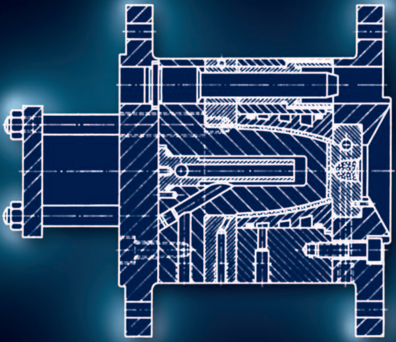
How to Make Injection Molds

Third Edition

Menges / Michaeli / Mohren



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Georg Menges
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Preface to the 3rd Edition

Injection molds are high-precision tools whose smooth-operation on a day-to-day basis is vital to the economic success of many plastics processors. Consequently, errors in design and construction of molds can have grave consequences.

That is where this book comes in. Building on the earlier editions, it draws extensively both on the literature and on the development work carried out at the Institute for Plastics Processing in the Technical University of Aachen with the aid of substantial private and public research funding.

We are especially grateful to those who participated in this edition and to those who laid the foundations for it in earlier editions, namely Dr. H. Bangert, Dr. P. Barth, Dr. W. Hoven-Nievelstein, Dr. O. Kretschmar, Dr. M. Paar, Dr. G. Pötsch, Dr. Th. W. Schmidt., Dr. Ch. Schneider, Prof. E. Schürmann and Prof. S. Stitz.

We are indebted to the co-workers and students in the institute who contributed to the success of this book through their unstinting work and their personal commitment. As they are too numerous to mention, we trust that Ms. G. Nelissen, Ms. I. Zekorn and Mr. W. Okon will accept our thanks on their behalf. Finally, we extend our appreciation to Carl Hanser Verlag, and especially to Dr. W. Glenz and Mr. O. Immel, for taking the manuscript and turning it into such a distinctive and attractive book.

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Contents

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1 Materials for Injection Molds

The injection molding technique has to meet the ever increasing demand for a high quality product (in terms of both consumption properties and geometry) that is still economically priced. This is feasible only if the molder can adequately control the molding process, if the configuration of the part is adapted to the characteristics of the molding material and the respective conversion technique, and a mold is available which satisfies the requirements for reproducible dimensional accuracy and surface quality. Therefore injection molds have to be made with the highest precision. They are expected to provide reliable and fully repeatable function in spite of being under extreme loads during the molding process, and a long service life to offset the high capital investment. Besides initial design and maintenance while in service, reliability and service life are primarily determined by the mold material used, its heat treatment and the machining operations during mold making [1.1, 1.2].

Injection molding uses almost exclusively high-strength molds made of metals, primarily steel. While the frames are almost always made of steel, the cavities are frequently made of other high-quality materials – metals or nonmetals – and inserted into the cavity retainer plate. Inserts made of materials other than steel are preferably used for cavities that are difficult to shape. They are often made by electrodeposition.

Recently, nonmetallic materials have been growing in importance in mold construction. This is due on the one hand to the use of new technologies, some of which are familiar from prototype production, and especially to the fact that users wish to obtain moldings as quickly and inexpensively as possible that have been produced in realistic series production, so that they can inspect them to rule out weaknesses in the product and problems during later production. The production of such prototype molds, which may also be used for small and medium-sized series, as well as the materials employed, will be discussed later.

An injection mold is generally assembled from a number of single components (see Figure 4.3). Their functions within the mold call for specific properties and therefore appropriate selection of the right material. The forming parts, the cavity in connection with the core, provide configuration and surface texture. It stands to reason that these parts demand particular attention to material selection and handling.

Several factors determine the selection of materials for cavity and core. They result from economic considerations, nature and shape of the molding and its application, and from specific properties of the mold material. Details about the molded part should provide information concerning the plastic material to be employed (e.g. reinforced or unreinforced, tendency to decompose, etc.). They determine minimum cavity dimensions, wear of the mold under production conditions, and the quality demands on the molding with respect to dimensions and surface appearance. The market place determines the quantity of parts to be produced and thus the necessary service life as well as justifiable expenses for making the mold. The demands on the mold material, on its thermal, mechanical, and metallurgical properties are derived from these requirements. Frequently a compromise must be made between conflicting demands.

1.1 Steels

1.1.1 Summary

Normally, steel is the only material that guarantees reliably functioning molds with long service lives, provided that a suitable steel grade has been selected from the assortment offered by steel manufacturers and this grade has been treated so as to develop a structure that produces the properties required in use. This necessitates first of all a suitable chemical composition. The individual alloying elements, according to their amount, have positive as well as negative effects on the desired characteristics. Generally several alloying elements will be present, which can also mutually affect one another (Table 1.1). The requirements result from the demands of the molder and the mold maker. The following properties are expected from steels:

- characteristics permitting economical workability (machining, electric discharge machining, polishing, etching, possibly cold hobbing),
- capacity for heat treatment without problems,
- sufficient toughness and strength,
- resistance to heat and wear,
- high thermal conductivity, and
- corrosion resistance.

The surface contour is still mostly achieved by machining. This is time consuming and calls for expensive machine equipment and results in a surface quality which, in most cases, has to be improved by expensive manual labor. There are limitations to machining because of the mechanical properties of the machined material [1.9]. Steels with a strength of 600 to 800 MPa can be economically machined [1.2] although they are workable up to about 1500 MPa. Because a strength of less than 1200 MPa is generally not sufficient, steels have to be employed that are brought up to the desired strength level by additional treatment after machining, mostly by heat treatment such as hardening and tempering.

Such heat treatment imbues steels with the required properties, especially high surface hardness and sufficient core strength. Each heat treatment involves risks, though (distortion, cracking). Lest molds be rendered unusable by heat treatment, for those with large machined volumes and complex geometries, annealing for stress relief is suggested prior to the last machining step. Eventual dimensional changes from distortion can be remedied in the final step.

To avoid such difficulties steel manufacturers offer prehardened steels in a strength range between 1100 and 1400 MPa. They contain sulfur (between 0.06 and 0.10%) so that they can be machined at all. Uniform distribution of the sulfur is important [1.10]. The higher sulfur content also causes a number of disadvantages, which may outweigh the advantage of better machining. High-sulfur steels cannot be polished as well as steel without sulfur. Electroplating for corrosion resistance (chromium, nickel) cannot be carried out without flaws. In the event of repair work, they cannot be satisfactorily welded and are not suited for chemical treatment such as photochemical etching for producing surface textures.

Table 1.1 Effect of alloying elements on the characteristics of steels [1.3–1.8]

Alloying element →	C	Si	S	P	Cr	Ni	Mn	Co	Mo	V	W	Cu	Ti
↓ Property													
Strength	↑	↑	–	↑	↑	↑	↑	↑	↑	↑	↑	↑	–
Toughness	↓	↓	↓	↓	↓	↑	↓	↓	↓	↓	↓	–	↓
Notched impact strength	↓	↓	↓	↓	↓	–	–	–	–	–	–	–	–
Elongation	↓	↓	↓	↓	↓	↓	↓	–	↓	–	↓	–	–
Wear resistance	↑	–	–	–	↑	–	↑	–	↑	↑	↑	–	↑
Hardenability	–	↑	–	–	↑	↑	↑	–	↑	–	–	–	–
Hardness	↑	↑	–	–	↑	↑	–	↑	↑	↑	↑	–	–
Machinability	↓	↓	↑	↓	↓	↓	↓	–	–	↓	↓	–	–
Weldability	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	–	–	–
Ductility	↓	↓	↓	↓	↓	↑	↓	↓	–	–	↓	–	–
Malleability	↓	↓	↓	–	–	–	–	–	↓	–	↓	–	–
Heat resistance/red hardness	↑	↑	–	↑	↑	–	–	↑	↑	↑	↑	–	–
Overheating sensitivity	↓	↓	–	–	↑	↑	↓	↓	↑	↓	↑	–	↑
Retention of hardness	↑	↑	–	↑	↓	–	↑	↑	↑	↑	↑	–	–
Corrosion resistance	–	↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	–

In recent years, electric-discharge machining, including spark erosion with traveling wire electrodes, has become a very important method of machine operations for - heattreated steel without sulfur.

If a series of equal cavities of small size has to be made (e.g. typewriter keys), coldhobbing is an economical process. Steels suitable for this process should have good plasticity for cold working after annealing. Therefore soft steel with a carbon content of less than 0.2% is utilized.

After forming, they receive adequate surface hardness through heat treatment. Such hardening is made possible by carburizing. These case-hardening steels are an important group of materials for mold cavities.

Distortion and dimensional changes often occur as a side effect of heat treatment. Dimensional changes are caused by thermal stresses and changes in volume resulting from transformations within the steel. They are unavoidable. Distortion, on the other hand, is caused by incompetent execution of heat treatment before, during, or after the forming process, or by faulty mold design (sharp corners and edges, large differences in cross sections etc.). Deviation from the accurate shape as a consequence of heat treatment is always the sum of distortion and dimensional change. The two cannot be strictly separated. Figure 1.1 points out the various effects which cause configurational changes. Use of steels with a low tendency to dimensional changes reduces such effects to a minimum [1.11, 1.12].

Prehardened, martensitic hardenable, and through-hardening steels should be preferred in order to avoid distortion. Pretreated steels do not need any appreciable heat treatment after forming. The required wear resistance of these steel grades is achieved by a chemical process (e.g. chrome plating) or a diffusion process (e.g. nitriding at temperatures between 450 and 600 °C). Because of the low treatment temperature of 400 to 500 °C for martensitic steels, only small transformation and thermal stresses occur in these steels, and the risks generally associated with heat treatment are slight [1.13]. In through-hardening steels, the heat treatment causes a uniform structure throughout the cross section and thus no appreciable stresses occur.

The range of applications for through-hardening steels is limited, however, since the danger of cracking under bending forces is high, especially in the case of molds with large cavities. Demands for molds with a tough core and a wear-resistant, hardened surface are best met with case-hardening steels (e.g. for long cores or similar items).

High wear in use is most effectively countered with high surface hardness. The best hardening results and a uniform surface quality can be achieved with steels that are free from surface imperfections, are of the highest purity and have a uniform structure. Completely pure steels are the precondition for the impeccably polishable, i.e. flawless, mold surface required for processing clear plastics for optical articles. A high degree of purity is obtained only with steels that are refined once or more. Remelting improves the mechanical properties, too. These steels have gained special importance in mold making for producing cavity inserts.

The maximum abrasive strength is obtained with steels produced by powder metallurgy (hard-material alloys).

Mold temperature and heat exchange in the mold are determined by the plastic material and the respective molding technique. The thermal effect of the mold temperature during the processing of the majority of thermoplastics (usually below 120 °C) is practically insignificant for the selection of the mold material. There are, however, an increasing number of thermoplastics with melt temperatures up to 400 °C that require a constant mold temperature of more than 200 °C during processing. Mold

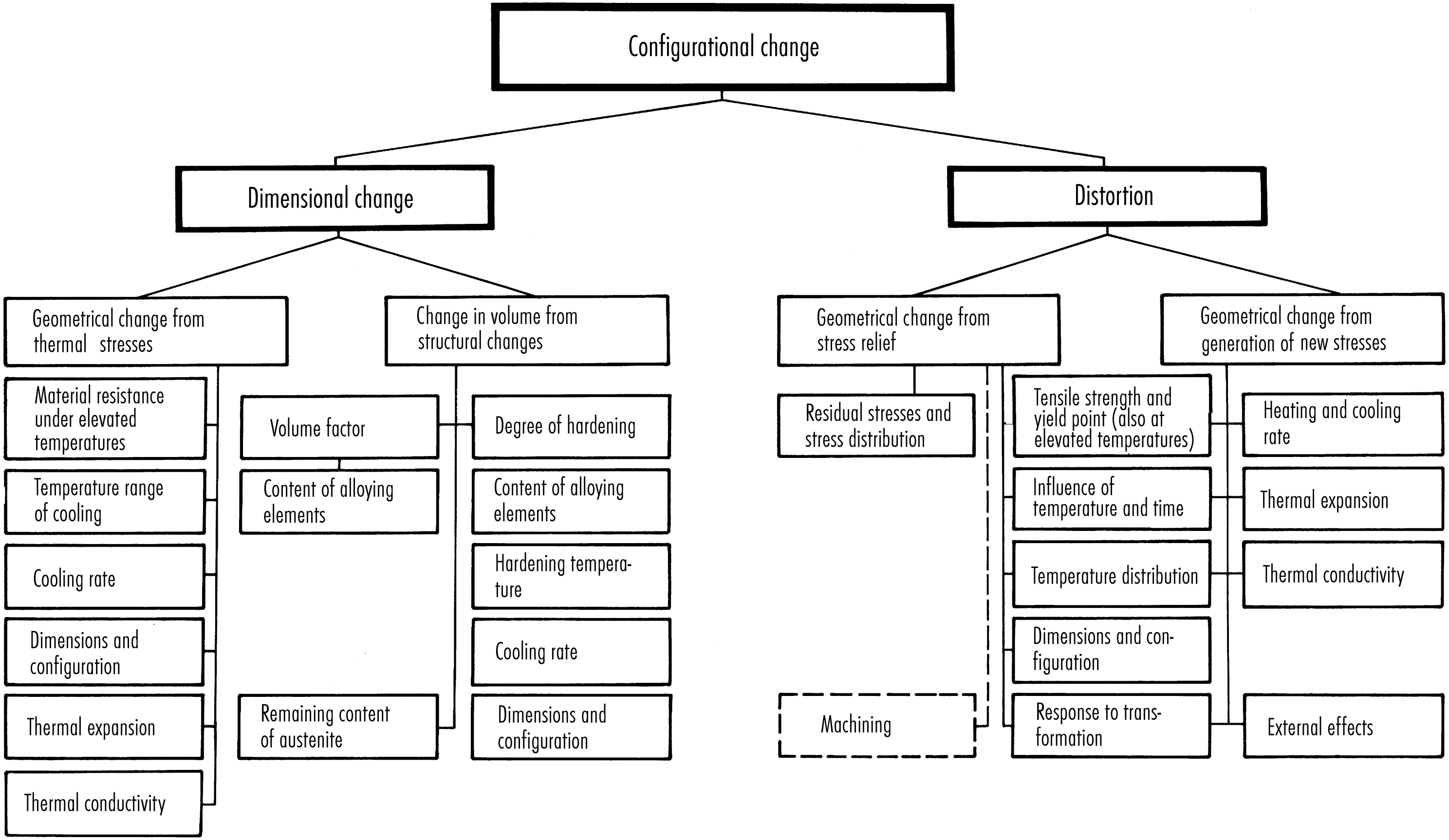

Figure 1.1 Summary of effects that cause configurational changes of steel parts during heat treatment [1.12]

temperatures for thermosets are also between 150 and 250 °C. At this point, the mechanical properties of the mold material are affected. Wear and tendency to distortion increase, creep to rupture data and fatigue resistance decrease [1.14]. This has to be taken into account through selecting the most suitable material. A heat-treatment diagram (hardness versus temperature) can indicate the permissible temperature of use if the latter is taken as 30 to 50 °C below the tempering temperature.

