1
Semi-solid Forming of Aluminium and Steel – Introduction and Overview*

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1.1
Introduction

The origins of semi-solid metal forming date back to the early 1970s, when Flemings and co-workers studied the flow behaviour of metals in a semi-solid state [1]. Soon the first industrialization by Alumax and ITT-TEVES was achieved for automotive applications such as chassis components, brake cylinders, rims and so on. Many patents, particularly concerning the production of the required specific primary material, hindered wider development during that time. At the end of the 1980s, an intensive development period started also in Europe. With the alternative electromagnetic stirring methods implemented by Pechiney (France), Ormet (USA) and SAG (Austria), primary material in variable dimensions and quality became available. New heating technologies and online-controlled pressure casting machines constituted the basis for appropriate production equipment. This led to various impressive mass production applications in the field of chassis (e.g. Porsche, DaimlerChrysler, Alfa Romeo) and car body components (e.g. Audi, Fiat, DaimlerChrysler, in addition to lower volume production for other fields. However, due to the increasing contest with the rapidly improving quality of highly cost-effective fully liquid casting processes, some of these activities have been terminated in the meantime. One reason, namely the cost disadvantage caused by the use of special primary material, could be reduced by the introduction of new rheocasting processes, which helped to keep several applications of forming in the semi-solid state. For example, STAMPAL (Italy) changed the production of some components from 'classical thixocasting' to 'new rheocasting'. Other challenges are the narrow process windows for billet production, reheating and forming, which have to be maintained to achieve highly repeatable production. This requires a fundamental and detailed understanding of the physical basics of each process step, taking into account details of the material behaviour and microstructure development.

* A List of Abbreviations can be found at the end of this chapter.

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The worldwide intensive efforts in industry and science to develop semi-solid metal forming are motivated by the significant technological and scientific potential which these innovative technologies can provide:

- *Compared with conventional casting*, the high viscosity of semi-solid metal allows macroscopic turbulence during die filling to be avoided and subsequently reduces part defects that could arise from air entrapment. A second advantage is that due to high solid fraction of about 40% during die filling the loss of volume during complete solidification is reduced, leading to correspondingly reduced shrinkage porosity or allowing higher cross-sectional changes than are possible in conventional castings. Furthermore, the low gas content leads to microstructures which are suitable for welding and heat treatment even in very filigree components, which among others is an essential argument for the existing thixocasting serial production of aluminium alloys for the automotive industry. In addition, the lowered process temperature of the semi-solid metal can lead to a significant increase in tool life compared with conventional die casting.
- *Compared with conventional forging*, thixoforming offers significantly reduced forming loads and the opportunity to produce complex geometry components, which could not be produced by forging. In addition the near net shape capabilities of thixoforming reduce machining to a minimum. However, the usually wrought high-strength aluminium alloys, which are typically used in forging, are not well suited for semi-solid forming, especially because they have a tendency for hot cracking during solidification. Therefore, the superior mechanical properties of forged components cannot completely be achieved by thixoforming. Also, the production cycles in forging are much shorter than in thixoforming, which requires time for solidification. Accordingly, a substitution of forging by semi-solid forming will only offer economic benefits if parts with significant added value can be produced. This could be achieved by increased geometric complexity, by weight saving when substituting steel by aluminium or by production of composite components. Additional benefits may arise if some final machining or joining operations can be avoided.

Industrial thixocasting of aluminium alloys is based on the benefits in comparison with casting processes, which have led to various serial production methods in spite of the additional costs for primary material and investment costs for heating equipment. However, there is strong competition with highly economical and improved casting processes such as vacuum casting, squeeze casting, fully automated die casting and optimized casting aluminium alloys such as AlMg5SiMn. This strictly limits the range of economically feasible semi-solid forming applications to such components, which fully exploit the technical advantages listed above. In addition, the narrow process window and the complexity of the process chain require significant experience in semi-solid metal series production, which is today available for example at SAG (Austria), Stampal (Italy), AFT (USA), and Pechiney (France).

Thixoforming of higher melting iron-based alloys has also been investigated in early work at MIT [2, 3], Alumax [4] and Sheffield University [5]. However, these activities, which showed impressive success, nevertheless faced significant technological challenges and they were not in the centre of general interest, which at that time was much more focused on aluminium alloys. Not before the middle of the 1990s did semi-solid forming of steel become the focus of various research activities worldwide [6–14]. In these projects, the general feasibility of semi-solid forming of higher melting point alloys was demonstrated. The major challenges, however, which still need to be overcome, are mainly related to the high temperature range, which causes high thermal loading of tools and dies and difficulties in achieving a homogeneous temperature distribution in the billet. Also, the tendency for oxidation and scale formation and in some alloys the complex microstructure evolution during reheating cause difficult problems to solve.

Concerning the competition between semi-solid forming of steels and conventional casting and forging technologies, the situation differs significantly from that discussed above for aluminium. The reason is that cost-efficient permanent mould casting processes for steel do not exist. This is currently restricted by the high thermal loading that the dies and injection systems would have to face. Thixoforming, however, is performed at lower temperatures and, even more important, the internal energy of semi-solid metals is significantly reduced compared with the fully liquid state. This means that using the high fluidity of semi-solid steels, it might for the first time become possible to manufacture near net shape steel components with complicated geometry in a single-step permanent mould process.

Conventionally forged steel components may also be geometrically complicated, but the relation between flow length and wall thickness is much smaller than in semi-solid forming. Also, complex geometries require multi-stage forging processes and significantly more final machining. This indicates that the application potential for semi-solid forming of steels could be significantly higher than for aluminium alloys. However, there are still challenging technical and scientific problems to solve.

The goals of this book are as follows:

- to summarize fundamental knowledge and technological applications for semi-solid forming;
- to contribute to a better understanding of the governing relations between the process parameters and the achieved part quality and to present selected technological solutions to overcome existing process challenges.

Since several books and longer reviews have already been written focusing on semi-solid forming of aluminium alloys and with respect to the market potential described above, most of this book is dedicated to semi-solid forming of steels. However, the methods applied and most of the results achieved are also valid for other alloy systems.

The rest of this introductory chapter will give a brief overview of the development and state of the art of the technology of semi-solid metal forming. Part One covers the material science aspects such as microstructure evolution and characterization in the semi-solid condition. Part Two is dedicated to numerical modelling of the constitutive material behaviour and its application in process modelling. This involves both two-phase modelling and micro–macro coupling, since both must be taken into account for an adequate representation of the material behaviour. Part Three is related to tool and die technologies, which are one of the major challenges for semi-solid forming of high-temperature alloys such as steel. Part Four presents technological applications and process alternatives of semi-solid forming.

1.2
Early Work on Flow Behaviour and Technology Development

1.2.1
Basic Findings Concerning the Rheology of Metals in the Semi-solid Condition

The development of semi-solid forming of metals dates back to early work of Flemings in the 1970s [15]. He and his co-workers studied the behaviour of solidifying metallic melts under conditions in which they form a suspension of globular primary solid particles in a liquid metallic melt (Figure 1.1b). At that time, this was achieved by stirring the slurry while cooling it to the desired temperature. The initial findings clearly showed that under such conditions the viscosity of metals in the semi-solid state depends on the solid fraction, shear rate and time history. Even though this behaviour is to be expected for two-phase emulsions, it was a fairly new discovery for metallic systems, which under normal conditions would have shown a dendritic microstructure (Figure 1.1a).

