served as a benchmark for several aircrafts made in different countries [1]. The Soviet Union was quick to follow. After World War I, Germany was not allowed to manufacture military aircraft, so the U.S.S.R. provided concessions for Junkers to build his aircraft in Moscow from 1923 to 1927. The designer A.N. Tupolev made his first aluminum plane, the ANT-2, in 1924 using Russian-made duralumin. Just a year later the United States followed with the passenger Stout Air Sedan and Ford 3-AT. Tupolev made a very large, all-metal heavy bomber, the ANT-4 (TB1), in 1925. This plane was 18 m long, with a 28.7-m wing span, and was powered by two engines. In the late 1920s, Ford produced several passenger planes, including the famous 4-AT “Tin Goose.” Despite all these efforts, only 5% of all aircraft in production by 1930 were of all-metal construction. In the 1930s the corrosion resistance of duralumin had been improved by cladding with pure aluminum, and a wide variety of airplanes were manufactured from aluminum alloys. The U.S.S.R. continued to design and build record-size heavy bombers and passenger airliners including the ANT25 in 1933 that flew 11,500 km nonstop in record time, in 1937 from the U.S.S.R. to the United States; the 8-engine ANT20 “Maxim Gorky” made in 1934 that was the largest aircraft of its time (33 m long with a 63-m wing span, and a passenger capacity of 48); and the ANT37 (DB2), a long-range bomber put in service in 1936. Junkers in Germany designed and produced midsize and practical passenger planes such as the Ju60 in 1932 and the Ju160 in 1934. In the United States Boeing started to produce passenger planes, the Boeing 200 in 1930 and the Boeing 247 in 1933, and was joined by Douglas with the DC1–DC3 in 1933–1935. The DC3 was the first aircraft that actually enabled airlines to make money from passenger rather than mail transport. In addition to the “main players”—Germany, the United States, and U.S.S.R.—other countries made their efforts as well. France manufactured the Devoitine D332 in 1933, and the United Kingdom produced the Ensign-1 in 1934 and the de Havilland DH95 in 1938. Some of the benchmark planes are shown in Figure 1.1 [1]. Throughout the industrialized world all-metal, mainly aluminum aircraft were dominant by the late 1930s. It became obvious that mass fabrication of wrought aluminum products was necessary to sustain the development of military and civil airplanes. Let us now consider the manufacturing technology for large-scale wrought aluminum ingots and billets required for rolling, extrusion, or forging.

From 1924 to 1939 the average weight of an aluminum flat ingot cast in a permanent mold increased from 20 to 500 kg [2]. By the mid-1930s most