Heat exchange between the solidifying molding and the mold has a substantial effect on the cost of a part. This heat exchange is considerably influenced by the thermal conductivity of the mold material which again is affected by its alloying components. Their different structures give rise to varying thermal conductivity. Notch sensitivity can be countered to a certain degree with case hardening or nitriding because such treatment causes compressive stresses in the surface [1.15]. Nevertheless, attention should be paid to avoiding notches during the design and manufacturing stages.

Some plastics release chemically aggressive substances during processing, such as hydrochloric acid, acetic acid or formaldehyde. They attack the mold surface if it is not protected with a deposit of hard chromium or nickel.

Since such deposits have a tendency to peel off if the molds are improperly designed (e.g., shape, sharp corners) or handled, corrosion resistant steels should be used for making molds which are employed under such conditions. Then no further precautions against possible corrosion from humidity or coolant are necessary.

The demands listed so far are partially contradictory. Therefore the mold designer and mold maker have to select that steel grade which is best suited for a particular job.

The following steel grades are presently offered for producing cavity inserts:

- case hardening steels,
- nitriding steels,
- through-hardening steels,
- tempered steels for use as supplied,
- martensitic-hardening steels,
- hard-material alloys,
- corrosion-resistant steels,
- refined steels.

The most important steels for mold making are shown in Table 1.2, along with their composition, heat treatment and application areas. A more detailed characterization of these groups of steels is provided below.

1.1.2 Case-Hardening Steels

Case-hardening steels best meet the qualifications for mold making. They are not expensive, and it should not come as a surprise that their share is about 80% of the total steel consumed in mold making [1.16] (This figure includes consumption for base and clamp plates). Unalloyed or low-alloyed steels offer a special advantage. Through case hardening, carburization or cementization (so-called because cementite is formed during subsequent hardening), a mold surface as hard as glass is generated and, at the same time, a tough, ductile core. The hard surface renders the mold wear resistant and the tough core confers resistance to shock and alternate loading [1.17].

There are other criteria favoring the application of case-hardening steels over highcarbon and through-hardening steels. Easy machining and, if properly produced and treated, very good polishing are especially worth mentioning. In carburization, there is the possibility of performing local hardening by covering certain areas. However, the extensive heat-treatment procedure required for carburization cannot prevent dimensional changes from occurring, with the result that additional outlay is required before the molds can be used [1.18]. Another advantage over the other steel groups is the low strength after low-temperature annealing. Case-hardening steels are therefore suitable for hobbing (see Section 2.3). This process is particularly suitable for small cavities and multi-cavity molds with a large number of equal cavities.

1.1.3 Nitriding Steels

Basically all steels which contain nitride-forming alloying elements can be nitrided. Such alloying elements are chromium, molybdenum, vanadium and preferably aluminum, which especially favors formation of nitrides. These steels absorb nitrogen from the surrounding medium by diffusion into their outer layer. This process can take place in a salt bath, in gas, powder or in the plasma of a strong corona discharge (ionitriding) at temperatures between 350 and 580 °C. Temperature and time are determined by the individual medium. This procedure causes the above mentioned alloying elements to form nitrides. They provide the steel with an extraordinarily hard and wear-resistant surface with a Brinell hardness between 600 and 800, the value depending on steel grade and process. The greatest hardness is not at the immediate surface but a few hundredths of a millimeter deeper. Therefore the mold should be appropriately larger and the dimensions corrected by grinding after nitriding [1.19]. Ionitrided molds do not need this posttreatment, and it should not be done, which is a special advantage of this process.

Nitriding has the following advantages:

- After nitriding, there is no need for heating, quenching or annealing since nitriding bestows the hardness direct.
- Nitrided parts are free from distortion because they are heated only to about 550 °C.
- The hardness of the nitrided layer is not affected by heating up to 500 °C (retention of hardness).
- Nitrided molds are thus suitable for processing thermosets and such thermoplastics that are shaped at high mold temperatures.
- Nitriding steels yield an extremely hard and at the same time wear-resistant outer layer having good surface slip.

Disadvantageous is the low extent to which the nitrided layer is anchored to the base material as the hard layer can peel off under high surface pressure [1.20].

1.1.4 Through-Hardening Steels

Through-hardening steels increase their hardness by the formation of martensite, which results from rapid quenching. The mechanical properties depend on the quenching medium and the cooling rate. Quenching media are water, oil or air. Water works fastest and has the most drastic effect, while oil and air are milder. Thermal conduction, among other factors, determines the cooling rate, too. The heat conduction depends on the

Table 1.2 Steels for injection molds [1.18, 1.26, 1.28]

Steel type	AISI No.	Composition (%)	Thermal conductivity (W/(m · K))	Thermal expansion $(10^{-6}\ \mathrm{K}^{-1})$
Carbon steel	1020	0.18–0.23 C 0.30–0.60 Mn 0.04 P 0.05 S	46.7	11–15
	1030	0.28–0.34 C 0.60–0.90 Mn 0.04 P 0.05 S	46.7	14.9
	1040	0.37–0.44 C 0.60–0.90 Mn 0.04 P 0.05 S	46.7	
	1095	0.90–1.03 C 0.30–0.50 Mn 0.04 P 0.05 S	43.3	11–14
Alloy steel	4130	0.28–0.33 C 0.30–0.60 Mn 0.20–0.35 Si 0.80–1.10 Cr 0.15–0.25 Mo 0.035 P 0.04 S	46.7	
	4140	0.38–0.43 C 0.75–1.00 Mn 0.20–0.35 Si 0.80–1.00 Cr 0.15–0.25 Mo 0.035 P 0.04 S		
	6150	0.48–0.53 C 0.70–0.90 Mn 0.20–0.35 Si 0.80–1.10 Cr 0.15 V 0.035 P 0.04 S	60.6	10–12
	8620	0.18–0.23 C 0.70–0.90 Mn 0.20–0.35 Si 0.40–0.70 Ni 0.40–0.60 Cr 0.15–0.25 Mo 0.035 P 0.04 S 46.7		
Tool steels				
Shock-resisting steels:	S1	0.50 C 0.75 Si 1.25 Cr 2.50 W 0.20 V	62.3	11–13
	S7	0.50 C 0.70 Mn 0.25 Si 3.25 Cr 1.40 Mo		14.9
Cold-work steels: – oil hardening	O1	0.90 C 1.20 Mn 0.50 Cr 0.50 W 0.20 V		
– medium alloy,	A2	1.00 C 1.00 Mo 5.00 Cr		
– air hardening	A4	0.95 C 2.00 Mn 0.35 Si 2.20 G 1.15 Mo		
– medium alloy, – air hardening	A6	0.70 C 2.00 Mn 1.00 Cr 1.00 Mo		
– high carbon, – high chromium	D2	1.50 C 1.00 Mo 12.00 Cr 1.00 V		
Hot-Work steels: – chromium base	H13	0.35 C 0.40 Mn 1.00 Si 1.40 Mo 5.00 Cr 1.00 V	24.6	12–13
– tungsten base	H23	0.30 C 12.00 Cr 12.00 W		
Special purpose steels: – low-alloy	L6	0.75 C 0.75 Mn 0.90 Cr 1.75 Ni 0.35 Mo		
Mold steels: – low carbon	P2	0.07 C 0.20 Mo 2.00 Cr		
– medium alloy	P20	0.35 C 0.80 Mn 0.50 Si 0.45 Mo 1.70 Cr	29.0	12.7
Stainless steel: (martensitic)	420	0.15 C (min.) 1.00 Mn 1.00 Si 12.00–14.00 Cr	23.0	11–12

Such tables are subject to change from time to time with new steels added or others eliminated, and comprosition of steels is sometimes altered. Current publications (AISI/SAE) should be consulted if latest information is desired.

surface-to-volume ratio of the mold and the alloying elements added to the steel. Ni, Mn, Cr, Si and other elements lower the critical cooling rate and, therefore, permit throughhardening of larger cross sections [1.17].

The hardening process consists in preheating, heating to prescribed temperature, quenching with formation of a hard martensitic structure and then normalizing to improve toughness. Because of the low toughness of through-hardening steels, molds with deep cavities have a higher risk of cracking.

Unlike tempering, normalizing reduces the hardness only slightly. The temperatures for normalizing are between 160 and 250 °C. Besides improving toughness, normalizing has the effect of reducing stresses. (Occasionally this treatment is, therefore, called stress relieving but it should not be confused with stress-relieving annealing.)

Through-hardening steels exhibit very good dimensional stability when heat-treated. Because of their natural hardening capacity they have high compressive strength and are especially suitable for molds with shallow cavities where high pressure peaks may be expected. They can also be recommended in molds for insert molding (with possible high edge pressure) and, due to good wear resistance and high normalizing temperatures, for processing thermosets [1.20, 1.21].

As far as the mechanical properties are concerned, through-hardening steels have a homogeneous structure. Major postmachining does not remove outer layers having special strength as is the case with case-hardening steels. Since the introduction of electrical discharge machining (EDM), the use of through-hardening steels has been steadily gaining in importance.

1.1.5 Heat-Treated Steels

These steels are tempered by the manufacturer and can therefore be used as supplied without the need for further heat treatment.

After hardening, these steels are submitted to a tempering process. At temperatures above 500 °C, the martensite decomposes into carbide and alpha iron. This causes a reduction in hardness and strength of these steels and, at the same time, an increase in toughness. Ductility and toughness increase with rising tempering temperatures; hardness and strength, however, decrease.

Through judicious choice of temperature (usually constant) and duration of tempering (1 to 2 hours), it is possible to obtain a certain degree of toughness, the exact value depending on the strength. 1200 to 1400 MPa yield strength can be assumed as the upper limit. Steels of higher strength can no longer be economically machined [1.22].

To improve the machining properties, sulfur (0.06%) is added to the heat-treated steels. However, this reduces the scope for electroplating the mold surfaces, such as by hard chroming. Similarly, photo-etchability is severely restricted by the manganese sulfides emitted at the surface.

These disadvantages are compensated by treating the steels in some cases with calcium as they are being made. The sulfur content can thereby be reduced (< 0.005%; these steels are said to be highly desulfurized) and the machinability and etchability improved simultaneously [1.18, 1.23].

Heat-treated steels are preferably employed for medium-sized and large molds. They have the additional advantage that corrections are more easily accomplished if deemed necessary after a first trial run [1.2, 1.25].

1.1.6 Martensitic Steels

Martensitic steels combine extreme strength and hardness with the advantage of simple heat treatment. They are supplied in an annealed state. Their structure consists of tough nickel martensite with a strength of 1000–1150 MPa. To an extent depending on their strength, their machinability is comparable to that of tempered steel. It takes about 10 to 20% more machine time than with mild steels.

After machining, molds are subjected to a simple heat treatment that harbors no risks. They are heated up to temperatures between 480 and 500 °C, kept at this temperature for 3 to 5 hours and slowly cooled in still air. No normalizing is done.

Due to the low hardening temperature, no distortion is to be expected. There is only a slight dimensional change from a shrinkage of 0.05 to 0.1% on all sides. The wear resistance of the mold surface can be improved even further by a diffusion process such as nitriding. Care should be taken not to exceed 480 to 500 °C when doing this. The preceding hardening step can be omitted if diffusion treatment occurs. The extraordinary toughness of martensitic steel at the high hardness of 530 to 600 Brinell is remarkable [1.2, 1.13, 1.20, 1.25].

The use of martensitic steels is recommended for smaller cavity inserts with complex contours that exhibit large differences in cross sections and detached thin flanges.

The use of other steel grades for such molds would definitely result in distortion. It should be noted that hardened martensitic steels can be easily welded using materials of the same kind without the need for preheating.

1.1.7 Hard Mold Alloys

Hard mold alloys are steels produced by a powder-metallurgical process that have a high proportion of small carbides which are uniformly embedded in a steel matrix of different composition, primarily a chromium-molybdenum-carbon matrix with added cobalt and nickel [1.18, 1.26–1.28]. These practically isotropic steels are produced in a diffusion process under pressure and temperature from homogeneous alloying powders of maximum purity. To an extent depending on the steel grade and manufacturer, these steels have a titanium carbide content of 50 vol.%. This high carbide content renders the steels extremely wear resistant. They are thus particularly suitable for processing wearpromoting compounds (thermosets and reinforced thermoplastics) and for various tool parts subjected to increased wear, such as nozzles, gate systems, etc.

Hard mold alloys are supplied in a soft-annealed state and may be machined. After heat treatment (6–8 hours storage at 480 °C), the hardness increases to 60–62 Rc. To increase the hardness further, storage may be combined with a nitriding treatment. The surface hardness increases as a result to 72–74 Rc [1.27].

Due to their isotropic structure and low coefficient of thermal expansion, hard mold alloys undergo extremely little distortion during heat treatment.