The observations concerning the flow behaviour, which were achieved in Couette-type rheometers, may be summarized as follows:

- *Influence of solid fraction*
  The viscosity strongly depends on the volume fraction of solid particles, typically showing a steep increase when the solid fraction becomes higher than 35–50%.

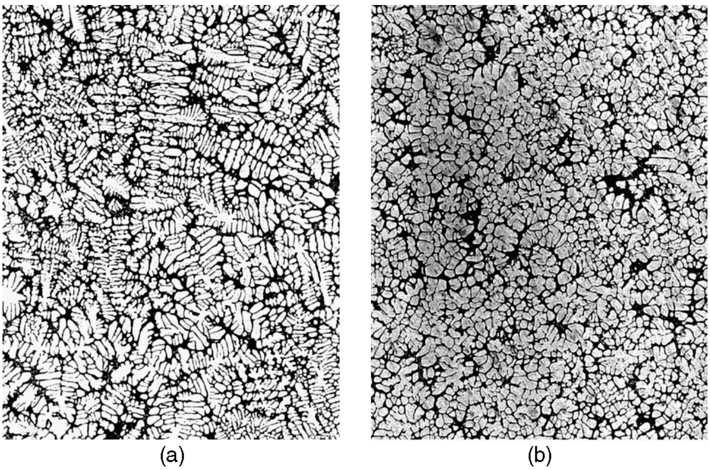


Figure 1.1 (a) Dendritic and (b) globular microstructure.

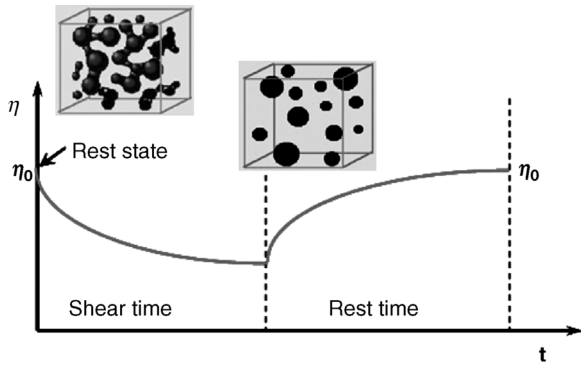


Figure 1.2 Time-dependent thixotropic behaviour.

- *Influence of shear rate*
  Varying the shear rate in the rheometer revealed that the apparent viscosity also depends strongly on the actual shear rate. For example, in an Sn–15Pb alloy at a solid fraction of 40%, the viscosity varies from about 10^6 Pa s at a shear rate $0.001\ s^{-1}$, which is typical for glass working, to 10^{-2} Pa s at $200\ s^{-1}$, which is similar to bicycle oil [15].

- *Influence of time history*
  If semi-solid slurries are allowed to stand, the globular particles tend to agglomerate and the viscosity increases with time. If the material is sheared, the agglomerates are broken up and the viscosity falls. This time-dependant thixotropic behaviour is shown schematically in Figure 1.2.

Many studies have been performed since then to investigate this behaviour in more detail for different alloys, to explain the governing mechanisms and to derive models to describe the material response. One mechanism, which distinguishes semi-solid metal slurries from other suspensions, is that the particle shape and size vary irreversibly with time, as shown in Figure 1.3.

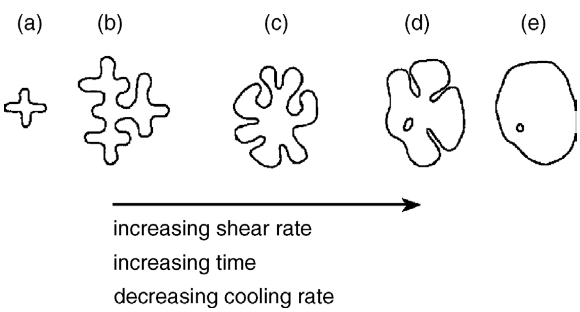


Figure 1.3 Schematic illustration of evolution of structure during solidification with vigorous agitation: (a) initial dendritic fragment; (b) dendritic growth; (c) rosette; (d) ripened rosette; (e) spheroid [15].

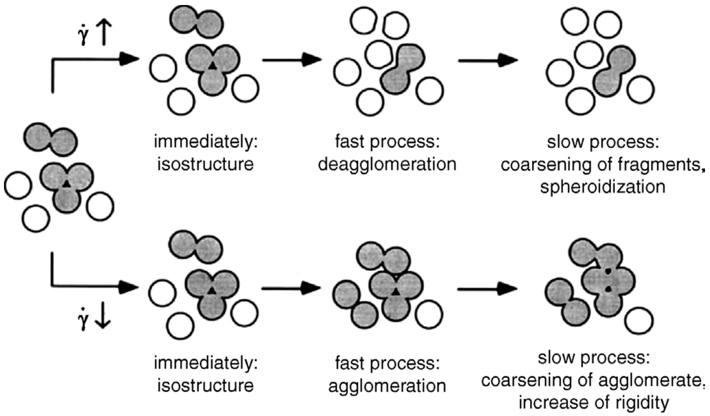


Figure 1.4 Schematic model describing the fast and slow processes in a semi-solid material's structure after up and down jumps of shear rate [16].

This mechanism is combined with agglomeration of particles and breakdown of agglomerates with increasing and decreasing shear rate (Figure 1.4). Thus the transient material behaviour is governed by a combination of fast, reversible and slow, irreversible mechanisms.

This combination and the tendency that under the influence of shear and pressure gradients a separation of liquid phase and solid particles may occur cause difficulties for appropriate material modelling. One-phase models, which assume a shear rate and time-dependent viscosity, can be sufficient to describe the die filling in semi-solid casting, especially in cases where metal flow is mainly governed by the imposed boundary conditions due to the geometry of the part. However, the part quality is also determined by the distribution of the chemical composition, which is dominated by the occurrence of liquid–solid separation. This can only be modelled using two-phase models, which solve the governing flow equations for the liquid and solid phase separately while imposing appropriate coupling terms. A comprehensive review concerning the rheology of semi-solid metal slurries and their material modelling has recently been prepared by Atkinson [16]. Here, Chapter 3 will be dedicated to this topic, describing experimental procedures and modelling approaches on both the micro- and macro-scales.

1.2.2
First Steps Towards a Semi-solid Metal-forming Technology

Already at a very early stage, the general idea arose that this specific flow behaviour could be beneficial for forming processes. Most of the potential advantages, which have been presented in Section 1.1, were already seen from the very beginning [15]. With respect to market potential and temperature range, it was straightforward that the technological exploitation concentrated on aluminium alloys, being of interest for many structural applications while offering a moderate temperature range below 600 °C for semi-solid processing. However, the idea of producing the slurry by cooling from liquid turned out not to be a practical solution at that time and the breakthrough was not achieved until an alternative route was found. This new route was based on the idea that a suitable suspension of globular solid particles in a liquid melt could also be achieved by reheating solidified billets to the desired liquid fraction, if these billets were prepared to have a fine-grained globular microstructure. Accordingly, the emerging technology, which was used to demonstrate the feasibility to manufacture complex parts, consisted of three major steps [18]:

- *Billet production:* Proprietary technologies were developed to cast billets with a fine-grained globular microstructure. These technologies included direct chill casting with active (mechanical or electromagnetic) or passive stirring and thermomechanical processing of solid feedstock (see Sections 1.3.1.1 and 1.3.1.2).
- *Reheating to the semi-solid condition:* The necessity to heat billets accurately and homogeneously to the semi-solid condition required specific heating strategies and the development of adequate equipment and control systems. Inductive heating was preferably used, but also conventional radiation/convection-type furnaces were applied in series production (see Sections 1.3.2.1 and 1.3.2.2).
- *Forming operations and applications:* After reheating, the semi-solid billet is usually formed into the final shape in just one forming operation. Two basic forming principles are generally applicable:
  - In thixocasting the billet is injected into a closed die, as in high-pressure die casting.
  - In thixoforging, the billet is formed by using an upper and a lower die which move against each other. Using these principles, relatively complex and challenging demonstrator parts were already manufactured in the 1980s, such as automotive brake master cylinders, automobile wheels, electrical connectors, valve bodies and plumbing fittings [18].