**FIGURE 1.1**

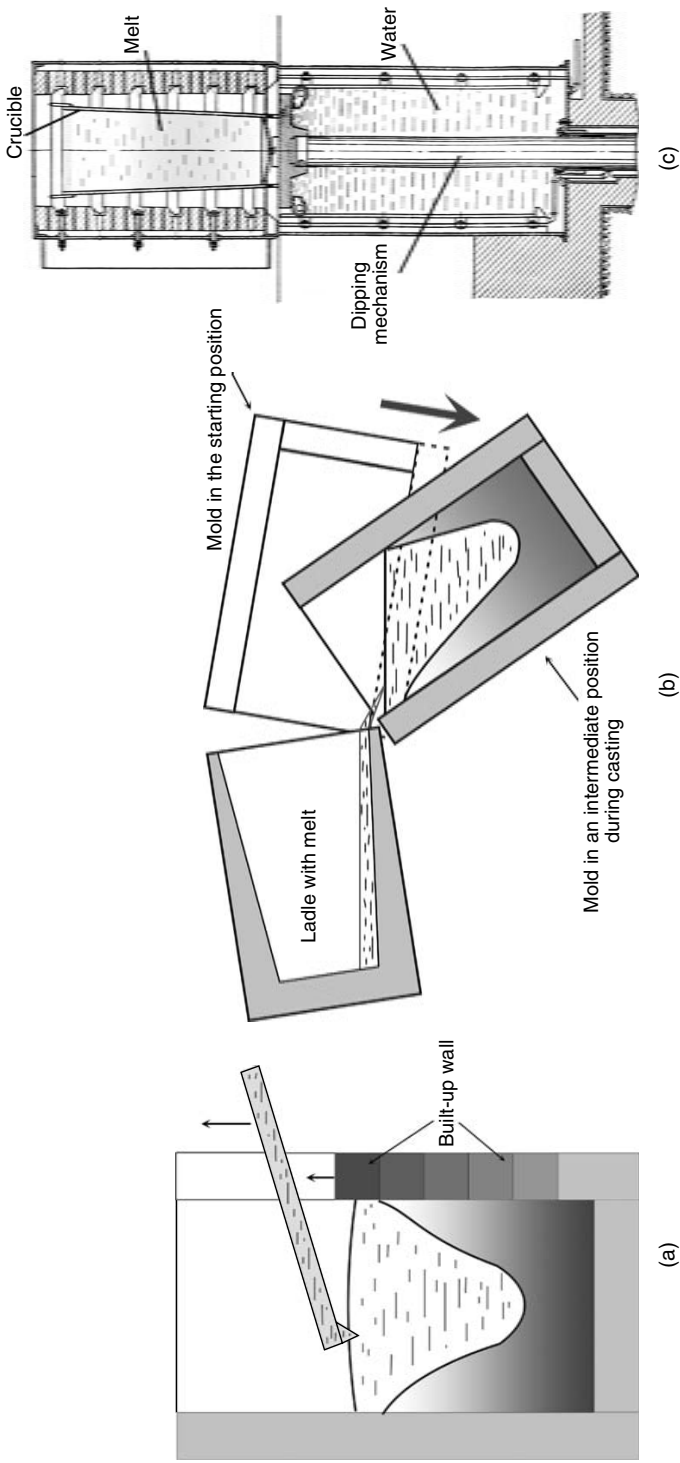
Examples of all-metal airplanes designed and built in the 1920s and 1930s: (a) the Junkers F13 (1919, Germany); (b) the ANT-4 (1925, U.S.S.R.); (c) the Ford 4-AT (1926, U.S.A.); (d) the Junkers Ju60 (1932, Germany); (e) the Boeing 247 (1933, U.S.A.); (f) the ANT-20 (1934, U.S.S.R.); (g) the Douglas DC-3 (1935, U.S.A.); and (h) the ANT-37 (DB2) (1936, U.S.S.R.) [1].

bulk ingots and billets were made by permanent-mold casting, while the increased volume and cross-section resulted in exponential deterioration of the structure and properties of the cast metal. Three main problems were intrinsically present in permanent-mold casting: turbulence during pouring; air-gap formation during cooling; and variable low cooling rate across the ingot. Several innovations were proposed to deal with these drawbacks. In the Züblin method the mold was filled gradually from the bottom to the top by moving the feeding nozzle upward and corresponding closure of the sidewall [3, 4]. This technique helped avoid large temperature gradients

and decreased chemical and structure inhomogeneity of the ingot. Another widely used technique was the so-called tipping mold, the main purpose of which was to avoid turbulence while filling the large volume. The idea was the same as the process of filling a glass with beer in order to avoid too much foaming: one starts to fill the tilted glass by pouring the beer along the glass wall and gradually straightens the glass until it is completely full without foam. Another casting technology that was a transition stage to the direct chill casting was casting by dipping the filled mold gradually into the water [5]. With this technique, solidification was almost directional from the bottom to the top and the solidification front was flat. As a result, the thermal gradients were low, and large ingots of $800 \times 1300 \text{ mm}^2$ could be cast. Figure 1.2 illustrates schematically these methods of casting. However, the problems of air-gap and low cooling rates, and thus the problems of uniform structure and properties, remained unsolved and required revolutionary change in technology. It was absolutely clear that there was no further room for improvement in the permanent-mold casting of large ingots and billets.