1.1.8 Corrosion-Resistant Steels

Some polymeric materials release chemically aggressive substances during processing that attack steel and harm the surface, e.g. by causing rusting. One way of protecting molds against corrosion is afforded by applying a protective electroplating coat (chromnickel plating). Complicated geometries make it difficult, however to apply uniform coatings, particularly on the corners and edges. It is therefore possible that the shape of the moldings will change as a result. In addition, protective electroplating coats tend to peel off very easily. If the molds are likely to be used in a corrosive setting, it is advisable to use corrosion-resistant steel.

The corrosion resistance of such steels is due to their having been alloyed with chromium. Given a chromium content of at least 12%, very dense, strongly adhering, invisible layers of chromium oxide are formed in contact with atmospheric oxygen or other oxygen-providing media. They protect the steel against corrosion. In this case the crystalline structure is a solid solution of iron and chromium. Adding other alloying elements to steel, especially carbon, may partially reduce the corrosion resistance. Carbon has the tendency to react with chromium and form ineffective chromium carbide. Only in the hardened state does carbon remain bound to the iron atoms or in solution, thereby allowing the chromium to fully play its anti-corrosive function. Through heat treatment above ca. 400 °C, part of the carbon escapes from the solution and can form chromium carbide. Thus, carbon binds part of the chromium, preventing it from performing its protective role. Because of the required mechanical properties, however, carbon cannot be dispensed with mold in stainless steels for mold making [1.28]. Therefore hardened chrome steel is always the best choice.

The corrosion resistance also depends on the quality of the mold surface. A rough surface presents a larger area for attack than a smooth, highly polished one. Chrome steel with only 13% chromium, for instance, is corrosion resistant only if the surface is highly polished. In addition, the plastics processor himself should make every effort to protect his molds from corrosion by cleaning them before storage.

Steels with 17% chromium and martensitic structure have better corrosion resistance but tend to coarseness and formation of soft ferritic parts in their crystalline structure. Only the hard material alloys (tool steels with the maximum carbide content produced by powder metallurgical processes) are not susceptible to these problems (see also Section 1.1.7).

1.1.9 Refined Steels

The cosmetic appearance of a plastic molding depends largely on the mold's surface quality. Particular attention to this fact should be paid when selecting a steel for mold inserts that will be employed for molding transparent articles such as lenses etc.

The better the steel can be polished, the higher is the surface quality of the mold. How well steels can be polished is determined by their degree of purity. This degree depends on the amount of nonmetallic inclusions in the steel, such as oxides, sulfides and silicates [1.19]. These inclusions, unavoidable in an open-hearth steel, can be eliminated by remelting. In modern practice three methods with self-consuming electrodes are applied: melting in an electric-arc vacuum oven, in an electron beam oven or by electro-slag refining.

For refining in an electric-arc vacuum oven, a normally produced steel rod as self-consuming electrode is burnt off in a cooled copper die under high vacuum (10^{-1} or 10^{-3} Pa).

In an electron beam oven, the rod is melted in an ingot mold by an electron beam.

Electro-slag refining has gained greatest importance in recent years. In this process, the electrode, which is in the form of a completely alloyed block, dips into electrically conductive liquid slag in a water-cooled mold and is melted [1.29]. The melt dripping from the electrode passes through the liquid slag and is purified by respective metallurgical reactions [1.30, 1.31].

Refined steels have the following advantages over those conventionally produced:

- more homogeneous primary structure and extensive freedom from ingot liquation and internal defects from solidification,
- less crystal liquation and therefore more homogeneous microstructure,
- reduced quantity and size and a more favorable distribution of nonmetallic inclusions, such as oxides, sulfides and silicates [1.32].

Remelted and refined steels are the purest steels presently on the market. Therefore they can be very well polished.

1.2 Cast Steel

The production of molds from forged or rolled steel is relatively expensive because of the high labor costs for machining and the expenses for the necessary equipment which is partly special machinery. In addition, there are high material losses from cutting operations, which can amount to 30 to 50% for large cavities [1.19]. Besides this, stylists and consumers demand a molding whose surface quality or texture cannot be produced in a cavity by conventional cutting operations. Solutions can be found in physical or chemical procedures or precision casting.

The most common casting steel grades and casting processes are discussed in detail in Sections 2.1.1–2.1.3. A summary of cast steel alloys is shown in Table 1.3.

1.3 Nonferrous Metallics

The best known nonferrous metals employed in mold making are:

- copper alloys,
- zinc alloys,
- aluminum alloys,
- bismuth-tin alloys.

1.3.1 Copper Alloys

The importance of copper alloys as materials for mold making is based on their high thermal conductivity and ductility, which equalizes stresses from nonuniform heating quickly and safely. The mechanical properties of pure copper are moderate. Although they can be improved by cold rolling or forming, they generally do not meet the demands on a mold material.

Therefore, copper serves in mold making at best as an auxiliary material, for instance, as components of heat exchangers in molds cast from low melting alloys. Beryllium-copper-cobalt alloys, however, are important materials for mold cavities.

Table 1.3 Cast steels for injection molds; composition – treatment – properties [1.38]

Carbon steels	AISI 1020	0.18–0.23% C 0.30–0.60% Mn 0.04% P 0.05% S annealed BH 122, normalized BH 134 Welding is readily done by most arc and gas processes. Preheating unnecessary unless parts are very heavy
	AISI 1040	0.37–0.44% C 0.60–0.90% Mn 0.04% P 0.05% S normalized and annealed BH 175 normalized and oil quenched BH 225 Welding can be done by arc, resistance and gas processes. To decrease cooling rate and subsequently hardness preheating to above 150 preferably 260 °C. Final heating to 600–650 °C restores ductility and relieves stress
Alloy steels	AISI 1330	0.28–0.33% C 1.60–1.90% Mn 0.20–0.35% Si 0.035% P 0.04% S normalized BH 187, normalized and tempered BH 160 Can be relatively easily welded with mild-steel filler metal
	AISI 4130	0.28–0.33% C 0.40–0.60% Mn 0.20–0.35% Si 0.80–1.10% Cr 0.15–0.25% Mo 0.035% P 0.04% S annealed BH 175 Welding same as 1330
	AISI 4340	0.38–0.43% C 0.60–0.80% Mn 0.20–0.35% Si 1.65–2.00% Ni 0.70–0.90% Cr 0.20–0.30% Mo 0.035% P 0.04% S normalized and annealed BH 200 quenched and tempered BH 300 Welding calls for pre- and postheating and filler metals of the same mechanical properties as the base metal. Stress relieving is desirable especially in repair work
	AISI 8630	0.28–0.30% C 0.70–0.90% Mn 0.20–0.35% Si 0.40–0.70% Ni 0.40–0.60% Cr 0.15–0.25% Mo normalized BH 240, annealed BH 175 Welding preferably with filler metal of the same chemical analysis. No preheating needed for sections up to 0.5 in. but stress relieving after welding
Heat-resistant steel	AISI 501	0.10% C 1.00% Mn 1.00% Si 4.00–4.00% Cr 0.40–0.65% Mo Welding similar to 8630

1.3.1.1 Beryllium-Copper Alloys

As with other alloys, the mechanical and thermal properties depend on the chemical composition of the alloy. With increasing beryllium content, the mechanical properties improve while the thermal properties deteriorate. Beryllium-copper alloys with more than 1.7% beryllium have prevailed in mold making. They have a tensile strength of up to 1200 MPa and can be hardened up to 440 Brinell. Hardening up to 330 to 360 Brinell is generally sufficient for practical purposes. In this range the material is very ductile, has no tendency to fragility at the edges, and is readily polishable [1.39].

Tempering, which provides a homogeneous hardness, can be done in a simple oven [1.40].

Alloys with a beryllium content below 1.7% are only used for functional components, such as heat conductors in heat exchangers, because of their diminished strength. Table 1.4 summarizes the technical data of some beryllium-copper alloys.

Molds made of beryllium copper are sufficiently corrosion resistant and can be chrome or nickel plated if needed. Protective coating is mainly done by electroless nickel plating today. It has the advantage of a more even deposit and a hardenability of up to 780 Brinell with an appropriate heat treatment at about 400 °C. Besides this, a nickel coating is less prone to cracking than a hard chrome coating [1.40]. In contrast to cast steel, beryllium-copper alloys are practically insensitive to thermal shock.

Mechanical damage can be repaired by brazing or welding. Beryllium-copper rods with about 2% beryllium are preferably used for welding with 250 Amps [1.39, 1.40]. The molds are appropriately preheated to 300 °C [1.40].

Molds of beryllium copper can be made by machining or casting. Cold-hobbing is only conditionally suitable for shallow cavities. The alloy can be better formed by hothobbing in a temperature range of 600 to 800 °C followed by solution annealing.

Beryllium-copper alloys are employed as materials for molds or functional components wherever high heat conductivity is important either for the whole mold or part of it. The temperature differential between cavity wall and cooling channel is reduced. This results in higher output with the same, or often better, quality with the same cooling capacity. These alloys also offer an advantage if high demands on surface accuracy have to be met. They are well suited for casting with patterns having a structured surface such as wood, leather or fabric grain.

1.3.2 Zinc and its Alloys

High-grade zinc alloys for casting are used in mold making only for prototype molds or molds for small production runs because of their inferior mechanical properties. They are more frequently utilized for blow molding or vacuum forming where molds are not under high mechanical loads. Zinc alloys, like copper alloys, are characterized by high thermal conductivity of about 100 W/(m · K).

Molds of zinc alloys are mostly cast. The low casting temperature (melting point ca. 390 °C, casting temperature 410 to 450 °C) is a special advantage. It allows patterns to be made of wood, plaster, or even plastics, in addition to steel. Patterns of plaster and plastics can be made especially easily and fast. High-grade zinc alloys can also be cast in sand and ceramic molds. Die casting, although possible, is used only rarely.

The excellent behavior of zinc alloys during casting produces smooth and nonporous surfaces of intricate and structured surfaces [1.39]. Molds, especially plaster molds, must be adequately dried before use (plaster for several days at 220 °C), since otherwise a porous and rough cavity surface results from the generation of steam [1.21].

Molds of high-grade zinc alloys can also be made by cold-hobbing. The blank is preheated to 200 to 250 °C before hobbing. Even deep cavities are produced in one step without intermediate annealing. Hobs with a Brinell hardness of 430 are employed. Vertical motion is sometimes combined with rotation. With such hobs cavity inserts for molding helical gears can be made [1.21].

Another process using high-grade zinc alloys is metal spraying (Section 2.2).

Because of low mechanical strength only cavity inserts are made of high-grade zinc alloys. These inserts are fitted into steel bases, which have to resist the forces from

Table 1.4 Technical data of beryllium-copper [1.41]

Designation	C 17 200	C 17 300	C17 000	C 17 510	C 17 500
Composition	Be 1.80–2.00% Co/Ni 0.20% min. Co/Ni/Fe 0.6% max., Cu balance	Be 1.80–2.00%, Co/Ni 0.20% min., Co/Ni/Fe 0.6% max., Pb 0.20–0.6%, Cu balance	Be 1.60–1.79% Co/Ni 0.20% min., Co/Ni/Fe 0.6% max., Cu balance	Be 0.20–0.60% Ni 1.40–2.20% Cu balance	Be 0.40–0.75% Co 2.40–2.70% Cu balance
Density kg/m^3	8250		8415	8610	8775
Therm. conductivity W/(m · K)	130		130	260	260
Therm. expansion 10^{-6} K^{-1}	17.5		17.5	17.6	18
Specifie heat capacity J/(kg · K)	420		420	420	420
Electric resistivity $10^{-8}\Omega \cdot$ m	7.7		7.7	3.8	3.8
Modulus of elasticity GPa	131		128	138	138
Tensile strength [MPa]	I 415–585 II 620–895 III 1140–1310 IV 1275–1480		I 415–585 II 620–895 III 1035–1310 IV 1170–1450	I 240–380 II 450–550 III 690–830 IV 760–900	
Yield strength [MPa]	I 140–415 II 515–725 III 1000–1200 IV 1140–1380		I 140–205 II 515–725 III 860–1070 IV 930–1140	I 140–310 II 340–515 III 550–690 IV 690–830	
Elongation [%]	I 35–60 II 10–20 III 3–10 IV 2–5		I 35–60 II 10–20 III 4–10 IV 2–5	I 20–35 II 10–15 III 10–25 IV 10–20	
Rockwell hardness	I B45–80 II B88–103 III C36–41 IV C39–44		I B45–85 II B91–103 III C32–39 IV C35–41	I B25–50 II B60–75 III B92–100 IV B95–102	

Notes: I: Solution heat treated
II: Cold drawn
III: Solution heat treated and age hardened
IV: Cold drawn and age hardened

clamping and injection pressure during the molding process. The most common highgrade zinc alloys, known under their trade names Zamak or Kirksite, are summarized in Table 1.5.

1.3.3 Aluminum Alloys

For a long time, aluminum was not used to any major extent for making injection molds. However, extensive improvements in properties, particularly mechanical properties, have led to this material being used more and more often in recent times. The main properties in favor of using aluminum for mold making are:

- low density,
- good machinability,
- high thermal conductivity, and
- corrosion resistance.

Aluminum alloys are available as casting and forging alloys. The casting alloys are not of much significance. Casting is difficult. Perfect molds presuppose correct choice of alloy, the appropriate melting and casting technique and a mold design amenable to casting. It is therefore advisable to collaborate with the manufacturer at the design stage.

More important for mold making are the forging alloys which, in the form of heathardening, high-strength aluminum-zinc-magnesium-copper alloys, have already shown their mettle in aircraft construction. These are now available commercially in the form of complete mold structures as well as plates that have been machined on all sides and as blanks [1.44]. The chemical composition and physical properties of a typical aluminum alloy used in mold making are shown in Table 1.6.