1.3 Today's Technologies of Semi-solid Metal Forming

Over the years, a family of process routes and process alternatives for semi-solid forming have evolved from this early work. Reviews concerning these technologies and their industrial application have been published [18–21]. Some of them have succeeded in being applied in industrial mass production; others are still limited to the laboratory scale. Generally, these process routes can be structured according to Figure 1.5.

Following the early idea of separating the slurry preparation from the forming operation, various methods to provide solid billets with a fine-grained globular microstructure have been developed. These will be briefly discussed in general in Section 1.3.1, whereas specific details are given later in Chapter 4. Before forming,

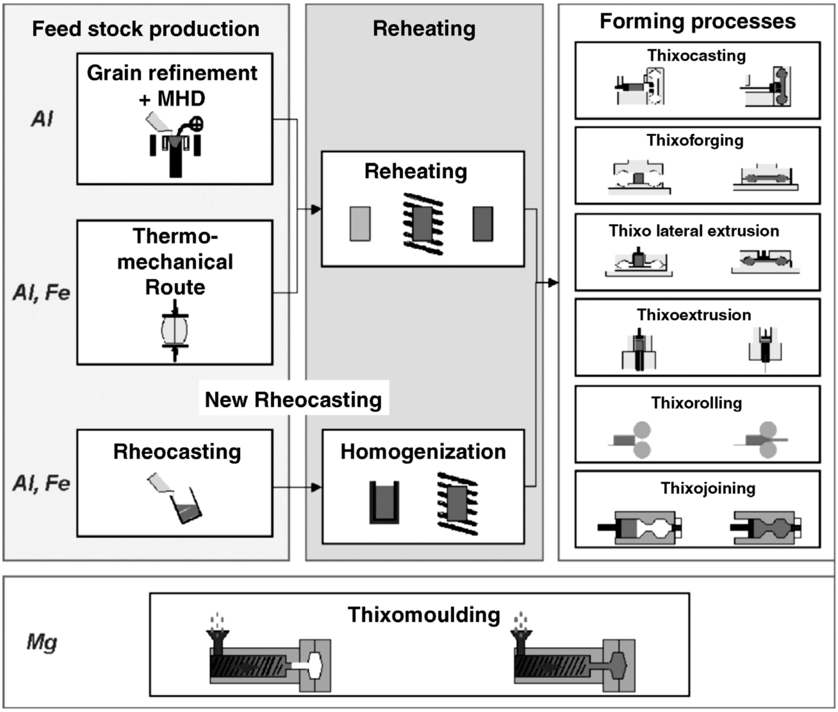


Figure 1.5 SMM process routes.

the billet has to be brought to a homogeneous semi-solid condition. Depending on the process route, this can be a reheating stage (see Section 1.3.2) or a homogenization and/or consolidation stage in the more recently developed routes which create the slurry directly from liquid stage (see the overview in Section 1.3.3 and discussion of specific aspects in Chapters 4 and 9). The further processing of the billet or slurry is then performed using modifications of conventional processes such as high-pressure die casting, forging, lateral extrusion, bar extrusion and rolling. Of these, only semi-solid casting and to a lesser extent modifications of semi-solid forging have so far been applied to industrial production (see Sections 1.3.4 and 1.3.5 for an overview and Part Four for specific details).

A completely different approach is the thixomoulding of magnesium alloys. This process uses magnesium chips and a modified injection moulding machine to produce magnesium components in a process similar to polymer injection moulding. The solid chips are fed through the screw system of the machine where they are heated to the semi-solid condition. The slurry is accumulated in the casting chamber and injected into the die. The process is commercially applied mainly for electronic products such as laptop housings and so on where magnesium substitutes polymers. The advantage lies in the fact that the problems which are related to the handling of liquid magnesium, as in hot-chamber high-pressure die casting, can be avoided.

1.3.1
Preparation of Billets for Semi-solid Forming

1.3.1.1 Direct Chill Casting

Direct chill casting is an established process for the production of aluminium billets for forging, extrusion and rolling. Accordingly, it was an obvious idea to use this process to produce billets with a fine-grained globular microstructure that were required for the thixoforming route. Transferring the observations from the early rheometer tests initially resulted in laboratory concepts using active mechanical stirring to produce a slurry before feeding it into the direct chill (DC) casting mould (Figure 1.6a). This, however, was soon replaced by DC casting with magnetohydrodynamic (MHD) stirring in the mould, thus directly influencing the solidification by vigorous agitation to avoid the formation of dendritic structures. Patents [22–24] introduced variations of this idea, such as circumferential or vertical stirring (Figure 1.6 c, d) and a combination of both stirring types.

Alternatives to electromagnetic or active mechanical stirring are the so-called passive stirring and chemical grain refinement. In passive stirring (Figure 1.6b), the liquid metal is forced to flow through a system of obstacles (i.e. ceramic balls) while being cooled into the semi-solid range. The shear generated by this forced flow prohibits the formation of large dendrites and creates 'nuclei' of crystals by dendrite fragments. This process was developed by Moschini [25] and has been used to supply feedstock for the mass production of pressure-tight fuel rails by semi-solid casting.

Also in conventional DC casting of forging or extrusion feedstock, the goal is to produce a fine-grained and homogeneous microstructure. For this purpose, various methods of chemical grain refinement have been developed, providing a large number of 'nuclei' by addition of Al–5Ti–B particles. It has been shown that these procedures in some cases can be adopted to produce feedstock which exhibits the typical microstructure and flow behaviour for semi-solid forming [26, 27].

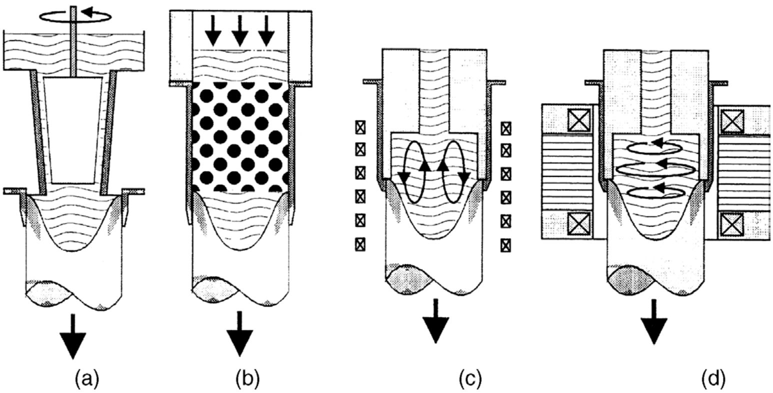


Figure 1.6 Stirring modes: (a) mechanical stirring; (b) passive stirring; (c) electromagnetic 'vertical' stirring; (d) electromagnetic 'horizontal' stirring.

1.3.1.2 Thermomechanical Treatment

In addition to casting, there also exist solid working routes to produce feedstock for semi-solid forming. These routes typically consist of plastic deformation followed by recrystallization during the reheating stage. If reheating is then performed into the semi-solid range, the fine grains start to melt at their boundaries, resulting in globular particles surrounded by liquid. Depending on whether the plastic deformation has been performed as hot working or cold working, the process is referred to as the strain induced melt activated (SIMA) route [22, 28].