In response to these demands, German and American engineers devised a solution that addressed two problems successfully and simultaneously: control of solidification and production of large ingots and billets. The solution was in the modification of a so-called continuous casting process that had been proposed and sluggishly developed for almost 80 years but never used in mass production.* Henry Bessemer, the inventor of modern steelmaking, suggested in 1856 the first method of steel strip casting by pouring the melt in the opening between two rotating wheels [6]. In 1886 B. Atha of the United States suggested casting molten steel into a high, water-cooled, bottomless mold and extracting the resulting billet with withdrawal rolls [6]. This method was used for semi-commercial production of $100 \times 100 \text{ mm}$ steel bars in the early twentieth century. However, these inventions had limited, if any, application, and the continuous casting of steel was not in high demand until the 1950s. A similar technique was developed by Siegfried Junghans in the early 1930s [7]. His machine was initially used at Wieland-Werke in Germany for casting brass [4]. The mold consisted of a copper tube open at both sides and surrounded by a water jacket. The melt was fed into the mold from the top and the solid part was withdrawn by rolls from the bottom. The melt feeding was adjusted to the withdrawal speed by a special system in such a way that a constant melt level was maintained in the mold. The mold was lubricated and given an up-and-down oscillating movement to prevent the sticking of the solid metal to the mold walls. Flying saws were positioned in the pit below the installation for continuous cutting of the billet into required lengths. This successful scheme was widely used for casting copper and aluminum alloys in Germany, the United States, and the U.S.S.R. Figure 1.3 depicts the Junghans method of continuous casting. Junghans later added

* The vertical DC casting of aluminum alloys is the main subject of this book. Other types of continuous casting are mentioned here only as predecessors or analogs of vertical DC casting.

**FIGURE 1.2**

Some typical methods used for casting large ingots and billets in permanent molds: (a) the Zibbin mold with a feeding trough and a built-up wall [4]; (b) a tipping mold in two positions [4]; and (c) a mold with a melt before being dipped in a water tank [5].

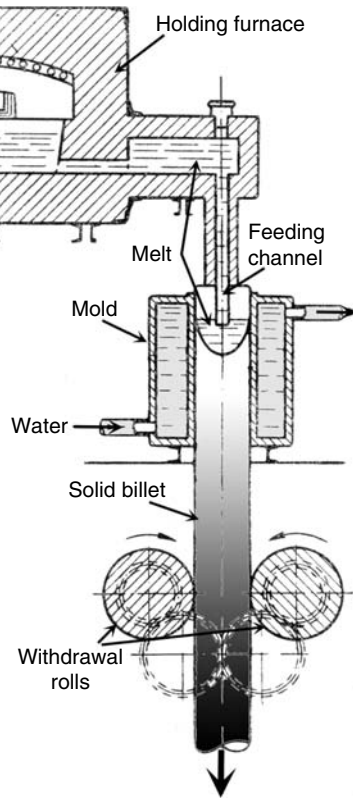


FIGURE 1.3

A diagram of Junghans method of continuous casting [8].

water spraying directly on the billet and made several innovations to the proper melt feeding/distribution system. Dobatkin [8] mentions that the maximum casting speed achieved for aluminum alloys with the Junghans machine was 300 mm/min for relatively small rods.

Compared with permanent-mold casting, the Junghans method offered the following advantages [9]:

- A truly continuous process with the possibility of advanced automation that increased productivity with less manpower
- Reproducible casting regimes that allowed the reproducible quality of billets
- Improved feeding of the central portions of billets with a correspondingly increased soundness of billets
- More uniform structure across the billet
- Better removal of gases during casting through the liquid portion of the billet
- Less scraped material

At the same time, this method did not solve all problems. The following drawbacks remained, most of which were related to the fact that the heat was still extracted through the walls of the mold [9]:

- Air gap formation, deep sump, and high thermal gradients
- Macrosegregation and inhomogeneous structure in large billets 300–500 mm in diameter
- Low casting speeds
- Need for a long mold with high surface quality requirements