Aluminum molds weigh less than steel molds due to their specific weights (between 2.7 and 2.85 g/cm^3, depending on alloying additives). Unfortunately this “positive characteristic” is not fully recognized because the individual plates, which are components of a mold, have to be about 40% thicker than steel plates because of their lower mechanical strength (modulus of elasticity is only roughly 30% that of steel; Table 1.6). In spite of this, aluminum molds weigh about 50% less than steel molds. This is a considerable advantage during mold making and assembly as well as later on during setup in the molding shop. With smaller molds, it is frequently possible to do without expensive lifting devices such as cranes and lift trucks.

Additional advantages result from good machinability, which can allow cutting speeds five times as fast as those for steel [1.44]. This holds particularly true if the recommendations of the producer are taken into account and those tools are used which are especially suited for aluminum. Distortion from machining is not to be expected because aluminum has very little residual stresses due to special heat treatment during production (the wrought products are hot-rolled, then heat-treated and stretched until stress-free). Aluminum can be worked with cutting tools as well as shaped by means of EDM.

Electrode material made of electrolytic copper or copper containing alloys are primarily used for this procedure. Here, too, the high eroding speed (6 to 8 times that of steel) is economically significant. Cut or eroded surfaces can be polished with standard machines and wheels and made wear resistant by chrome plating or anodizing. Service lives of up to 200,000 shots per mold have been achieved with aluminum molds, the

Table 1.5 High-grade zinc alloys for injection molds [1.42, 1.43]

Designation	Density (kg/m^3)	Melting point (°C)	Shrinkage %	Thermal expansion (10^{-6}/K)	Tensile strength (MPa)	Elongation (% in 50 mm)	Brinell hardness BH	Compressive strength (MPa)	Shear strength (MPa)
Zamak	6700	390	1.1	27	220–240	1–2	1000	600–700	300
Kirksite A	6700	380	0.7–1.2	27	226	3	1000	420–527	246
Kayem	6700	380	1.1	28	236	1.25	1090	793	–
Kayem 2	6600	358	1.1	–	149	Very low	1450–1500	685	–

Table 1.6 Chemical composition and physical properties of a typical heat-hardening aluminum forging alloy used for mold making [1.44, 1.45, 1.47]

<table>
<tr><td colspan="10">Chemical composition</td></tr>
<tr><td rowspan="2">A.A. No.</td><td colspan="9">Composition (wt. -%)</td></tr>
<tr><td>Cu</td><td>Cs</td><td>Fe</td><td>Mg</td><td>Mn</td><td>Si</td><td>Ti</td><td>Zn</td><td>Others</td></tr>
<tr><td>3.4365</td><td>1.2–2.0</td><td>0.18–0.28</td><td>0.5</td><td>2.1–2.9</td><td>0.3</td><td>0.4</td><td>0.2</td><td>5.1–6.1</td><td>Ti + Zr = 0.25</td></tr>
</table>

<table>
<tr><td colspan="7">Physical properties</td></tr>
<tr><td rowspan="2">A.A. No.</td><td>Density</td><td>Yield strength</td><td>Ultimate tensile strength</td><td>Modulus of elasticity</td><td>Coefficient of thermal expansion</td><td>Thermal conductivity</td></tr>
<tr><td>kg/dm^3</td><td>N/mm^2</td><td>N/mm^2</td><td>MPa</td><td>W/(m °C)</td><td>W/(K · m)</td></tr>
<tr><td>3.4365</td><td>2.82</td><td>410–530</td><td>480–610</td><td>72000</td><td>23.7</td><td>153 (0–100 °C)</td></tr>
</table>

number depending on the application [1.48, 1.49]. Surface treatment will be discussed later.

The thermal conductivity of the materials used for the molds is critical to injection molding. When aluminum alloys are used, it ensures good, rapid heat distribution and dissipation. This shortens cycle times and may lead to enhanced quality of moldings.

In the presence of atmospheric oxygen, a dense, strongly adhering oxide layer about 0.001 μm thick forms on the surface of the aluminum [1.44, 1.46]. This layer protects the underlying materials, particularly in dry environments, against atmospheric attack. If it is destroyed or removed during machining, it re-forms anew spontaneously. It is damaged by acids formed from salts and gases in contact with moisture (water of condensation). If this kind of stress is expected during operation, surface treatment is advisable. Good results in this connection have been produced by

- chrome plating,
- nickel plating,
- anodizing, and
- PVD coating.

Surface treatment enhances not only corrosion resistance but also wear and abrasion resistance and sometimes facilitates demolding. Layer thicknesses and hardnesses obtained with the aforementioned coating methods are summarized in Table 1.7.

Table 1.7 Coating processes for aluminum and properties obtained [1.45, 1.47]

Process	Layer thickness	Hardness
Chrome plating	20–200 μm	900–1100 HV
Nickel plating	35–50 μm	500–600 HV
Anodizing	30–60 μm	350–450 HV
PVD coating	5–10 μm	

Due to the positive aspects for mold making described above, mold plates already milled and surface-ground to finished dimensions, with the corresponding bores for guide systems right through to complete mold structures, are now commercially available.

Designs combining aluminum with steel have yielded good results. This construction has the advantage of allowing the more resistant steels to be used for areas subject to high wear and abrasion. It therefore combines the advantages of both materials.

The service life of aluminum molds depends on the plastic to be processed (reinforced or unreinforced), its processing conditions (injection pressure, temperature) and the geometry of the molding. The literature contains reports of molds that have produced 15,000–200,000 moldings. Aluminum is of little or no suitability for processing thermosets on account of the high processing temperatures and the associated thermal stress [1.45, 1.49].

1.3.4 Bismuth-Tin Alloys

Bismuth-tin alloys are marketed under the trade name Cerro alloys. They are relatively soft, heavy metals, which generally react to shock in a brittle manner but exhibit plasticity under constant loading. The strength of these alloys increases with aging [1.51].

Table 1.8 Bismuth-tin alloys (Cerro® alloys) for injection molds [1.52]

Designation (registered trademark)		Cerrotru	Cerrocast
Density	kg/dm^3	8.64	8.16
Melting point or range	°C	138	138–170
Specific heat	kJ/kg	1.88	1.97
Thermal expansion	10^{-6}	15	15
Thermal conductivity	W/(K · m)	21	38
Brinell hardness	BHN	22	22
Ultimate tensile strength	MPa	56	56
Elongation (slow loading)	%	200	200
Max. constant load	MPa	3.5	3.5
Composition % Bi % Sn		 58 42	 40 60

Bismuth-tin alloys are compositions of metals with low melting points (between 40 and 170 °C depending on composition). They are suitable for normal casting as well as for die or vacuum casting. They can also be used with a special spray gun. Those alloys which do not change their volume during solidification are particularly suited for making molds.

Because of their moderate mechanical properties, bismuth-tin alloys are primarily used for prototype molds in injection molding. More common is their use for blow molds, molds for hot forming and for high-precision matrices in electrolytic depositing. Besides this, they are used as a material for fusible cores, which will be discussed in more detail later on (Section 2.10). Table 1.8 shows the physical and chemical Properties of some Cerro alloys.

1.4 Materials for Electrolytic Deposition

Electrolytic deposition of metals has two applications in mold making. A distinction is made between “decorative” plating and electrolytic forming. The techniques are similar but their end products and their intended use are very much different. In plating, a thin layer, usually about 25 µm thick, is deposited. This layer is intended to protect the metal underneath from corrosion, to facilitate demolding, and to reduce forming of deposits and facilitate the cleaning of molds.

To do this, the electrolytic deposit must adhere well to the substrate.

In electrolytic forming, a considerably thicker layer is deposited on a pattern that has the contours and dimensions of the later cavity insert. The thickness of the deposit is arbitrary and limited only by production time. After the desired thickness is obtained and further work in the form of adding a backing is completed, the structure should detach easily from the pattern.

There are a number of materials that can be electrolytically deposited. The most important ones are nickel and cobalt-nickel alloys. Nickel is the most frequently - employed metal for electrolytic forming because of its strength, toughness, and corrosion resistance. Besides this, the process is simple and easily controlled. Hardness, strength,

Table 1.9 Characteristics of electro-deposited nickel [1.53, 1.55]

Hardness	4500–5400 MPa
Tensile strength	360–1510 MPa
Typ. strength for molds	1400 MPa
Yield strength	230–640 MPa
Typ. strength for molds	460 MPa
Elongation	2–37%
Typ. elongation for molds	10%
Temperature resistance	max. 300 °C
Corrosion and wear resistant	
Fine, ductile grain	

ductility, and residual stresses can be varied within a broad range by selecting certain electrolytic solutions and process conditions [1.53, 1.54].

Even the hardest forms of electrolytically deposited copper and iron are too soft for cavity walls. Copper is primarily used for backing an already formed nickel shell. The rate at which copper can be deposited is a very desirable feature of this procedure.

By contrast, electrolytically deposited chromium is so hard that postoperations such as drilling holes for ejector pins are impractical. In addition chromium exhibits high residual stresses, which can easily lead to cracks in the chrome layer. Therefore chromium is used only for protective coatings in mold making.

1.5 Surface Treatment of Steels for Injection Molds

1.5.1 General Information

As already explained in Section 1.1, materials for mold making have to exhibit distinctive properties. Frequently, a compromise becomes necessary because the properties of steels depend largely on their chemical composition and the alloying components affect each other.

Therefore it is reasonable that steel producers and users, together with plastics processors, keep looking for suitable processes to improve the quality and particularly the service life of injection molds. This can be done by numerous surface treatments. The goal of all these processes is to improve

- surface quality,
- fatigue and wear resistance,
- corrosion resistance,
- sliding ability, and
- to reduce the tendency to form material residues and deposits in the mold.

The surface properties of components of injection molds can be considerably modified by suitable machining, controlled heat treatment or a change in the alloying elements in the surface layers, by diffusion or build-up. Special demands can thus be met.

Before the details of some selected procedures are discussed below, it must be pointed out that the application of the various processes calls for specialist knowledge and, in some cases, considerable technical resources. Therefore such work is ordinarily done by specialists. Steel producers also provide advice in this respect.

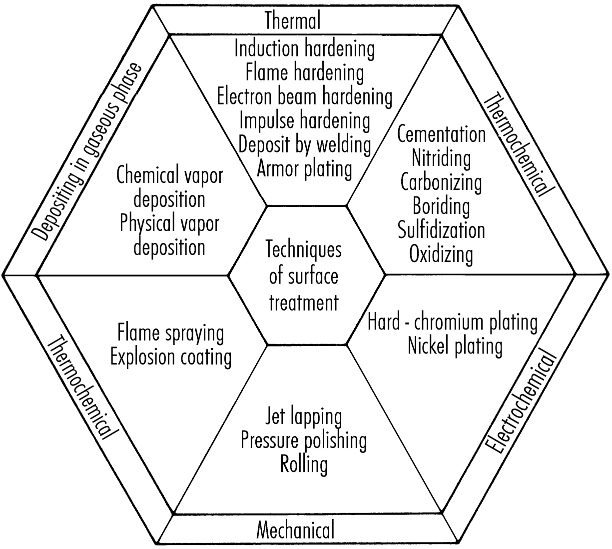

Figure 1.2 Techniques of surface treatment [1.56, 1.57]

Currently, the most common surface treatments for mold steels are shown in Figure 1.2. Some are presented in more detail below.

1.5.2 Heat Treatment of Steels

In traditional heat-treatment processes changes in the crystalline structure are caused by simple heating and cooling. This confers distinct properties on the steel. To this end, the steel producers provide special heat-treatment information showing the feasibility of treatments and the resulting properties. Such “simple” treatments do not require – as long as small dimensions are considered – a great amount of technique. They only assume a theoretical understanding of the reactions occurring during heat treatment. Annealing, hardening and tempering are considered “simple” treatments.

1.5.3 Thermochemical Treatment Methods

Unlike their thermal counterparts, thermochemical methods utilize chemical elements that diffuse from a gaseous, liquid or solid state into the material surface to produce a hard, wear-resistant layer [1.56]. A distinction is drawn between

- carburizing,
- nitriding, and
- boriding.

1.5.3.1 Carburizing

In carburizing, the carbon content of layers close to the surface of steel, having a low carbon content of ordinarily less than 0.25%, and therefore not soluble is increased to as much as 0.9% at temperatures between 850 and 980 °C. If quenching is done immediately from the carburizing temperature, this process is called direct hardening [1.58]. Carburizing produces a hard surface, which is supported by a soft, tough interior core [1.58].

After hardening the steel is tempered. The tempering temperature is determined by later application or temperature at which the mold is used [1.56] and determines the hardness of the surface. Tempering at temperatures between 100 and 300 °C yields a hardness of 600 to 700 Brinell.

1.5.3.2 Nitriding

Nitriding (see also Section 1.1.3) can be done in a salt bath, in gas, or powder. The medium determines the temperature and duration of the process. The aim of all processes is to saturate the outer layer of the workpiece by diffusion of nitrogen so as to increase hardness, wear resistance or corrosion resistance.

In nitriding in a bath, the molds are preheated to 400 °C. The nitriding itself is done at 580 °C. The nitriding time depends on the desired depth of nitriding, but two hours are generally sufficient. A special form of nitriding in a bath is the Tenifer treatment, which is characterized by an aerated nitriding bath of special composition. The required surface hardness for injection molds is likewise achieved after two hours at a temperature of 570 °C [1.59].

Much longer nitriding times are necessary for gas nitriding. The desired surface hardness takes at least 15 to 30 hours treatment, the exact time depending on the steel grade. The treatment is performed at temperatures between 500 and 550 °C. It is possible to selectively nitride certain areas by partially covering the surface with a coating of copper or nickel or with a special paste [1.59].

When nitro-carburizing in gas, a reaction component that provides carbon is used in addition to ammonia. This enriches the connecting zone with carbon. Applicable components are endogas, exogas or combinations thereof as well as natural gas or liquids that contain carbon dioxide. The treatment temperatures are about 570 °C, and the time is 2 to 6 hours.