Economically, these thermomechanical routes cannot compete with MHD casting of the typically applied aluminium alloys since they involve an additional extrusion step which is usually limited to smaller diameters. However, some high-performance alloys and composites are generally delivered in extruded condition (i.e. after spray forming) and can be used in this condition for semi-solid forming.

However, regarding thixoforming of steels, the thermomechanical route has so far been the most suitable method to provide adequate feedstock from various steel grades. With respect to large-scale production units for steel, there is not much chance of economically casting relatively small amounts of small-diameter feedstock by special DC casting processes.

1.3.2 Reheating of Billets and Alternative Slurry Production

1.3.2.1 Heating Furnaces and Strategies

In the classical thixoforming route, the billets are reheated to the semi-solid condition prior to forming. This reheating step is critical, because it defines the microstructure and flow behaviour of the billet and, depending on the alloy, the reheating may also directly influence the mechanical properties of the final part. For example, when reheating the typically used AlSi7Mg alloy (A357), it is not only important that the final temperature of 580 °C is reached, but also that the holding time allows one to bring the coarsened silicon particles completely into solution, which would otherwise reduce the elongation to fracture since they form relatively large brittle inclusions [29]. On the other hand, undesired grain growth will occur during slow reheating and the mechanical stability of the billet decreases the longer it is maintained in the semi-solid condition.

With respect to these effects reheating of the billets must be:

- quick to avoid grain growth and for economic reasons;
- precise to achieve the desired liquid fraction very reproducibly;
- homogeneous throughout the billet volume to avoid property gradients.

In an industrial environment, mostly inductive heating or radiation/convection heating are used. Although both processes have been applied for industrial heating of billets to semi-solid forming, the use of a classical radiation/convection furnace has only been reported by Moschini [25]. However, this installation was one of the first to perform successfully the mass production of pressure-tight automotive components. The advantage of this concept is the relatively cheap furnace and a robust process control structure. The main disadvantage is the long heating time, which is a consequence of the necessity to transfer the heat through the billet surface.

Typically, inductive heating is used due to the advantages given by shorter heating time and the possibility of flexible process control. Induction allows faster heating, because the heat is generated by eddy currents inside the billet volume even though the so-called skin effect leads to a higher power density close to the billet surface. The skin effect can be characterized by the so-called penetration depth, which is the distance from the billet surface within which approximately 86% of the total power is induced into the billet. For a given billet and induction coil geometry, this penetration depth decreases with increasing frequency of the oscillator. This suggests using low-frequency heating if only the homogeneity of the temperature distribution would have to be considered. On the other hand, low frequency means high electromagnetic forces, which are in contradiction to heating a soft semi-solid billet. Accordingly experience has shown that for typical billet diameters from 76 to 150 mm, induction furnaces in the medium frequency range from 250 to 1000 Hz are to be preferred.

Due to the skin effect, the requirements of homogeneous and fast reheating to the desired semi-solid state are contradictory. Fast reheating would require a high power input, which leads to significant radial temperature gradients. Accordingly, typical heating cycles as shown in Figure 1.7 consist of several stages starting with high power for rapid heating until the surface reaches the target temperature. Consequently, the power is reduced in order to compensate for heat losses due to convection and radiation and in addition allows temperature homogenization by heat conduction inside the billet. In addition to the radial gradients due to the skin effect there are also corner effects at the billet's ends. These can be reduced by special coil design or other standard measures to guide the electromagnetic field [13, 30].

To realize these heating cycles and to reach the cycle time of typical forming operations such as high-pressure die casting, two types of machines have been developed: carousel-type machines and individual billet heating systems. Carousel-type machines consist of a certain number of induction coils (12–16) which are placed around the circumference of a billet carousel (Figure 1.8). During heating, the billets are placed on ceramic pedestals and are indexed from coil to coil by rotating the carousel. Thus a large number of billets are heated at the same time. Typically, several

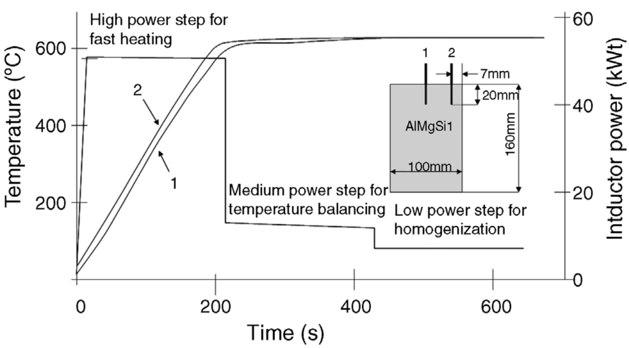


Figure 1.7 Typical heating cycle for AlMgSi1.

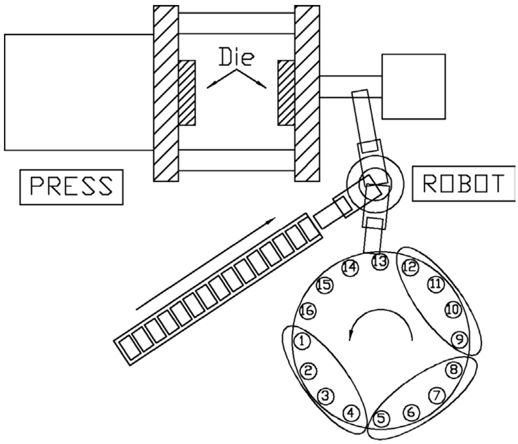


Figure 1.8 Carousel-type machine billet heating system.

groups of coils are created and each group is connected to one frequency generator supplying the group of coils with a certain power input. The heating cycle is realized by passing the billets from group to group. The main advantage of this system is a relatively cheap power supply, which typically consists of three frequency generators each of which is designed for either high, medium or low power input. Also, the mechanical design is relatively simple, requiring a drive for the turntable and a simple pick and place device for billet handling.

The main disadvantage is a lack of flexibility and control, and especially that there is no possibility of controlling the heating cycle of each billet individually. This causes problems at least if there is an unexpected interruption of the forming machine, since it is not possible to put such a system into a 'hold' condition.

This disadvantage led to the development of the individual coil concept, which also heats several billets at the same time. However, in this case each billet is placed in its individual coil, each of which is connected to a separate frequency generator (Figure 1.9). This requires that the number of generators is as large as the number of coils (i.e. 12) and that each generator is designed for the maximum power input required during the initial fast heating period. The advantage is that the heating cycle of each billet can now be controlled individually. The disadvantage is high cost, because in such a case a large number of high power generators are required. Also, the mechanical handling of the billets is more expensive because each coil requires its individual loading device and additionally a robot or other more complex feeding system is required to handle the billets in the different coil locations.

There are two types of individual billet heating set-ups, one where the billet stands in an upright position on the pedestal and the other in a lying position in a transport shell. The first concept has the advantage of easier handling because of the unhindered reachability with regard to automation, but is limited to relatively short billets and lower liquid fraction due to the decrease in the billet's stability. The second concept offers higher flexibility regarding the liquid fraction and the billet's size but has the disadvantage that a container is required for handling.