To eliminate these shortcomings, it was necessary to develop a technology where the heat would be extracted mainly through the solid part of the casting. As a result, the sump of the casting would be shallower and the solidification profile would be flatter. The macrosegregation, structure inhomogeneity, and radial stresses would be much less pronounced. These needs were met by a new casting technology developed, again almost simultaneously and independently, in Germany and the United States. The technology was given the German name “Wasserguß” or “water-casting,” and was later called “direct chill casting.” Berthold Zunkel in 1935 [10], Walter Roth in 1936 [11], and William T. Ennor in 1938 [12] filed and subsequently received patents for the casting technology with several common features. Melt was poured from the top in an opened, relatively short, water-cooled mold that at the beginning is closed from the bottom by a dummy block connected with a hydraulic or mechanical lowering system. After the melt level in the mold reaches a certain level, the ram is lowered and the solid part of the billet or the ingot is extracted downward. The melt flow rate and the casting speed are adjusted in such a way that the melt level in the mold remains constant. As soon as the solid shell emerges from the bottom part of the mold, water is applied to the surface in the form of spray or water film. Cooling of the solid billet (or ingot) is further intensified by lowering it into a pit filled with water. The process is semi-continuous. As soon as the ram reaches its lowest position in the pit, the casting is stopped and the billet (or ingot) is removed from the pit. Figure 1.4 shows schematic drawings of these three inventions, clearly demonstrating that their similarities are more important than any differences. The new casting technology provided flexibility in casting applications. Trials started immediately with round billets, rectangular ingots (or rolling slabs), and hollow billets (pipes). In addition, multiple casting was possible with several molds positioned on a single casting table. DC-casting inventions were commercialized in Germany at Vereinigte Leichtmetall-Werke beginning in 1936 [4] and in the United States at ALCOA from 1934 [13]. The water cooling or direct chill in these first patents was done either by dipping the billet directly into the water bath or by spraying water onto the surface using separate sprinklers located along the billet length. Already in his 1937 patent application in Great Britain (GB Patent 492216) Roth suggested using openings in the lower part of the water-cooled mold for spraying the coolant onto the billet surface. Roth, Patterson, and Kondic

were also among the first to publish scientific papers based on extensive research of this new technology [14–18]. In 1939, the U.S.S.R. began extensive work on the development and use of DC casting of aluminum alloys, building mainly on the German inventions as shown in Figure 1.4d [8]. This rapid advance was facilitated by close economical links between the U.S.S.R. and Germany with many Russian and German engineers exchanging ideas and technological knowledge. Well-known names in Russian DC casting include S.M. Voronov, V.A. Livanov, R.I. Barbanel, and V.I. Dobatkin. Extensive reports on the Russian experience in DC casting and physical metallurgy of the process were published immediately after World War II [8, 9, 19]. Roth, Livanov, and Dobatkin recognized the important role of heat transfer, thermal contraction, and the dimensions of the semi-solid region in the billet and made the first attempts to explain the formation of hot and cold cracks, macrosegregation, and the homogeneity of structure and properties distribution.

The early reports on the application and mastering of the new technology highlight the great difficulties that engineers had to overcome on the casting floor. In addition to mechanical difficulties, one of the main problems reported was splitting and fracture of ingots, especially from high-strength alloys such as duralumin and emerging Zn-containing aluminum alloys [13]. Today we still face these problems, known as cold cracks and hot tearing. It was soon acknowledged that the main drawback of DC casting that caused cracking problems was the high thermal gradient between the surface and the interior of the billet (ingot) that resulted from direct cooling with water. Kondic put it this way: “The problem of continuous casting is essentially a matter of heat exchange between the metal cast and the cooling medium” [17]. Another problem was bleed-out, when the solid shell was fractured below the mold and the melt went through it. On the other hand, high cooling (and solidification) rates achieved during DC casting, especially in short molds, were advantageous for structure formation, producing fine and homogeneous structure across the billet (ingot). Livanov wrote in 1945: “The essence of direct chill casting is the possibility to sharply increase the cooling rate” [19].

Kastner suggested two ways of decreasing the danger of cracking and bleed-outs: either increase the distance between the point where direct cooling was applied and the bottom of the mold or decrease the casting speed in such a way that the billet was solidified completely over the whole cross-section before it reached the region of direct cooling [4]. Later, it was shown that sound billets and ingots could be obtained under a variety of conditions, provided the casting processes were well understood.

Direct chill casting had a unique feature that distinguished it from other casting techniques. The solidification occurred in a narrow layer of the casting inside and below the mold. During the steady-state stage of casting, the shape and the dimensions of this region remained constant and reproducible from one heat to another. By regulating the melt distribution during feeding the mold, cooling conditions inside the mold, direct cooling below the mold, and the casting speed, the shape and dimensions of the solidification region