Activator content, nitriding time and temperature determine the quality of the results of powder nitriding for a particular steel grade. It is carried out at temperatures between 450 and 570 °C [1.59].

Ionitriding is nitriding in the plasma of a high-amperage corona discharge. It causes nitrogen to be deposited on the mold surface. The hardening depth can range from a few micrometers to 1 mm. The greatest hardness is achieved here immediately at the surface, reaching 800 Brinell for some steel grades. Posttreatment of the surface is, therefore, unnecessary. The treatment is done in the temperature range between 350 and 580 °C. Treatment times start at a few minutes and are practically unlimited (20 min to 36 h) [1.60].

Distortion of molds through nitriding or ionitriding does not normally occur. After heat treatment, molds are obtained which are tough and free of stresses, have high surface hardness and improved corrosion resistance.

Nitriding steels are annealed before delivery and can be machined without difficulties.

1.5.3.3 Boriding

In boriding, layers close to the surface are enriched with boron. The result is a very thin but extremely hard (1800 to 2100 HV 0.025 [1.56]) and wear-resistant layer of iron boride, which is interlocked with the base metal. Boriding can be effected in a solid compound, through treatment in gas or in borax-based melts, both with and without electrolyte.

Boriding is carried out in a temperature range of 800 to 1050 °C. The usual duration is between 15 minutes and 30 hours. Treatment time, temperature and base material determine the thickness of the layer. Thicknesses of up to 600 μm can be achieved. Partial boriding is feasible.

After boriding, workpieces can be heat-treated to confer a higher “load capacity” on the base material. The use of a heat-treated steel is a precondition for this. The temperature depends on the base material. This treatment should be limited to workpieces with a medium layer of boride (100 to 120 μm). Thicker layers are liable to crack [1.61].

Borided surfaces usually have a dull-gray appearance, and build-up of the boride layer on the surface is possible, the extent depending on the processing conditions. Therefore, a finishing operation in the form of grinding, polishing, lapping or honing is often necessary.

1.5.4 Electrochemical Treatments

During processing, some polymeric materials release chemically aggressive substances, mostly hydrochloric or acetic acid. In such cases, the molds are frequently protected by electrolytic plating with chromium or nickel.

Not only is corrosion resistance enhanced, but also the antifriction properties and, in the case of chromium, the wear resistance as well.

This plating is permanently effective only if the thickness of the deposit is uniform and sharp edges in the mold are avoided. Nonuniform thickness and sharp edges cause stresses in the protective layer, which can lead to peeling off under loads. The risk of a nonuniform deposit is particularly great in molds with intricate contours (undercuts etc.). Plated thin flanges subject to bending stresses are very susceptible to cracking.

Before protective plating by electrolytic depositing can be performed, the molds have to be finished accordingly. Build-up and surface quality of the deposit depend on the quality of the base material. Ground, or even better, polished and compacted surfaces give the best results.

1.5.4.1 Chrome Plating

The thickness of electrolytically deposited layers of chromium depends on the current density and the temperature of the electrolyte. Their hardness also depends on the temperature of the heat treatment after plating. Common thicknesses lie between 5 and 200 μm, in special cases between 0.5 and 1 mm [1.56]. A surface hardness of 900 HV 0.2 is obtained. Because the chrome layer is deposited electrolytically, it builds up in lumps and needs to be reground to the requirements imposed on the quality of the coated workpiece.

1.5.4.2 Nickel Plating

A distinction is drawn between electrolytic and chemical nickel plating. The properties of the deposits also depend on the processing parameters. Nickel deposits are relatively soft and therefore not wear resistant.

1.5.4.3 NYE-CARD Process

In order to remedy this disadvantage, procedures have been developed, such as the NYE-CARD process, with which 20 to 70% by volume silicon particles of 25 to 75 µm are incorporated into a nickel-phosphorus layer. The nickel phosphorides contain 7 to 10% phosphorus.

The temperatures to which the material to be coated is exposed are less than 100 °C during the process. If subsequent heat treatment to improve adhesion is intended, the temperature should be about 315 °C. Besides steel, materials such as aluminum or copper alloys can be coated. It makes sense, however, to employ hardened base materials due to of the low thickness of the deposit, and to bring the surface quality of the base up to the required standard.

1.5.4.4 Hard Alloy Coating

Hard alloy coatings are electrolytically deposited protective layers of either tungsten-chromium (Hardalloy W) or vanadium-cobalt (Hardalloy TD). They are applied to a surface that has previously been smoothed and compacted by an ion beam [1.62].

1.5.5 Coating at Reduced Pressure

Common coating techniques based on the principle of deposition from the gas phase are chemical vapor deposition (CVD) and physical vapor deposition (PVD) and their respective variants. Both techniques have specific advantages and disadvantages. Because CVD requires high temperatures above the retention of hardness for tool steels, steel materials require subsequent heat treatment. However, this may lead to imprecise dimensions and shapes due to distortion. PVD techniques do not require subsequent heat treatment. However, CVD layers generally yield higher adhesive strength and depth of penetration into deep, narrow openings.

1.5.5.1 CVD Process

The CVD process (chemical vapor deposition) is based on the deposition of solids from a gaseous phase by a chemical reaction at temperatures above 800 °C [1.56]. It is shown schematically in Figure 1.3.

In a CVD process, carbides, metals, nitrides, borides, silicides or oxides can be deposited on the heated surface of molds at temperatures between 800 and 1100 °C. Depending on location and mold type, layers having a thickness of 6 to 30 µm and a strength of up to 4000 MPa may be deposited, e.g. a coating of titanium carbide with a thickness of 10 µm. The deposits faithfully copy the surface of the mold, that is, traces from machining of the surface such as scratches and grooves are not hidden by a CVD process. Therefore the mold surface must already have the same quality before coating that is expected from the finished tool [1.64].

The high temperatures needed for this process cause the base material to loose hardness and strength. This disadvantage must be compensated by another heat treatment and associated hardening of the base material. Appropriate steel grades should be used.

Because every heat treatment involves risks such as distortion, efforts are being made to lower the process temperatures with a view to improving the technique. Temperatures of 700 °C and lower are being discussed [1.65].

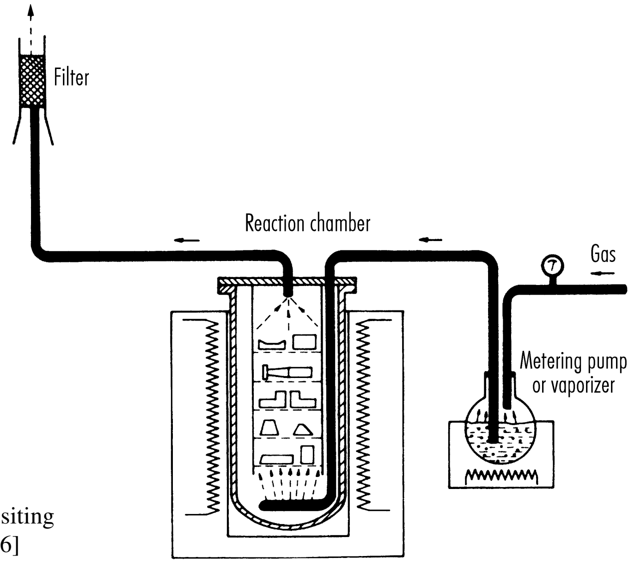

Figure 1.3 Equipment for depositing titanium carbide (schematic) [1.56]

1.5.5.2 PVD Process

The term PVD (physical vapor deposition) summarizes all those coating techniques by which metals, their alloys and their chemical compounds such as oxides, nitrides, and carbides can be deposited in a vacuum under the simultaneous effects of thermal and kinetic energy through particle bombardment [1.56]. The process is shown schematically in Figure 1.4.

PVD techniques include

- deposition through evaporation in high vacuum,
- ion plating,
- sputtering [1.56].

In contrast to the CVD process, the coating of molds by this physical procedure occurs at temperatures between 500 and 550 °C. This temperature is in many cases below the tempering temperature of the base material and so further heat treatment (with the associated risk of distortion) after coating does not become necessary. This process is suitable for all tool steels [1.64].

For the PVD technique, the quality and cleanliness (freedom from rust and grease) of the mold surface before coating are also crucial to the bond and surface quality after coating.

A variant of PVD, namely PVD arc coating, makes it possible to deposit virtually any coating material in monolayer and multilayer systems. The coating materials are generally chosen on the basis of attainable hardness, coefficient of friction, corrosion resistance and cost. Candidate coating materials or systems include TiN, TiC, TiCN, TiAlN, CrN and CrAlN [1.66, 1.67]. The thinnest hard layers are obtained by ion implantation, e.g. of nitrogen or carbon [1.68].

PVD coatings have the advantage of being independent of the surface contour for all practical purposes. They do not affect either the fineness of shape or the dimensional

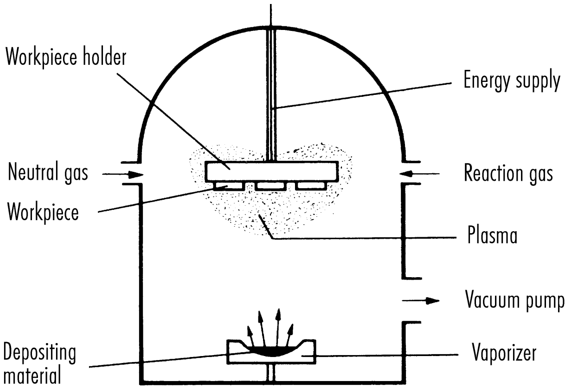

Figure 1.4 Basics of the PVD technique [1.56]

accuracy. Changes in dimensions are of the order of less than 5 µm and roughness values of less than 0.5 µm are attainable [1.37].

So far, titanium nitride (TiN) layers have frequently been used in practice. Titanium is vaporized in vacuum at temperatures of 550 °C, and together with the nitrogen present, forms a golden wear-resistant deposit up to 5 µm thick on the metal surface [1.36].

The use of PVD layers greatly reduces deposit formation and makes it possible to perform less risky cleaning of the surface.

The use of PVD layers can in some cases considerably extend the service life of the molds (by as much as 20 times). Greatly extended service lives have been demonstrated in molds exposed to corrosive attack, e.g. from the processing of flame-retardent polyamide or acetal [1.57]. A further major advantage is a lowering of release forces.

1.6 Laser Surface Treatment

Laser surface treatment methods rank among the special finishing procedures. Aside from its widespread use for cutting and welding, laser surface treatment is finding more and more widespread application in industrial practice. Laser surface treatment methods can be divided into two groups, namely thermal and thermochemical. Laser treatment therefore presents an alternative to conventional hardening techniques for increasing the service life of molds with high component costs.

Thermal variants include laser hardening and laser remelting while thermochemical methods include laser alloying, laser dispersing and laser coating. With the thermochemical methods, the material properties are affected not only by the heat treatment but also by the addition of extra materials. The outer layer properties are improved in respect of the mechanical, tribological, thermochemical and chemical wear resistance of the surface [1.35].

Laser sources nowadays are industrial carbon dioxide lasers rated between 1 and 25 kW and Nd:YAG lasers rated at 0.5 to 3 kW. The beam is focused on the surface of the workpiece, which becomes heated by absorption. The extent of absorption or reflection depends on the wavelength, the material's properties and the texture of the workpiece. Heat incorporation also depends on the intensity of the beam and the exposure time. The exposure time is derived from the rate at which the beam is moved across the surface of the workpiece. Processing usually occurs in adjacent tracks that may or may not overlap. It is thus possible to perform large-scale and partial surface coating [1.35].

1.6.1 Laser Hardening and Re-Melting

All steel and cast-iron materials with a carbon content exceeding 3% can be laser hardened since they harden martensitically. In laser hardening, the workpiece is heated to temperatures above the austenitizing temperature; at the surface, heating is due to absorption of the infrared laser beam and down to a certain depth in the lower zones, due to heat conduction. This heating process occurs so quickly that the cooling which occurs immediately afterwards creates an extremely steep temperature gradient between the workpiece surface and the rest of the workpiece. As the laser beam is moved on, the absorbed quantity of heat is dissipated so quickly inside the workpiece that the critical cooling rate for martensite formation is exceeded (self-quenching) [1.34].

Laser hardening is a partial hardening process in which the focused beam is guided back and forth across the area to be hardened. The advantage of this is that selective hardening can be performed at points where increased wear is expected. As a result, hardening can be performed with very little distortion, zones of partial hardening can be reproducibly created and the workpiece suffers only minor thermal stress. However, the disadvantage is that large areas have to be hardened in several steps.

Laser re-melting is primarily used for cast materials. The heating and subsequent -selfquenching generate supersaturated solutions, metastable phases and amorphous structures. Re-melting generates homogeneous, extremely fine-grained structures in the outer layer of the component. These structures are notable for their high strength and, at the same time, high toughness [1.35].

1.6.2 Laser Alloying, Dispersing, and Coating

Laser alloying is used for completely dissolving additional materials into the base material. Convection and diffusion processes in the melting bath lead to homogeneous mixing of the base and additional materials. The high cooling rates ensure that the additives stay in solution even after cooling. The additive elements and compounds primarily increase the wear and corrosion resistance.

By contrast, laser dispersing does not dissolve the additive but rather keeps it finely dispersed in the base structure. Standard high-melting or dissolving-resistant additives for laser alloying are SiC, TaC, TiC, VC and WC.

Finally, the aim of laser coating is not to cause any mingling of the base and additive materials. A homogeneous, strongly adhering layer is generated on the substrate material. The additive material is completely melted on top and the base structure is only melted in the narrow edge zone to create a metallurgical bond. The most common additive materials are usually low-melting Ni or Co alloys.