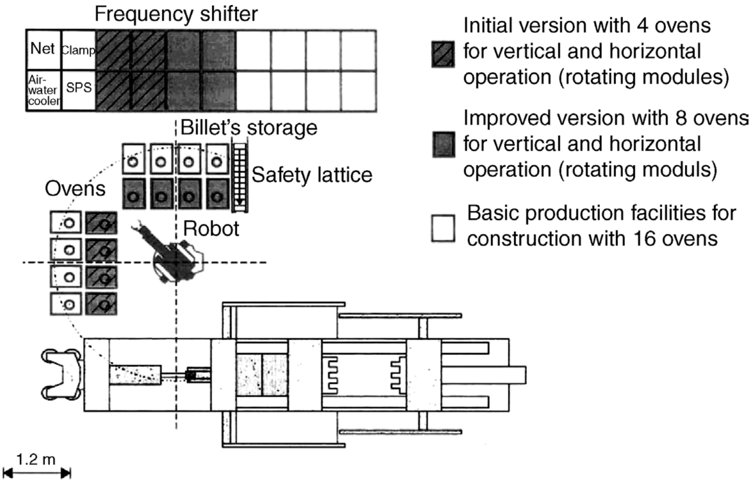


Figure 1.9 Individual coil heating system [31, 32].

In the case of heating steel, protection against the oxidation of the surface by flushing with a protective gas such as Ar or N_2 is required, since otherwise inclusions in finished parts might occur during the subsequent forming operation. This also reduces radiation heat loss, since an oxidized dark steel surface causes increased radiation loss compared with a blank surface.

1.3.2.2 **Control of the Billet Condition During and After Reheating**

A general problem is how to identify whether the heating process has reached the desired condition. A very popular way is to cut the billets with a knife by hand, which gives a lot of information about the general condition and the local 'softness' distribution if it is performed by an experienced person. However, this test does not give quantitative numbers, it destroys the billet and, because it is performed after the process, it cannot be used to control the billet condition during the heating process. The measurement of temperature by thermocouples can be used as an aid in process setup, but it is not precise enough to adjust the liquid fraction accurately because in the semi-solid interval very small changes in temperature can lead to significant changes in liquid fraction (Figure 1.10).

Accordingly, also in the individual billet heating the heating process in many cases is controlled by giving a predetermined power–time curve without control of the billet condition. This results in limited reproducibility if there are some other disturbing factors such as variations in billet composition, billet volume or ambient temperature. An improvement that has been introduced into industrial production plants is to measure the energy that has been induced into the billet. This can basically be achieved by measuring electric parameters which are available in the system [34]. However, even in this case some assumptions concerning efficiency and losses have to be made, which are not completely independent of the mentioned variations of the other process parameters.

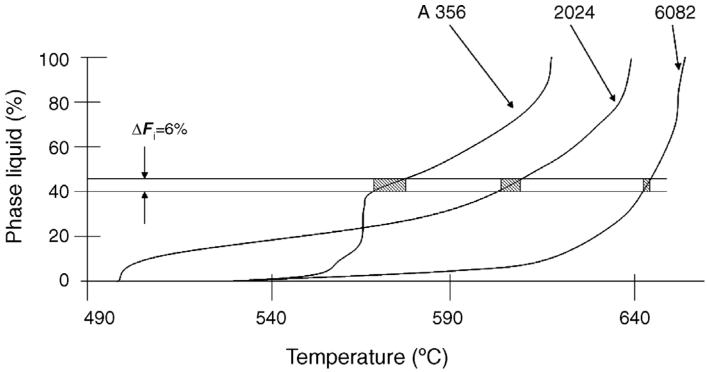


Figure 1.10 Liquid fraction as a function of temperature for various aluminium alloys [33].

In order to set the desired target liquid fraction reproducibly despite the given process fluctuations, some different control concepts have been tested successfully, for instance applying an electromagnetic sensor [33]. This sensor is introduced in the pedestal and detects the change in electric conductivity in aluminium billets resulting from melting. It could be demonstrated that feedback control based on this sensor could manage holding periods within the heating cycle. However, also for this sensor the output values depend on the chemical composition of the billet, which may vary slightly from batch to batch, so that initial adjustments are always necessary. In Part Four, a more detailed discussion concerning the heating strategy for steel will be given and the use of a hybrid strategy will be presented, where a pyrometer is used to detect the onset of melting and from then on a defined power–time curve is used.

1.3.3
Alternative Routes for Slurry Preparation

A major factor contributing to the higher costs of the thixoforming process is the high premium associated with the costs of producing the primary billets with globular microstructure by MHD casting, billet cutting and reheating them to the semi-solid condition. In trying to avoid these costs and also associated metal losses, cheaper and shorter routes to achieve the slurry would be very attractive. In recent years, a family of processes have been developed, which create the slurry during cooling from the melt: cooling slope, low superheat casting, single slug production method, continuous rheoconversion process, SEED process, a method of billet production directly using liquid electrolysed aluminium. Most of these processes make use of the high nucleation rate associated with low-temperature casting and chill cooling, but chemical reactions and other principles are also used.

1.3.3.1 The UBE New Rheocasting Process

The new UBE rheocasting process is based on the principle of feedstock production by manipulating the solidification conditions [35, 36]. The molten metal at near-liquidus temperature is poured into a tiled crucible and grain nucleation occurs on the side of the crucible. The grain size is fine because the temperature is near liquidus. There is no need for specially treated thixoformable feedstock and scrap can be readily recycled within the plant. This new rheocasting route has a lower unit cost than thixoforming, due to the lower starting material cost [35].

1.3.3.2 The Cooling Slope Method

The slurries in the cooling slope method are made by the simple process of pouring the slightly superheated melt down a cooling slope and subsequent solidification in a die. Granular crystals nucleate and grow on the slope wall and are washed away from the wall by fluid motion. The melt, containing a large number of these nuclei crystals, solidifies in the die, resulting in a fine globular microstructure. The size of the ingot is determined by the weight of the molten metal and the die diameter [37]. The ingots can be used directly for rheo- or thixoprocessing after the appropriate reheating. The running costs of the process are significantly reduced in comparison with DC casting with MHD or mechanical stirring, and no special equipment is needed.

1.3.3.3 Low Superheat Casting

The low superheat casting route is shorter than the cooling slope route, using only a die. A slightly superheated melt is poured directly into the die and solidified. For aluminium alloy A356, low superheat casting into a cooper die with melt superheat of more than 10 °C results in a dendritic microstructure after reheating the billet to a semi-solid state (580 °C). Two conditions are necessary when casting ingots appropriate for thixoforming: one is that the superheat is lower than 10 °C, and the other is that the molten metal is rapidly solidified because the cooling rate of the material in the die affects the shape of the primary crystals [37].

1.3.3.4 Single Slug Production Method (SSP Method)

The globulitic structure is generated in the same way as in the MHD-method. A magnetic field causes stirring of the molten mass. The growing dendrite structure is destroyed by shear forces generated by the flow. In comparison with MHD, the microstructure of the single slug production (SSP)-processed billet has a fine globular α-phase [38]. Using the SSP process, billets can be produced in near net shape quality directly in the heating device. This method provides the flexibility to change alloys rapidly and the capability to process alloys that are usually difficult to cast. For more details, see [38].

1.3.3.5 The Continuous Rheoconversion Process (CRP)

The continuous rheoconversion process (CRP) is based on a passive liquid mixing technique in which the nucleation and growth of the primary phase are controlled using a specially designed 'reactor'. The reactor provides heat extraction, copious nucleation and forced convection during the initial stage of solidification, thus leading to the formation of globular microstructure. The CPR reactor is mounted above the shot sleeve of a die casting machine. During each run, a dosing furnace is used to pump melt from the holding furnace to the inlet of the reactor. The melt flows through the reactor into the shot sleeve. The slurry fraction solid is adjusted by changing the temperature and flow rate of the cooling water.

