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Continuous cast iron
for innovative parts
manufacture
Continuous cast iron for innovative parts manufacture

There are numerous examples of how grey (GJL) and SG (GJS) iron can be used to technical and financial advantage. The advantages of these cast iron materials have mainly been described for static casting. The following article looks at continuous cast iron in the form of cast semi-finished products, from which components for all sorts of applications can be manufactured. Continuous cast iron has not yet been standardised. On the initiative of the German Foundry Association (DGV) in Düsseldorf, therefore, four European continuous casting foundries assessed the current development status of continuous cast iron, which is described below.

1 Introduction

In the manufacture of continuous cast iron solidification begins in a water-cooled, open-ended die. Because the thermal conditions are different from those for sand casting, solidification is faster. Depending on the process, this results in properties that differ from those obtained by sand casting and a particularly close-grained, dense material structure. Very high pressure-tightness in respect of liquids and gases is a feature of continuous cast iron [1, 2].

There are no international (ISO), European (EN) or national standards for this continuous cast iron. Representatives of the following four firms therefore analysed the current production status of continuous cast iron and came up with an initial proposal for future standardisation:
- ACO Guss, Kaiserslautern (D)
- Contifonte Groupe Kuhn, Saverne (F)
- Gontermann-Peipers, Siegen (D)
- TASSO, Odense (DK)

Prof. Dr.-Ing. habil. Klaus Herfurth, Solingen, coordinator of the DGV’s “Continuous Casting” ad hoc working party

2 Principles of continuous casting

Continuous cast grey and SG iron is manufactured using the horizontal continuous casting method. Figure 1 shows the three main subassemblies in a horizontal continuous casting plant: a receiver with a flange-mounted, water-cooled, open-ended die that can be changed quickly, a driving and pulling mechanism with an electronic control system, and a cutting and breaking mechanism. As the most important subassembly, the open-ended die is largely responsible for the surface quality of the cast strand, freedom from defects, crystalline structure and casting speed. It is made of graphite and is enclosed by a water-cooled jacket.

The cubic capacity of the receiver depends on the production rate of the continuous casting plant and the supply cycle for the molten iron. The receiver is replenished with molten iron at regular intervals during the continuous casting process, ensuring that the process is uninterrupted.

Having been tapped from the melting furnace, the molten iron is treated (magnesium addition, inoculation) before being poured into the receiver. This process is repeated every 15 to 30 minutes, depending on the strand size and casting speed. Depending on what size of strand is being cast, the temperature of the molten iron in the holding furnace is between 1180 and 1300°C. Because of the thermal balance, the thinner the strand being cast, the higher the overheating temperature must be.

The external, supporting, solid skin of the strand forms during the initial cooling phase of the cast iron in the open-ended die – primary cooling. This is followed by secondary cooling, where the strands are allowed to cool in still air. When the strand leaves the open-ended die, it has not yet solidified all the way through. The core of the strand remains molten for a time. The continuous casting die, which is largely made of electrographite, performs the task of shaping and, by virtue of its physical properties and cooling intensity, sets the strand’s rate of cooling to what is required. The water cooling of the open-ended die can be regulated. This allows the cooling intensity to be varied. The lubricating effect of the graphite reduces friction between the continuous casting die and the strand. The ferrostatic head of the molten metal in the holding furnace acts on the strand like a feeder. The liquid and solidification contraction of the material is equalised by the constant flow of molten metal. At the same time, the expansion of the material that occurs during solidification as a result of graphite separation counteracts cavitation. Continuous casting therefore produces a cavity- and pore-free structure that is particularly dense and homogeneous.
The strand is pulled by a drive unit, which, together with the electronic control system, undertakes the intermittent withdrawal of the strand with the open-ended die stationary. The withdrawal cycle is generally made up of a movement phase and a rest phase (waiting time). The strand movement, which is made up of a sequence of pulling and rest phases, is very pronounced in continuous iron casting. Depending on the strand size and the type of cast iron, the pulling length can be between 30 and 80 mm. Before the casting process commences, the discharge end of the continuous casting die is sealed with a dummy bar. The drive unit is followed by devices for dividing...
the strand into individual strand lengths. The moving strand is cut part of the way through with a cutting device (saw or gas cutter), which moves parallel to the strand. The resulting strand length is then broken off by a breaking device.

**Figure 2** shows various continuous casting plants in operation with receiver, continuous casting die and one, two or four strands. Continuous cast iron is often requested at very short notice. The customer or middleman will therefore demand excellent supply readiness and fast, punctual delivery of the material by the supplier. So as to be able to deliver at any time despite all the different types of cast iron and strand sizes, foundries maintain a permanent stock of their full range (**figure 3**). The strand cross-section is mainly round, square or rectangular. This produces round, square and flat bars, which come in various sizes and lengths.

The manufacturing process for continuous cast iron is illustrated in **figure 4** in two different variants. Variant 1 shows what has generally been the case until now: the foundry delivers the strand length in the required dimensions and with specific mechanical properties to the customer, who manufactures parts by means of machining. Nothing is done to improve the properties of the material and the usage properties of the component further.