1.7 Electron Beam Hardening

In principle, electron beams may be used instead of laser beams. Consequently, electron beam hardening works on the same principle as laser hardening. Bombardment by the electron beam causes rapid heating up and subsequent self-quenching of the outer layer of the workpiece. Since an electron beam is extremely diffuse under ambient conditions and the necessary intensity cannot be attained, processing can only be carried out in high-vacuum chambers. This restriction increases the processing time because a high vacuum has to be produced after the vacuum chamber has been set up. In addition, the cramped conditions of the electron beam equipment restricts the size of the components that can be processed. For these reasons, this process has so far found little industrial use.

1.8 Lamcoat Coating

The Lamcoat process was developed in the USA for smooth, sliding surfaces. In it, a soft layer based on tungsten disulfide is applied mechanically to the mold surface at room temperature. To this end, the mold is first thoroughly cleaned in an alcoholic ultrasonic degreasing bath by means of special high-pressure micro-sprays (no material ablation occurs). Then the tungsten disulfide is applied manually in a spray booth with the aid of dry, purified compressed air at high pressure. The coating material does not accumulate on the surface, however, but penetrates extensively into it to form molecular bonds with the base material. Excess material does not material. As a result, a very thin layer measuring 0.5–1.5 µm is formed that cannot be made any thicker.

Studies in the USA have shown that a Lamcoat coating reduces friction by up to 70%. This leads to lower injection pressures and increases flow paths by up to 10%. Further positive results are shorter cycle times and a 30–70% increase in mold service life [1.33]. This coating technology is currently offered by two companies in Germany.

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2 Mold Making Techniques

Injection molds are made by a highly varied number of processes and combinations thereof.

Figure 2.1 demonstrates the relative costs for cavities made from various materials. Accordingly, steel cavities appear to be many times more expensive than those made of other materials. In spite of this, a cavity made of steel is normally the preferred choice. This apparent contradiction is explained with the consideration that the service life of a steel mold is the longest, and the additional costs for a cavity represent only a fraction of those for the whole mold.

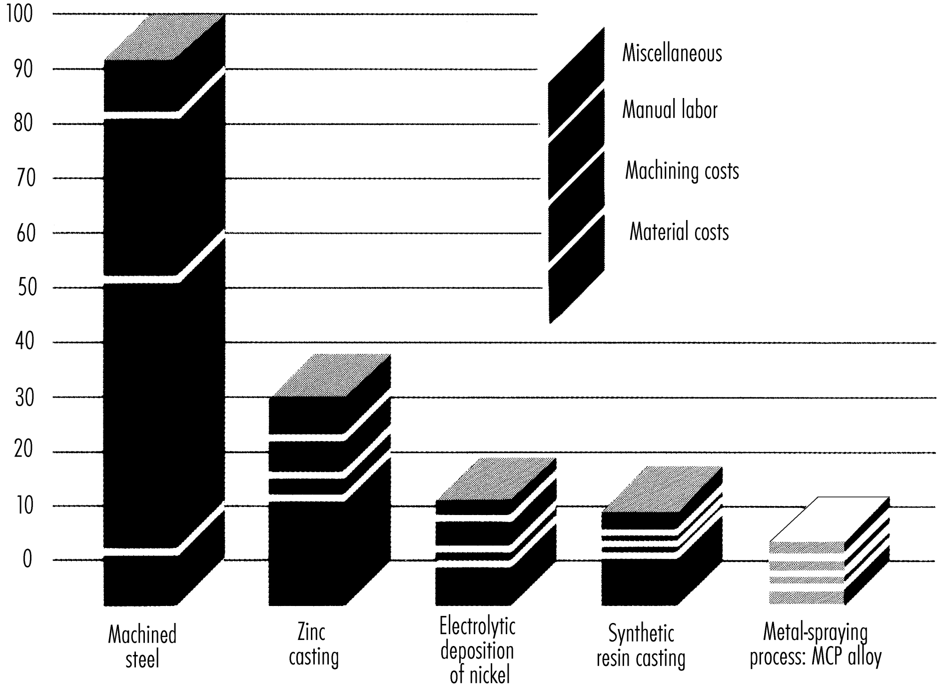


Figure 2.1 Comparison of costs: production methods in mold making [2.1]

Cavities made by electrolytic deposition as well as other procedures, which cannot be done in-house, call for additional working hours until the mold is finally available. This may be rather inconvenient. The making of an electrolytically deposited insert takes weeks or even months. A cavity made of heat-treated steel can be used for sampling without problems and still be finished afterwards. The high production costs also justify the application of a superior material because its costs are generally only 10 to 20% of the total mold costs.

In spite of all the modern procedures in planning, design, and production, mold making calls for highly qualified and trained craftsmen and such personnel are in short supply nowadays. Thus, the production of molds always poses a bottleneck.

It is clear, therefore, that only up-to-date equipment is found in modern mold-making facilities such as numerically-controlled machine tools. With their help one tries to reduce the chances of rejects or to automate the working process without human operator (e.g. EDM).

2.1 Production of Metallic Injection Molds and Mold Inserts by Casting

The production of mold inserts, or whole mold halves by casting, attained a certain preeminence in some application areas for a time. The reason was that the casting process offers suitable alloys for nearly every type of application and that there are hardly any limits concerning geometry. Molds requiring extensive machining could therefore be made economically by casting. Another application area is the simple, more cost effective production of injection molds for low production runs and samples, particularly of non-ferrous metals. Only a brief account of the casting methods for producing mold inserts is provided below. Readers requiring more detailed information are referred to the literature at the end of the chapter.

2.1.1 Casting Methods and Cast Alloys

Of the numerous casting methods available [2.2, 2.3], variants of sand casting and precision casting are used to make mold inserts. The choice of casting method depends on the dimensions of the mold, the specified dimensional tolerances, the desired faithfulness of reproduction and the requisite surface quality.

After casting, the mold essentially has the contours necessary for producing the molding. For large molds cast in one piece, the heat-exchange system can be integrated directly by casting a tubing system or by means of a special arrangement of recesses at the rear through which the temperature-control medium can flow freely.

Generally, the inner contours of the mold (the mold recesses) are cast slightly larger and so require only a minimal amount of additional machining. Another critical factor is the requirements imposed on the surface quality of the molding. Any posttreatment of the surfaces (e.g. polishing) that may be necessary is performed by the same methods as in conventional mold making. Grained and textured surfaces such as can be produced by precision casting mostly do not require posttreatment. With cast molds, just as in conventional mold making, incorporation of holes for ejector pins, sprue bushings and inserts as well as the fitting of slide bars and the application of wear-resistant protective layers are all performed on the cast blank.

The metallic casting materials suitable for mold making fall into two groups:

- ferrous materials (cast steel alloys, cast iron materials), and
- non-ferrous materials (aluminum, copper, zinc and tin-bismuth alloys).

Only cast steel will generally satisfy the mechanical demands of mold inserts that are required for more than just experimental and low-production runs. Furthermore, only steel has an adequate degree of polishability. Many of the steel grades successfully employed in mold making are amenable to casting. However, it must be borne in mind that castings always have a coarse structure that is not comparable to the transformation structure of forged or rolled steels. At the macroscopic level, castings have different primary grain sizes between the edge and core zones. There is limited scope for using subsequent heat treatment to eliminate the primary phases that settle out on the grain surfaces during solidification. For these reasons, when making cast molds, it is best to use steel grades that have little tendency to form coarse crystals or to separate by liquation [2.4]. Some common cast steel grades are shown in Table 1.3.

Not only does thermal posttreatment bring about the improvement in structure mentioned above but it also enhances the mechanical properties, and the necessary notch resistance and stress relief are obtained. The strength, which depends on the carbon content, is lower than that of rolled or forged steel, and so too are the toughness and ductility [2.5]. However, they meet the major demands imposed on them. The service life of cast steel molds depends on the wear resistance and, under thermal load, on the thermal shock resistance. Given comparable steel grades, the thermal shock resistance of cast steels is generally lower than that of worked steels.

Mold inserts of copper and aluminum alloys are made both by casting and machining. Refined-zinc cast alloys for injection molding are used only for making mold inserts for experimental injection, for the production of low runs and for blow molding molds. Refined-zinc cast alloys, like copper alloys, have excellent thermal conductivity of 100 W/(m · K). The mold-filling characteristics of zinc alloys so outstanding that smooth, pore-free surfaces are even obtained in the case of pronounced contours with structured surfaces [2.6]. The most common refined-zinc alloys, sold under the names Zamak, Kirksite and Kayem, are summarized in Table 1.5.

Tin-bismuth alloys, also called Cerro alloys, are comparatively soft, heavy, low-melting metals (melting point varying according to composition between 47 and 170 °C) [2.7]. Particularly suitable for mold making are the Cerro alloys that neither shrink nor grow during solidification. Due to their moderate mechanical properties, Cerro alloys in injection molding are only used for molds for trial runs or for blow molds. Moreover, they serve as material for fusible cores. The physical and mechanical properties of some Cerro alloys are shown in Table 1.8.

2.1.2 Sand Casting

This process is used to produce medium-to-large molds weighing several tons per mold half. It consists of three major production steps:

- production of a negative pattern (wood, plastic, metal),
- production of the sand mold with the aid of the negative pattern, and
- casting the sand mold and removing the cooled casting.

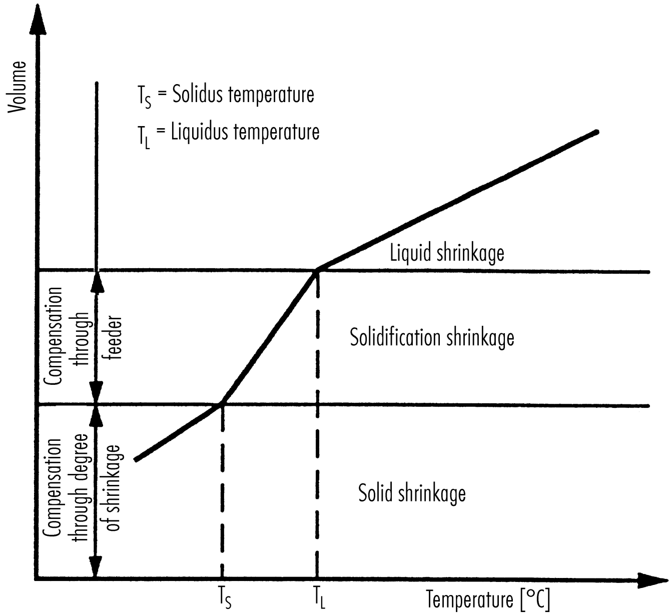
The negative pattern is made either direct or from an original or positive master pattern. To an extent depending on the shape, dimensions, alloy and sand-casting method, allowance must be made for machining and necessary drafts of 1° to 5°. When making the pattern, allowance for shrinkage has to be made. To determine the shrinkage, the dimensional change of the cast metal from solidification and cooling and the shrinkage of the plastics to be processed in the mold have to be taken into account (does not apply to wooden patterns) [2.8]. Typical allowances for a number of cast metals in sand casting are listed in Figure 2.2. The exact measurements in each case depend on the casting method, part size and part shape. These should be set down in the design phase after consultation with the foundry.

The casting mold is made by applying the mold material to the pattern and solidifying it either by compaction (physically) or by hardening (chemically).

A wide range of synthetic mold materials of varied composition is available [2.2]. Washed, classified quartz sand is the predominant refractory base substance. For special needs, e.g. to prevent high-alloy casting materials (cast-steel alloys) from reacting with the melt, chromite, zirconium or olivine sand may be used. The binders used for mold sands are organic and inorganic. The inorganic binders may be divided into natural and synthetic types. Natural inorganic binders are clays such as montmorillonite, glauconite, kaolinite and illite. Synthetic, inorganic binders include waterglass, cement and gypsum.

Organic binders are synthetic resins such as phenol, urea, furan and epoxy resins. In practice, the molds are made predominantly of bentonite-bound (a natural inorganic binder) mold materials (classified quartz sand) that have to be mechanically compacted in order that adequate sag resistance may be obtained.

After the mold has been produced, the pattern is removed. To an extent depending on the requirements imposed on surface texture and alloy, the finished sand mold may or may not be smoothed with a facing. After casting, the finished mold is more or less ready. The sand mold is destroyed when the mold is removed.



Material	Solidification shrinkage in %	Shrinkage in %
Cast iron:		
With lamellar graphite	–1 to 4	0.9 to 1.1
With spheroidal graphite	1 to 6	0.8 to 0.9
Malleable cast iron	5.5 to 6	0.5 to 1.9
Cast steel	5 to 6	1.5 to 2.8
Aluminum base	5 to 6	0.9 to 1.4
Copper base	4 to 8	0.8 to 2.4

Figure 2.2 Shrinkage on solidification and shrinkage for different casting alloys

A somewhat different procedure is employed in the lost foam method. In this, a polystyrene foam pattern is embedded in sand, remains in the casting mold, and is gasified by the casting heat only when the liquid metal is poured into the casting mold. Polystyrene patterns may be milled from slab material (once-off production) or foamed in mold devices (mass production). Since the pattern is generally only used a few times to make inserts for injection molds, the use of CAD interfaces can allow a polystyrene pattern to be milled quickly and cost effectively.

The major advantage of cast molds is the fact that the mold is ready for use almost immediately after casting. Posttreatment is limited, especially if a heat-exchange system has already been integrated by embedding a prefabricated tubing system before casting.

2.1.3 Precision Casting Techniques

Precision casting is used for mold inserts that must satisfy particularly high demands on reproducibility. The techniques are eminently suitable for fine contours and, owing to the very high reproducibility, for the faithful reproduction of surface structures, such as that of wood, leather, fabrics, etc.

A number of different types of precision casting process exist [2.9] that vary in the sequence of processes, the ceramic molding material and the binders employed. Mold inserts are usually made by the Shaw process (Figure 2.3) or variants thereof. For molding, a pattern is required that already contains the shrinkage allowance (see also Section 2.1.2). The patterns are reusable and so further castings can be made for replacement parts. This pattern forms the basis for producing the ceramic casting mold (entailing one, two or more intermediate steps, depending on method chosen). The liquid ceramic molding compound usually consists of very finely ground zirconium sand mixed with a liquid binder. After the mold has been produced, it is baked for several hours at elevated temperatures. It is then ready to be used for casting. After casting, the ceramic mold is broken and the part removed.