Recently, the CRP has been scaled up for industrial applications. Experimental results with various commercial aluminium alloys indicated that the CRP is effective for manufacture high-quality feedstock. Process advantages include the simplicity of the process, a wide process window and the feasibility of recycling scrap metal within the process flowstream [39].

1.3.3.6 The SEED Process

A liquid-based slurry-making process known as the SEED technology for semi-solid forming is currently entering the industrial stages. The SEED process helps to overcome problems with high costs of feedstock. A large range of foundry and wrought alloy compositions (e.g. A206, A319, A356/357, AA6061 and AA6082) can be processed by this technology. In addition, the process can produce different slug dimensions and weights up to approximately 18 kg.

The technology involves two main steps: (1) heat extraction to achieve the desired liquid–solid mixture and (2) drainage of excess liquid to produce a self-supporting semi-solid slug that is formed under pressure. The principle is based on achieving rapid thermal equilibrium between the metallic container and the bulk of the metal by proper process parameter selection such as pouring temperature, eccentric mechanical stirring and drainage of a portion of eutectic liquid. For more details, see [40].

1.3.3.7 Low Superheat Pouring with a Shear Field (LSPSF)

The process named low superheat pouring with a shear field (LSPSF) uses solidification conditions to control nucleation, nuclei survival and grain growth by means of low superheat pouring, vigorous mixing and rapid cooling during the initial stage of solidification, combined with a much slower cooling thereafter. So far, the investigations on A356, A201 and A380 alloys have revealed no eutectic entrapped within the primary phase. The advantages of the LSPSF include process simplicity with high efficiency, easy incorporation into existing metal forming installations and a wide process window for pouring temperature [41].

1.3.3.8 The Gas Bubbles Technique

Flowing of gas bubbles in the melt is another effective means to provide agitation during the initial stages of solidification. The experiments with aluminium alloy A357 showed the possibility of creating a globular semi-solid metal microstructure. With a gas diffuser placed in the bottom of the melt, fine argon gas bubbles are produced. The process is carried out until the predetermined target temperature or solid fraction in the melt is achieved. Then, bubbling is stopped and the melt is allowed to cool, thus leading to a fine globular microstructure [42].

1.3.3.9 Method of Billet Production Directly Using Liquid Electrolysed Aluminium

Another possibility for producing billets with a globular microstructure on an industrial scale is a production line of semi-solid aluminium alloy billets directly using liquid electrolysed aluminium. The line can produce various aluminium alloy billets for the SSP industry (e.g. for an existing production line in China: withdrawal rate 1000 mm min^{-1} or productivity 25 tons per day, diameter range 60–90 mm and set length 4 m [43]).

After the electrolysed aluminium refinement, the liquid alloy is continuously poured into the mould system at a temperature 0–10 °C above the liquidus. Through the electromagnetic stirring, mechanical vibration and cooling, the liquid alloy is formed into a semi-solid slurry. More detailed information is given in [43].

1.3.4
Process Alternatives for Semi-solid Forming

Of the forming process alternatives listed at the beginning of Section 1.3, only the production of individual components has achieved industrial application, semi-solid rolling and extrusion being limited to laboratory trials. For semi-solid forming of shaped parts, the process variants shown in Figure 1.11 utilize the specific flow and forming properties of semi-solid materials with specific modifications in terms of process design and the installed equipment.

Thixocasting (a) describes a process where an ingot billet with liquid fraction in the range 40–60% is squeezed into a closed die by a shot piston, comparable to high-pressure die casting. The process is mainly performed on conventional real-time controlled die casting machines where the shot chamber system is adapted to the semi-solid billet insert. In thixocasting, the die filling velocity is significantly faster than in thixoforging but lower than in conventional high-pressure die casting. The flow properties of the semi-solid material lead to a laminar die filling. By the closed flow front, air enclosed in the die cavity is evenly conducted through venting channels and the division plane. The use of a faceplate within the gating system reduces the entry and inclusion of damaging surface oxides from the reheated billet [14]. Since the highly advanced die technology from high-pressure die casting can be used in this

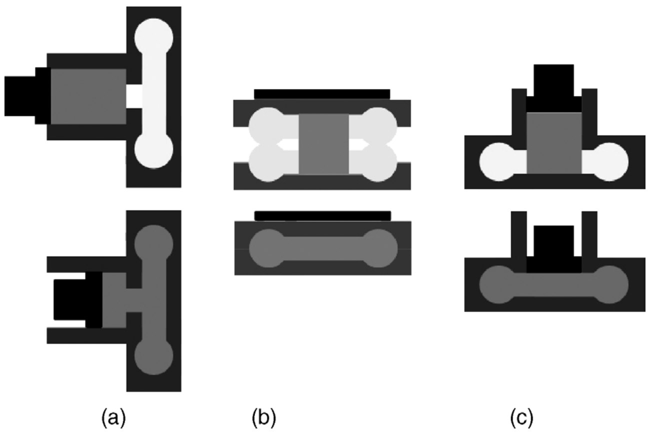


Figure 1.11 Schematic view of different thixoforming processes: (a) thixocasting; (b) thixoforging; (c) thixo lateral extrusion.

process, it is possible to manufacture very complex components. A potential disadvantage is that feeding of shrinkage porosity in some cases might be limited because it mainly has to be performed through the gating system [17].

In thixoforging (b), the semi-solid billet of significantly lower liquid fraction (30–40%) is inserted straight in the lower half of the horizontally sectioned tool analogous to the conventional drop forging process. The forming operation is performed by closing either one or both of the die halves. In contrast to thixocasting, the force transmission for the forming and densification step is applied over the whole tool surface so that hydrostatic pressure is affected evenly during solidification. However, the geometric complexity is limited to geometries which allow forging without flash and oxides on the billet surface must be reduced to a minimum, because there is the risk of including surface during forming.

The process alternative of thixo lateral extrusion (c) is characterized by squeezing the semi-solid material into an already closed die. Using servo-hydraulic presses, the forming velocity is of the same order of magnitude as in thixoforging. However, in terms of the diversity of parts, it allows an increased degree of geometric freedom, for example undercut sections in tooling [17].

1.3.5 Industrial Application Potential

This chapter is intended to give a brief overview of industry-oriented applications of semi-solid metal forming. While industrial mass production is basically limited to semi-solid casting of AlSi7Mg, there have been numerous industrially driven prototype developments with other alloy systems related to automotive and other applications. Most of these applications have been reported in the biennial series of the International Conference on Semi-Solid Processing of Alloys and Composits and there is a review dedicated to light metal alloys [20]. Therefore, this section will only discuss some basic aspects of semi-solid casting of light metals and will give an overview concerning demonstration projects on semi-solid casting and forming of iron-based alloys.