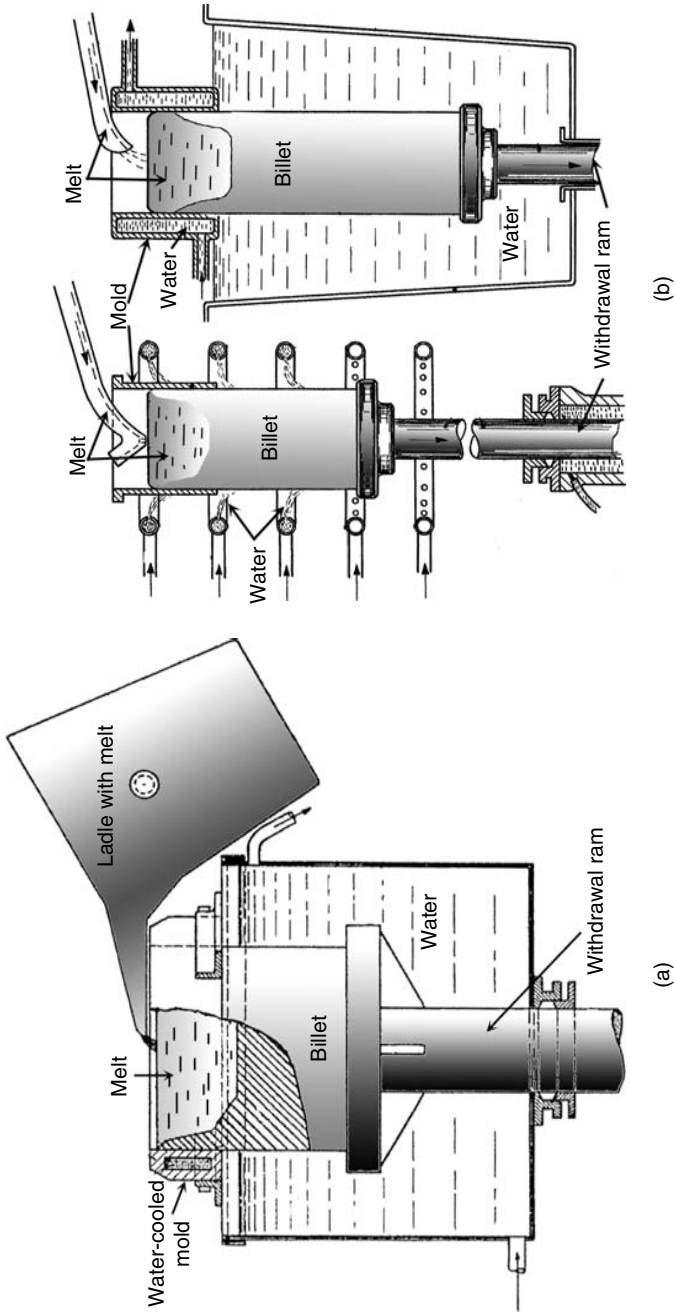


FIGURE 1.4 DC casting methods patented by Zunkel [10] (a), Roth [11] (b), and Ennor [12] (c), and a scheme of a working DC casting machine used in the 1940s [8] (d).