Precision-cast parts may be made from the same molding steels employed for making injection molds, but all other casting alloys may also be used. Posttreatment of precision-cast parts is generally restricted to the mounting and mating surfaces, as well as all regions that comprise the mold parting surface.

2.2 Rapid Tooling for Injection Molds

Time and costs are becoming more and more important factors in the development of new products. It is therefore extremely important for the injection molding industry to produce prototypes that can go into production as quickly as possible. To be sure, rapid prototyping is being employed more and more often but such prototypes frequently cannot fully match the imposed requirements. Where there is a need for molds that are as close to going into production as possible, rapid tooling (RT) is the only process by which the molds can be made that will enable the production of injection molded prototypes from the same material that will eventually be used for the mass-produced part. Rapid tooling allows properties such as orientation, distortion, strength and long-term characteristics to be determined at an early stage in product development. Such proximity to series production, however, also entails greater outlay on time and costs. For this reason, RT will only be used where the specifications require it.

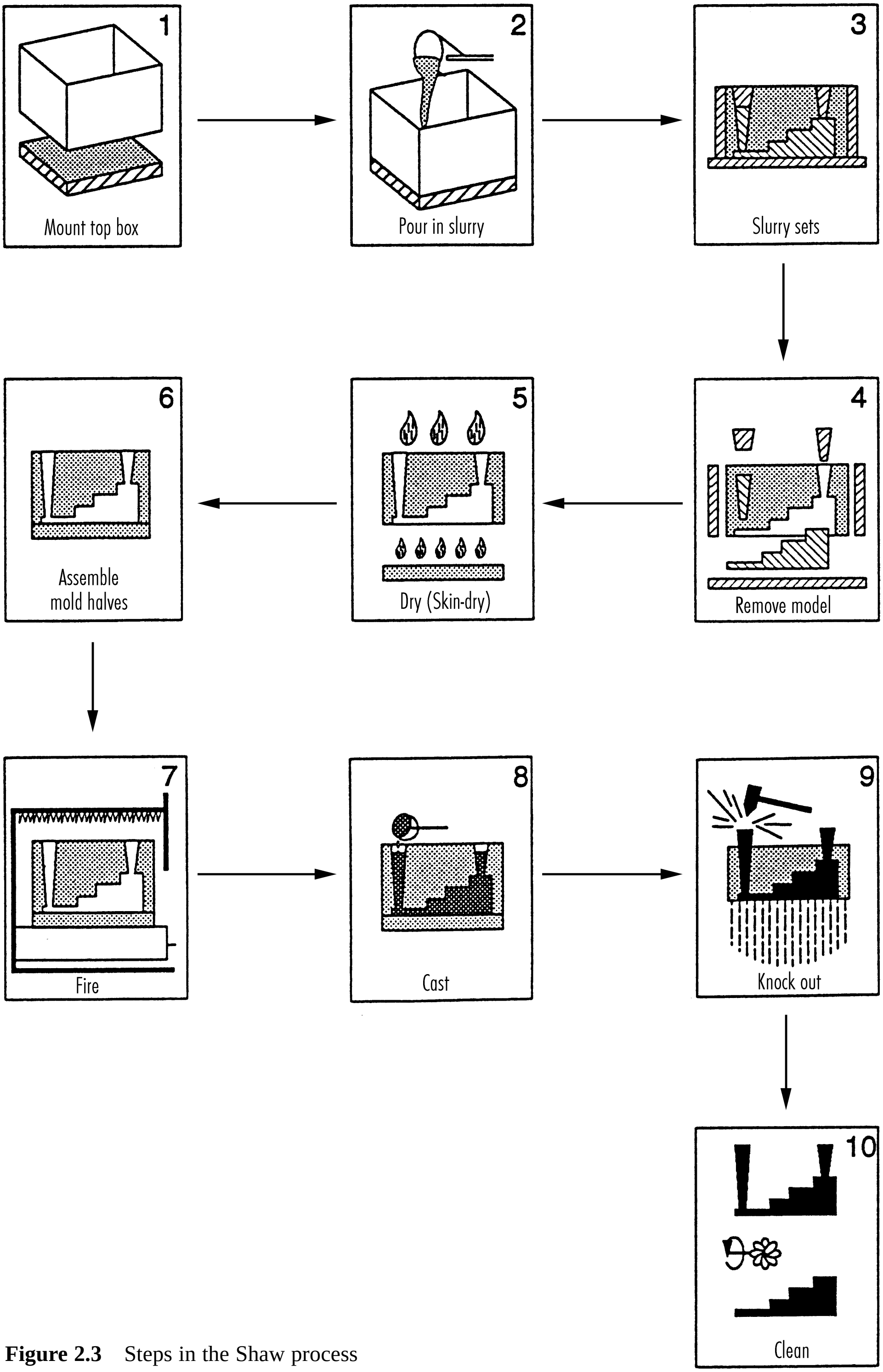


Figure 2.3 Steps in the Shaw process

2.2.1 State of the Art

A breakdown of all RT techniques is shown in Figure 2.4. The material additive processes lead fastest to moldings and are therefore the most promising. These also include new and further developments in RP. Examples of such techniques are laser sintering, laser-generated RP and stereolithography, which enable mold inserts to be made directly from a three-dimensional CAD model of the desired mold.

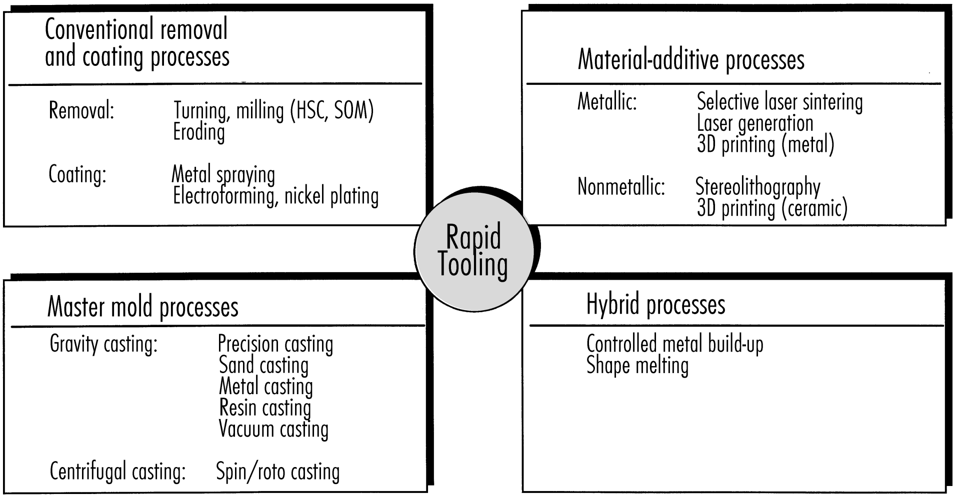


Figure 2.4 Classification of RT processes

RT also covers conventional processes for removal or coating. These include high-speed cutting (HSC) [2.10] with direct control through the processing program generated by the computer from the CAD model; erosion with rapidly machining graphite electrodes; and metal spraying, which has been used for decades in mold making.

Master molding techniques like precision and resin casting may be considered as belonging to RT. These process chains become rapid tooling techniques when an RP technique is used to produce the necessary master mold.

Whereas, in the techniques mentioned so far, the prototype mold is produced either directly by means of a material additive method or in several processing stages, the so-called hybrid techniques integrate several such stages in one item of equipment. These processing stages are a combination of processes from the other three groups (conventional, master-molding, and material additive techniques). Because hybrid techniques combine sequential processes in unit, they can be just as fast as the material additive techniques. All these techniques are still in one development, however.

For a better understanding of the diverse processes and combinations involved, the different RT techniques will be presented and discussed in this chapter.

Figure 2.5 illustrates the general procedure for RT. All methods rely on the existence of consistent 3D CAD data that can be converted into closed volume elements. These data are processed and sliced into layers. 2D horizontally stacked, parallel layers are thus generated inside the computer that, with the aid of a technique such as laser sintering,

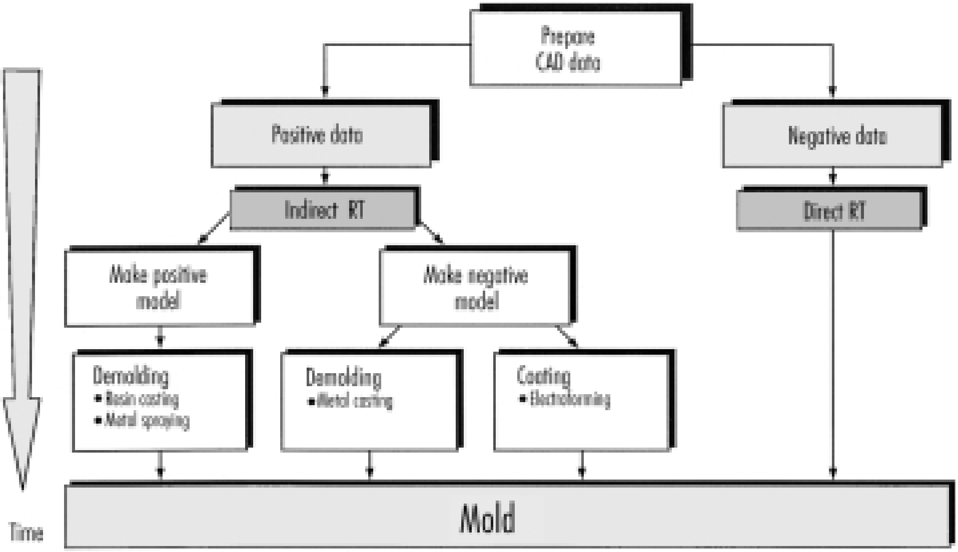


Figure 2.5 Basic approaches to RT

can be successively created within a few hours without the use of tools or a mold [2.11]. Furthermore, there is generally no need for supervision by an operative.

To an extent depending on the principle underlying the chosen RT method, either a positive pattern, i.e. the molding to be fabricated later, or a negative pattern (the requisite mold geometry) is produced. Once a physical positive pattern has been produced, usually any number of moldings may be made by master-molding and coating techniques, which will ultimately lead to a prototype mold after one or more stages. Examples of such process chains are resin casting and metal spraying.

The systematic use of 3D CAD systems during design affords a simple means of generating mold cavities. Most 3D CAD systems already contain modules that can largely perform a conversion from positive to negative automatically.

Once the data have been prepared thus, there are two possibilities to choose from. One is to create a physical model of the moving and fixed mold halves (negative patterns) so as to make a certain number of moldings that will lead to a mold. Metal casting is an example of this. Alternatively, the negatives, perhaps made by stereolithography, may be electrostatically coated. This process chain is shorter than the molding chain just mentioned.

Because the possibilities presented so far involve a sequence of different processes, they are known as indirect tooling. By contrast, direct tooling involves using the generated negative data without intervening steps to produce on an RP/RT system, as is the case with selective laser sintering. Although this is undoubtedly a particularly fast option, the boundary conditions need closer examination. Some of the resultant molds entail laborious postmachining, which is more time consuming.

A major criterion other than subdivision into direct and indirect RT is the choice of tooling material. These are either metallic or so-called substitute materials, the latter usually being filled epoxy resins, two-component polyurethane systems, silicone rubber [2.12] or ceramics.

The more important and promising RT methods are presented below.

2.2.2 Direct Rapid Tooling

The goal of all developments in the field of RT is automated, direct fabrication of prototype molds, whose properties approach those of production parts, from 3D CAD data describing the mold geometry. This data set must already allow for technical aspects of molds, such as drafts, allowance for dimensional shrinkage and shrinkage parameters for the RT process.

Processes for the direct fabrication of metallic and nonmetallic molds are presented below. In either case, the mold may be made from the CAD data direct.

2.2.2.1 Direct Fabrication of Metallic Molds

Direct fabrication of prototype molds encompasses conventional methods that allow rapid processing (machining) of, e.g. aluminum.

2.2.2.1.1 Generative Methods

A common feature of generative methods for making metallic molds is that the workpiece is formed by addition of material or the transition of a material from the liquid or powder state into the solid state, and not by removal of material as is the case with conventional production methods.

All the processes involved here have been developed out of RP methods (e.g. selective laser sintering, 3D printing, metal LOM (Laminated Object Manufacturing), shape melting, and multiphase jet solidification) or utilize conventional techniques augmented by layered structuring (laser-generated RP, controlled metal build-up).

In selective laser sintering (SLS) of metals, a laser beam melts powder starting materials layer by layer, with the layer thickness varying from 0.1 to 0.4 mm in line with the particle size of the metal powder [2.13, 2.14]. The mold is thus generated layer by layer.

Sintering may be performed indirectly and directly. In the indirect method (DTM process), metal powder coated with binder is sintered in an inert work chamber (e.g. flooded with nitrogen). Heated to a temperature just below the melting point of the binder, the powder is applied thinly by a roller and melted at selected sites. The geometry of the desired mold inserts is thus obtained by melting the polymer coating. The resultant green part, which has low mechanical strength, is then heat-treated. The polymer binder is burned out at elevated temperatures to produce the brown part, which is then sintered at a higher temperature. At an even higher temperature again, the brown part is infiltrated with copper (at approx. 1120 °C), solder alloy or epoxy resin [2.15], this serving to seal the open pores that were formed when the polymer binder was removed (Figure 2.6).

In direct laser sintering manufacture, metals are sintered in the absence of binder (EOS process). The advantage of not using coated powders is that the laborious removal of binder, and the possibility of introducing inaccuracies into the processing stage, can be dispensed with. Nevertheless, the part must be infiltrated since it has only proved possible so far to sinter parts to 70% of the theoretical density [2.16]. After infiltration, posttreatment is necessary and generally takes the form of polishing.