1.3.5.1 AlSi7Mg (A356, A357)

The volume fraction of eutectic in these alloys is about 45%. This and the distribution of liquid fraction as a function of temperature (Figure 1.10) reduce the difficulties to reheating these alloys to a defined liquid fraction just above the eutectic temperature. They also show a good casting behaviour in terms of flow length, joining of flow fronts and little tendency to form hot cracks during solidification. These advantages significantly widen the process window during reheating and forming, allowing defect-free components to be produced. In addition, these alloys show good corrosion behaviour and they offer a wide range of mechanical properties, including conditions of high strength or high elongation to fracture, which can be adjusted by heat treatment procedures and by the choice of the Mg content (0.25–0.45% in A356 and 0.45 to 0.60% in A357). Accordingly, these alloys are dominant in industrial production by semi-solid casting. Since industrial applications are mostly driven by a

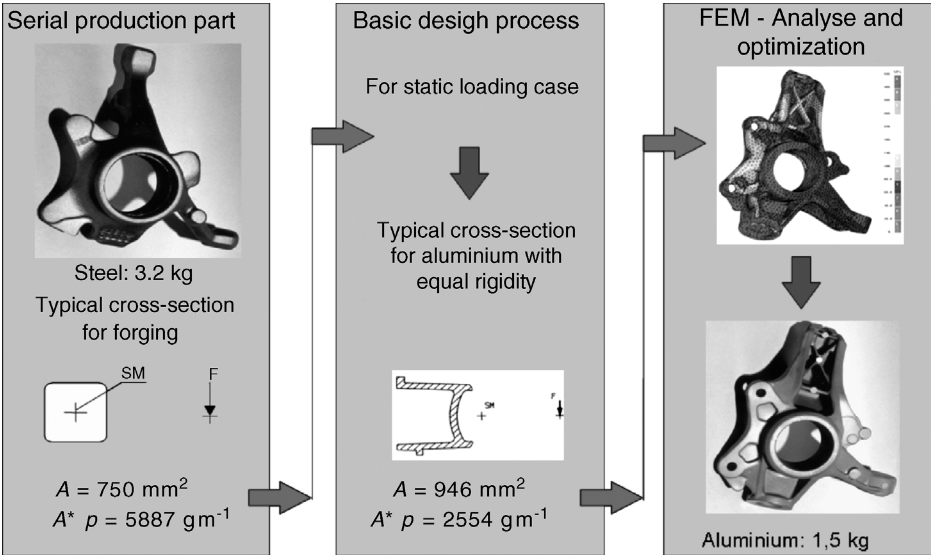


Figure 1.12 Substituting original forged steel steering knuckle (weight 3.2 kg) by A357 semi-solid casting (weight 1.5 kg) [44].

cost–performance relation, successful serial applications make use of the specific superior properties of semi-solid formed components to compensate for the additional costs involved. Examples of such applications include pressure-tight components such as fuel rails (Magneti Marelli), automotive structural chassis and suspension components such as steering knuckles and connecting rods (Stampal), taking advantage of the high mechanical properties, or front door pillars (SAG), requiring close tolerances and high weldability.

One difficulty when introducing the semi-solid metal (SSM) process is that usually it is not sufficient to substitute only the process for a given part geometry. In most cases a process-specific redesign will be required to achieve substantial benefits. This especially holds if the goal is to achieve significant weight savings, that is, by substituting steel forging by semi-solid forming of aluminium. As an example, Figure 1.12 shows the redesign of a forged steering knuckle [44]. The new design uses the process capabilities of semi-solid casting and reduces weight by creating 'hollow' cross-sections with high stiffness, which is not possible in forging. The component, which has been semi-solid cast in A357 alloy, fulfilled all dynamic testing procedures that were required for this component while reducing the part weight to 50% of the original steel solution.

1.3.5.2 Other Aluminium Alloys

Even though the broad range of mechanical properties achievable by the AlSi7Mg alloys covers many technical fields, some applications require specific properties which could be better achieved by other alloy systems. This has led to various alloy developments and demonstration tests to exploit the potential of semi-solid forming also for such cases. These developments show that in most considered aluminium alloys it is in principle possible to create the fine-grained globular microstructure required for semi-solid forming [45, 46]. However, during heating and forming the difficulties in achieving sound parts vary significantly depending on, for example, reheating behaviour, flow behaviour and hot crack sensitivity. Witulski *et al.* have given a list of criteria which can be used to judge the suitability of a specific alloy for semi-solid forming [46]. Selected examples and results are given below:

Applications Requiring High Wear Resistance High wear resistance can be achieved by semi-solid forming of hypereutectic silicon alloys, such as AlSi17Cu4Mg (A390), or by using metal matrix composites (MMCs). Both materials are difficult to cast by conventional processes and may also cause high tool wear in machining. In semi-solid forming, A390 has proved to allow good die filling while achieving a microstructure in which the primary silicon particles are evenly distributed (Figure 1.13).

Feedstock billets from SiC particle-reinforced metal matrix composites such as Duralcan [47] can be produced by MHD casting if particle sedimentation is avoided in

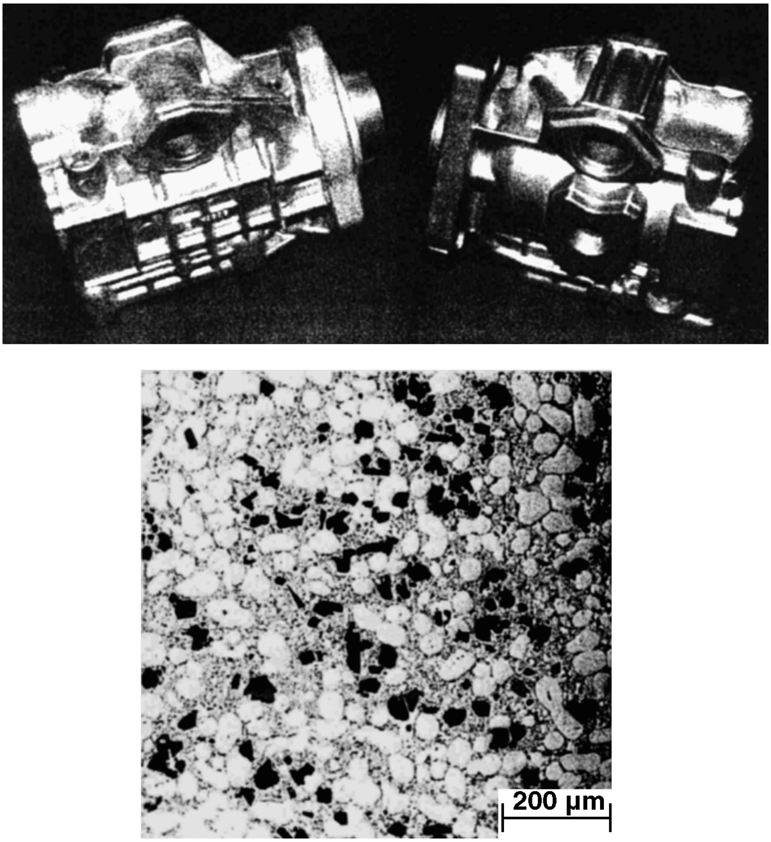


Figure 1.13 Diesel injection pump housing semi-solid cast from A390 and microstructure with even distribution of primary silicon.

Figure 1.14 Space frame node demonstrator and alloy casting performance [49].

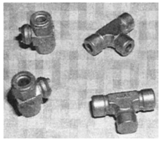
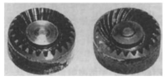
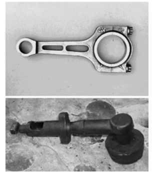
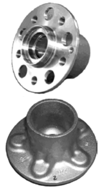
the furnace by appropriate stirring. Then the reheating and semi-solid casting behaviour of these billets is relatively easy due to the stabilizing effect of the non-melting particles. A significant advantage of semi-solid forming instead of casting these materials is that the particles do not agglomerate or separate during the solidification of the parts.