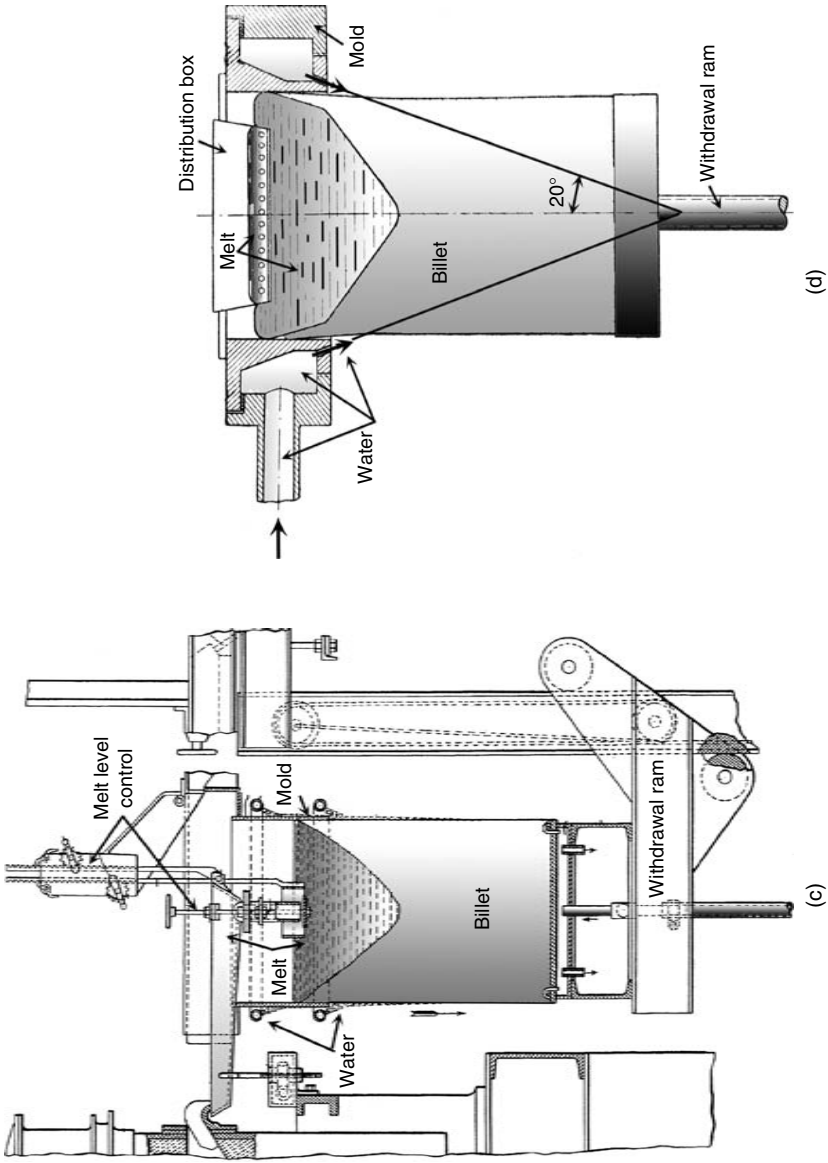


FIGURE 1.4 (Continued)

could be controlled. Because shape and dimensions determined the thermal gradient and were responsible for cracking, macrosegregation, and structure homogeneity, the occurrence of these defects could also be controlled.

Determination of a correct casting recipe for each alloy and size was essential. The main rules were formulated as follows [8, 19]. The melt level in the mold should be minimum; the water should be applied onto the billet surface as close to the bottom part of the mold as possible and at the minimum angle to the billet axis; and the melt should be evenly fed into the sump using special distribution boxes or bags. Maintaining these rules, Dobatkin reported that the optimal casting speed for 400-mm billets from high-strength aluminum alloys ranged between 40 and 85 mm/min [8]. The interrelation between the casting speed and the shape and dimensions of the sump and the transition region (between liquidus and solidus isotherms) was quickly recognized and main relationships were established between the physical properties of the alloy, the dimensions of the billet, and the process parameters [8, 15, 19]. Roth showed that the depth of the billet sump (H) is directly proportional to the casting speed (V_{cast}) and to the squared radius (R) [15, 16]:

$$H = AV_{\text{cast}}R^2 \quad (1.1)$$

This dependence was confirmed by Livanov [19] and Dobatkin [8].

Livanov found out that the solidification rate (the velocity of the solidification front) depends on the casting speed as

$$V_s = V_{\text{cast}} \cos \alpha_n, \quad (1.2)$$

where α_n is the angle between the billet axis and the normal to the solidification front [19]. As a result, the solidification rate is a function of the shape of the solidification front and is usually maximum in the center and at the periphery of the billet. It was also shown that the ratio between the sump depth and the billet diameter can be maintained constant if $V_{\text{cast}}R = \text{const}$ [8]. However, for each billet size and alloy there exists a maximum solidification rate that cannot be exceeded by further increasing the casting speed [8]. This maximum solidification rate is lower for larger billet diameters. These fundamental relationships provided the basis for scaling up the technology to very large castings. Today round billets more than 1000 mm in diameter and 4700 mm long and ingots over $2400 \times 1000 \text{ mm}^2$ in cross-section and 4400 mm long can be successfully cast from high-strength aluminum alloys [20].

Extensive research undertaken in close connection with industrial DC casting produced outstanding results. By the end of World War II all high-strength aluminum alloys in the United States and the U.S.S.R. were cast using this new technique.

The comparison of DC casting and Junghans' method showed the following advantages of the former [9]:

- Considerably reduced centerline segregation
- Increased density of the central portion of a billet