Aside from pure metal powders and powders treated with binder, multicomponent metallic powders are used. These consist of a powder mixture containing at least two metals that can also be used in the direct sintering process. The lower-melting component provides the cohesion in the SLS preform and the higher-melting component melts in the furnace to imbue the mold with its ultimate strength. Candidate metals and

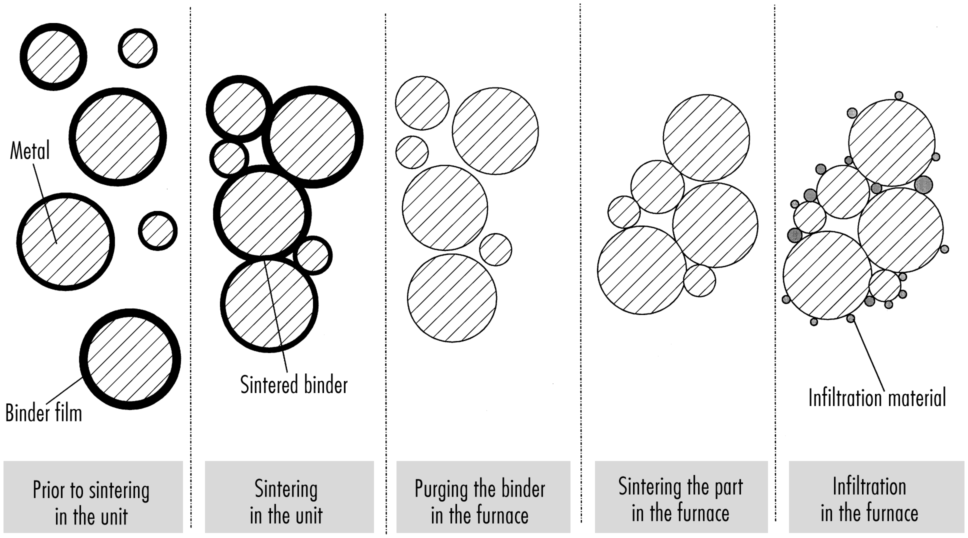


Figure 2.6 Indirect sintering followed by infiltration

metal alloys for direct and indirect sintering are, according to [2.17]: aluminum, aluminum bronze, copper, nickel, steel, nickel-bronze powder and stainless steel. The maximum size capable of being made by laser sintering is currently $250 \cdot 250 \cdot 150$ mm^3.

Another way to apply metal is by laser-generated RP. Powder is continually added to the melt in a movable process head [2.18]. The added material combines with the melted material on the preceding layer. The layers can be added in thicknesses of 0.5 to 3 mm. Metal powder is blown in and melted in a focused laser beam. As the process head moves relative to the work surface, fine beads of metal are formed. The materials used are chrome and nickel alloys, copper and steel. Laser-generated RP is not as accurate as laser sintering and can only generate less complex geometries due to the process setup.

A further development of laser-generated RP is that of controlled metal build-up [2.19]. This is a combination of laser-generated RP and HSC milling (Figure 2.7). Once a layer 0.1 to 0.15 mm thick has been generated by laser, it is then milled. This results in high contour accuracy of a level not previously possible with laser-generated RP. The maximum part size is currently 200 mm^3 for medium complexity. No undercuts are possible.

Other processes still undergoing development are shape melting and multiphase jet solidification [2.20]. Both processes are similar to fused deposition modeling, which is an RP process [2.21]. In shape melting, a metal filament is melted in an arc and deposited while, in multiphase jet solidification, melt-like material is applied layer by layer via a nozzle system. Low-melting alloys and binders filled with stainless steel, ceramic or titanium powder are employed. As in SLS, the binder is burned out, and the workpiece is infiltrated and polished. However, the two processes are still not as accurate as SLS.

3D printing of metals is now being used to fabricate prototype molds for injection molding, but it is not yet commercially available. Figure 2.8 illustrates how the 3D printing process works. After a layer of metal powder has been applied, binder is applied selectively by means of a traversing jet that is similar to an ink jet. This occurs at low

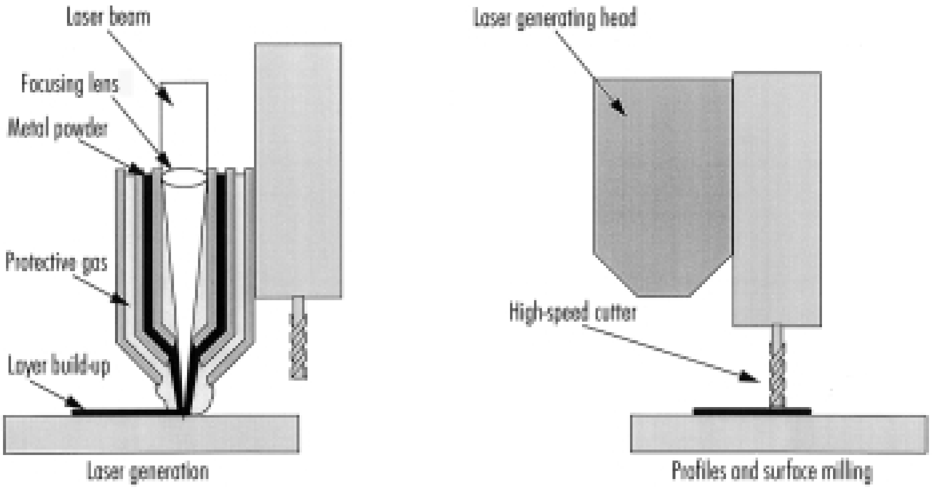


Figure 2.7 Controlled metal build-up after [2.19]

temperatures because only the binder has to be melted. Whereas local heating in direct laser sintering can cause severe distortion, this effect does not occur in 3D printing. Once a layer has been printed, an elevator lowers the platform so that more powder can be applied and the next layer generated. The coating is 0.1 mm thick. When steel powder is used in 3D printing, bronze is used for infiltration. Shrinkage is predictable to ± 0.2%. Part size is still severely restricted by the equipment and currently cannot exceed an edge length of 150 mm [2.21].

Another process currently being developed for the fabrication of metallic molds is that of metal LOM in which metal sheets of the same thickness are drawn from a roll, cut out by laser and then joined together. The joining method is simply that of bolting, according

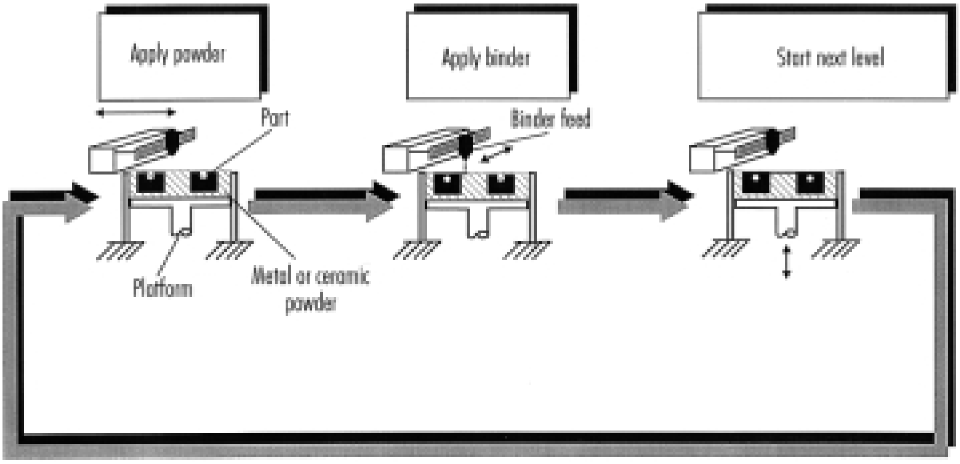


Figure 2.8 Steps in 3D printing

to [2.22]. So far, molds made in this way have only been used for metal shaping and for injection molding wax patterns for precision casting. The advantage of molds joined by bolts is that the geometry can be modified simply by swapping individual metal sheets.

The variant developed by [2.23] is a combination of laser cutting and diffusion welding. Unlike metal LOM and most other RT processes, which grow the layers at constant thickness, this process variant allows sheets of any thickness to be used. As a result, simple geometric sections of a mold may be used as a compact segment, a fact which allows RT only to be used where it is necessary and expedient. Possible dimensional accuracy is in the order of 0.1%. Due to the process itself, it is never lower than ± 0.1 mm in the build direction. The tolerances of laser cutting are from 0.001 to 0.1 mm. Unlike most of the processes mentioned so far, this process imposes virtually no restrictions on part size [2.24].

Direct RT processes are still in their infancy. Apart from selective laser sintering and 3D printing of metals, all the processes discussed in this section are still being developed and so are not yet available on the market. This explains why stereolithography, despite the fact that it is a direct fabrication process involving nonmetallic materials, is virtually the only one used for these purposes. Because it has constantly evolved over the last 10 years and is offered by many service providers, it is readily available. Moreover, many large companies are in possession of stereolithographic equipment and still elect to use it for making prototype molds.

2.2.2.1.2 Direct Fabrication of Nonmetallic Molds

While most direct methods for making metallic molds require posttreatment (infiltration and mechanical finishing), the production of molds from auxiliary materials largely dispenses with this need.

Stereolithography (STL) is based on the curing of liquid, UV-curing polymers through the action of a computer-controlled laser. The laser beam traverses predetermined contours on the surface of a UV-curable photopolymer bath point by point, thereby curing the polymer. An elevator lowers the part so that the next layer can be cured. Once the whole part has been generated, it is postcured by UV radiation in a postcuring furnace [2.24].

STL‘s potential lies in its accuracy, which is as yet unsurpassed. Because it was the first RP process to come onto the market, at the end of the 1980s, it has a head-start over other technologies. Ongoing improvements to the resins and the process have brought about the current accuracies of 0.04 mm in the x- and y-axes and 0.05 mm in the z-axis.

The process was originally developed for RP purposes but is also used for rapid tooling of injection molds because of its accuracy and the resultant good surfaces which it produces. When STL is used to make a mold cavity, the mold halves are generated on the machine and then mounted in a frame. Usually, however, the shell technique is employed. In this, a shell of the mold contour is built by STL and then back-filled with filled epoxy resin [2.25]. The use of the shell technique to produce such an RT mold is illustrated in Figure 2.9.

Parts made by stereolithography feature high precision and outstanding surface properties. Unlike all other direct methods for making metallic molds, no further treatment is necessary other than posttreatment of the typical step-like structure stemming from the layered build-up by the RP/RT processes. This translates to a considerable advantage time-wise, particularly when the mold surfaces must be glossy and planar. The downside is the poor thermal and mechanical properties of the available resins (acrylate, vinyl ether, epoxy), which cause the molds to have very short service

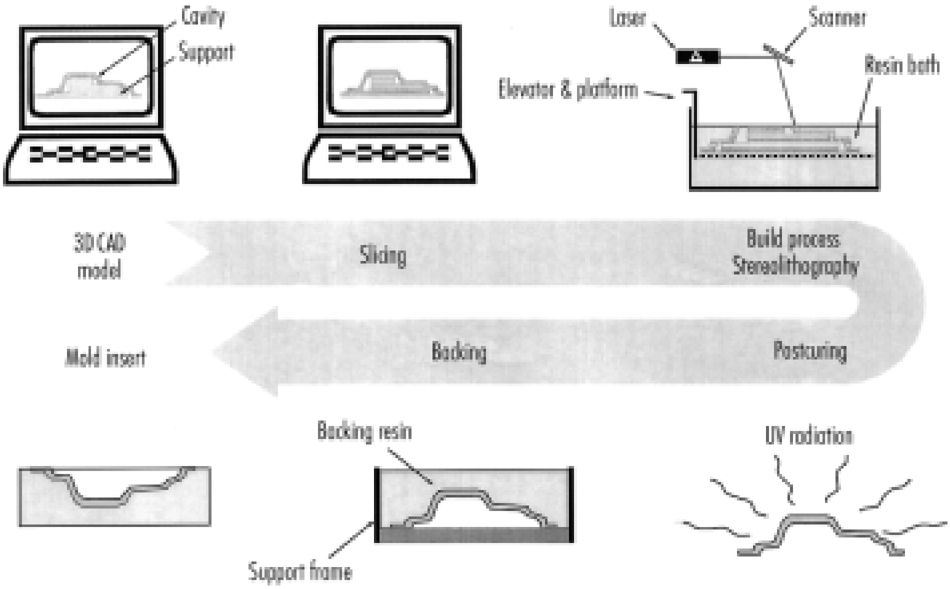


Figure 2.9 The shell technique for generating an STL mold

lives. The best dimensional and surface properties are obtained with epoxy resins; the use of particularly powerful lasers makes for faster, more extensive curing of the resin even during the stereolithography process, and this in turn minimizes distortion [2.26].

Although STL has primarily been used for RP, the number of RT applications is on the increase. It is used to make molds for casting wax patterns as well as for injection molding thermoplastics. Such molds serve in the production of parts for a pilot series, which can yield important information about the filling characteristics of the cavities. Moreover, it is even possible to identify fabrication problems at this very early stage.

Ceramics are other materials used for direct rapid tooling. Bettany [2.27] has reported on the use of ceramic molds for injection molding. They are employed in the 3D printing process described in the previous section as well as in ballistic particle manufacturing (droplets of the melted material are deposited by means of piezoelectric ink-jet nozzle). The advantage over metallic molds is the high strength of ceramic molds. This comes particularly to the fore when abrasive, filled polymers are processed.

2.2.3 Indirect Rapid Tooling (Multistage Process Chains)

An RT chain is defined here as a succession of individual molding stages. The use of such a molding chain leads from a master pattern to a cavity that may be used for injection molding. In the sense of this definition, intermediate stages such as machining or simple assembly of already finished cavity modules do not count as individual links in this chain. A good RT chain is notable on the one hand for having a minimum number of molding stages (chain links). The lower the number of molding stages, the more accurately the part matches the master pattern and the faster a prototype mold can be made. Every intermediate pattern can only be as good as the pattern from which it