Usually Wrought Alloys (*i.e.* 2*xxx*, 5*xxx*, 7*xxx* Series) These alloys, which are usually forged, are well known for their superior mechanical properties at room and elevated temperature. There have been various attempts to use these alloys also in semi-solid casting [45, 46], but they suffer from a very narrow temperature window, limited 'flow length' and a tendency to form hot cracks. Some success has been achieved using modified alloy compositions of the type AlMg5Si2Mn [48, 49], for example the space frame node for an Audi car structure, which requires a yield strength between 120 and 150 MPa, an ultimate strength above 180 MPa and elongation above 15% (Figure 1.14). This thin-walled structure must achieve these properties without heat treatment to avoid distortion, so that AlSi7Mg was not a possible solution. It has been semi-solid cast successfully from MHD cast billets of AlMg5Si2Mn [49].

1.3.5.3 High Melting Point Alloys (*i.e.* Steels)

In contrast to aluminium, SSM forming of higher melting alloys such as steel has not yet reached the state of industrial applicability due to technological problems, mostly due to the higher process temperature. The investigation of the semi-solid processing of steel started in the 1970s at MIT [2, 3] and was followed by Alumax [4] and the University of Sheffield [5]. These investigations showed by means of successfully produced parts that it is possible to apply SSM to the production of steel components. In the late 1990s, the semi-solid forming of steel again became the focus of great interest because of the expected market potential which was already described in Chapter 1.1. Since then, several Japanese and European projects have been carried out [6–14]. The target of these projects was the development of the necessary technology for semi-solid production of steel components and their common focus was the investigation of suitable steel grades and tool materials. To give an overview of the past research work on semi-solid forming of steels, representative parts of the projects are shown in Table 1.1. It can be seen that part weights from less then 200 g up to more than 3 kg have been produced using carbon steels, tool steels and cast iron.

Table 1.1 Overview of semi-solid processed steel part examples.

					
Year	1992	1992	1996	1997	2003
Process	Thixoforging	Thixoforging	Thixoforging	Thixocasting	Thixo lateral extrusion
Weight	<200 g	~1.3 kg	137 g	1010 g (2 kg*) 379 g (870 g*)	~250 g
Alloy	X105CrMo17, X5CrNi18-10	HS6-5-2, CoCr28MoNi4	FC-10/20/30, FCD-45 (cast iron)	C70S6, 100Cr6, HS6-5-2	100Cr65, HS6-5-3
Tool material	—	Graphite	—	X38CrMoV5-3, TZM	NiCu20TiAl9
No. of part	>1000	~30	—	~250	<30
Reference	[4]	[5]	[6]		[7, 8]
					
Year	2003	2003	2004	2004	2004
Process	Thixoforging	Thixocasting	Thixoforging	Thixocasting	Thixo-, rheoforging
Weight	~630 g	—	3.5 kg	385 g (2985 g) 66 g (3 p. in a shot)	360 g
Alloy	C38, C60, C80, HS6-5-3	FCD450-10 (cast iron)	49MnVS3, 70MnVS5	X210CrW12	X210CrW12, HS6-5-2, 100Cr6
Tool material	Si3N4 ceramics, X38CrMoV5-1, X38CrMoV5-3	Co-base alloy (NGK Insulators, MC-9)	Si3N4 ceramics, X45MoCrV5-3-1, Ni-base alloys	X38CrMoV5-1, Laser sintered direct steel powder	TZM, X38CrMoV5-1, X45MoCrV5-3-1
No. of part	>100	>1200	>100	~30	>100
Reference	[10, 11]	[12]		[17]	[13, 14]

Billet weight.

The temperature window for these alloys is well above 1250 °C and may reach up to 1500 °C depending on the material chosen (see Chapter 3). This means that the heating procedures must take into account severe heat loss due to radiation and also surface degradation caused by scale formation. Accordingly, specific technologies have been developed to achieve acceptable precise, homogeneous and reproducible billet heating results (see Chapter 9). However, as a result of the high temperature differences between the billet and the surroundings, it would require extensive efforts to bring temperature gradients within the billet down to the same homogeneity as in the processing of aluminium alloys.

The excessive cyclic thermal loading of tools and dies causes another challenge for the process. Even though the energy content of semi-solid steel is far below that of fully liquid steel, it causes high temperature gradients and thermal stresses within the tools and dies. So far no efficient tool material that can survive several thousand semi-solid forming operations has been developed. Therefore, the selection of tool materials has to be made by considering given load profiles during the forming operation depending on the forming concept and material. Characteristic properties of several tool materials, which have already been applied in different studies (see Table 1.1), and their suitability regarding semi-solid processing are summarized in Table 1.2. Specific heat capacity, thermal conductivity and density (not included in Table 1.2) are decisive for the thermal balance between workpiece and tool material. On the one hand, high values of these quantities lead to accelerated extraction of heat from the workpiece, which causes a premature solidification, thus resulting in a poor flow length. On the other hand, low values of these quantities lead to an elevated tool temperature on the contact surface, which can cause severe material damage depending on its temperature resistance. The mechanical damage on the tool surface occurs if the local forming pressure exceeds the strength of the tool material at a given local temperature (hot strength). Damage can also occur as a form of corrosion, abrasion or adhesion due to the contact with workpiece material, especially with the steel melt when it comes to semi-solid state. Another typical type of tool damage is propagation of a crack. For a metallic tool material, hot cracking occurs after a large number of thermal shock cycles as a consequence of thermal fatigue. For ceramic tool materials, cracks occur instantaneously when a certain magnitude of thermal shock is exceeded. Even though silicon nitride ceramics possess high thermal shock resistance compared with other ceramics, crack propagation can only be inhibited by maintaining sufficient compressive stress, for example via reinforcement, since it possesses very poor tensile strength, contrary to its high compressive strength. Generally, the combination of high heat capacity, high heat conductivity and low thermal expansion leads to a good thermo-shock resistance, for example for Mo-base alloys. It is possible to combine some of these tool materials within a set of forming dies in order to adjust the tool to the local load profile. In this case, the different expansion coefficients of the tool materials have to be carefully considered for tool construction. Furthermore, an improvement of the applicability of metallic tool materials may be realized by surface coating technologies. For this purpose, different coating concepts are currently being investigated. As tool life is one of the decisive criteria for the economic performance of semi-solid forming of steels, this topic is dealt with in detail in Chapter 8.

Table 1.2 Rating matrix of different tool materials for semi-solid forming of steel.

Material properties and criteria		Hot-work tool steels [51, 52]	Ni-base alloys [51, 52]	Mo-base alloys [53]	Cu-base alloys [51]	Silicon nitride ceramics [50]	Graphite [54, 55]
Specific heat capacity ($J\,kg^{-1}\,K^{-1}$)		480–710	440–550	~310	400–430	700–1200	700–2200
Heat conductivity ($W\,m^{-1}\,K^{-1}$)		25–40	12–55	90–135	250–350	10–20	75–80
Strength ($N\,mm^{-2}$)	at 20 °C	~1500	~1200	~800	440–500	~1000	50–100
	at 600 °C	~1000	~1200	~500	—	~900	65–130
	at 1000 °C	—	~200	~450	—	~600	75–150
Expansion coefficient ($10^{-6}\,K^{-1}$)		11–13	~13	~5.3	~19	2.7–3	3.9–5.3
Temperature resistance		−	0	++	−	++	++
Thermoshock resistance		0	0	+	0	−	+
Adhesion resistance		−	−	+	+	++	−
Flow length		+	+	0	−	++	+

List of Abbreviations

DC	direct chill
MHD	magnetohydrodynamic
MMC	metal matrix composite
SIMA	strain induced melt activated
SSM	semi-solid metal
SSP	single slug production
CRP	continuous rheoconversion process
LSPSF	low superheat pouring with a shear field

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