**Figure 5** presents the manufacturing process for variant 1 on the left once more, this time in visual form. It also includes heat treatment after continuous casting, which may be necessary in some cases. Comprehensive quality control at the end of the foundry’s manufacturing process is a matter of course these days. Extensive in-process

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**The continuous casting process**

- **Melting**
- **Strand drawing**
- **Heat treatment (optional)**
- **Machining**
- **Quality control**

**Figure 5:** Manufacturing sequence for continuous iron casting (picture: Gontermann-Peipers, Siegen (D))
inspection takes place throughout the production process.

In variant 2 (figure 4, right), on the other hand, processes are carried out after rough machining to improve the material properties in the direction of greater strength/resistance and other usage properties by means of targeted heat treatment and coating or surface re-forming.

Table 1 lists the various test methods for quality control by continuous cast iron manufacturers. These test methods include visual and dimensional inspection, evaluation of the microstructure, chemical analysis, quantification of mechanical properties by means of tensile testing and Brinell hardness testing, and non-destructive tests: dye penetration testing, ultrasonic testing and magnetic particle testing.

Continuous cast bars of a certain length are traditionally supplied unmachined or machined by the manufacturer. All-over machining to finished size as per customer specifications is also offered by manufacturers (figures 6 and 7). This saves the customer having to carry out additional machining operations. Square and rectangular bars are machined on six sides. Angular precision is < 0.05 mm per 100 mm, while plane parallelism and length tolerance are < 0.04 mm per 100 mm.

Drilled retaining holes and precise pre-centring of drilling positions are also available. Round bars can be accurately machined to a required size [2].

<table>
<thead>
<tr>
<th>Test method</th>
<th>Machining-state</th>
<th>Type of cast iron</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GJL</td>
<td>GJS</td>
<td></td>
</tr>
<tr>
<td>Visual inspection</td>
<td>raw</td>
<td>GJL</td>
<td>x x</td>
</tr>
<tr>
<td></td>
<td>machined</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Dimensional inspection</td>
<td>raw</td>
<td>GJL</td>
<td>x x</td>
</tr>
<tr>
<td></td>
<td>machined</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Hardness test</td>
<td>raw</td>
<td>GJL</td>
<td>x x</td>
</tr>
<tr>
<td></td>
<td>machined</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>raw</td>
<td>GJL</td>
<td>x x</td>
</tr>
<tr>
<td></td>
<td>machined</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Analysis</td>
<td>raw</td>
<td>GJL</td>
<td>x x</td>
</tr>
<tr>
<td></td>
<td>machined</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Mechanical characteristics</td>
<td>raw</td>
<td>GJL</td>
<td>x x</td>
</tr>
<tr>
<td></td>
<td>machined</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Dye penetration test</td>
<td>raw</td>
<td>GJL</td>
<td>x x</td>
</tr>
<tr>
<td></td>
<td>machined</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Ultrasonic testing</td>
<td>raw</td>
<td>GJL</td>
<td>x x</td>
</tr>
<tr>
<td></td>
<td>machined</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Magnetic particle testing</td>
<td>raw</td>
<td>GJL</td>
<td>x x</td>
</tr>
<tr>
<td></td>
<td>machined</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Selected test methods for continuous cast iron

Figure 6: Rough cutting of continuous cast iron lengths as a service to the customer (picture: ACO Guss, Kaiserslautern (D))

Figure 7: With blocks that have been rough-machined to the right outside dimensions, precision machining can start immediately. (Picture: K. Vollrath, Rees)

Figure 8: Glass mould manufacture is an interesting and important area of application for continuous cast iron. (Picture: ACO Guss, Kaiserslautern (D))
There are several groups of cast iron, including:

- grey iron – GJL (DIN EN 1561) [3]
- vermicular iron – GJV (VDG (German Foundrymen’s Association) Bulletin W 50, March 2002) [4]
- SG iron – GJS (DIN EN 1563) [5]
- austempered ductile cast iron – ADI (DIN EN 1564) [6, 7, 8]
- malleable cast iron – GJMB/GJMW (DIN EN 1562) [9]
- austenitic cast iron – GJLA-X/GJSA-X (DIN EN 13835) [10, 11]
- wear-resistant cast iron – GJN (DIN EN 12513) [12]

The technical literature quoted [3 to 13] provides a detailed description of the basic metallurgy of cast iron materials together with their properties, standardisation and areas of application.

The materials are classified on the basis of the shape of the graphite crystals precipitated, the formation of a special basic structure by alloying or heat treatment, or, in the case of malleable cast iron, the precipitation of the graphite from the structure by means of heat treatment once it has solidified to white cast iron.

The following remarks only relate to grey and SG iron. These cast irons are iron-carbon-silicon materials with a carbon content of 2 - 4 % and a silicon content of 2 - 3 %. If no other alloying elements are added to these materials, they are referred to as unalloyed despite the high silicon content. The metallic matrix of these cast iron materials is on a par with a eutectoid steel with a carbon content of around 0.7 % and a silicon content of 2 - 3 %, in which graphite crystals of different shapes are embedded.

The phase and structure transformations that take place during manufacture or heat treatment therefore have to be described with the phase diagrams for ternary systems (Fe-C-Si). These phase diagrams have four variables and so can normally only be displayed in three dimensions. If, however, a section is taken at a constant value for one of the variables, a two-dimensional diagram can be produced once more. Just such a pseudobinary section through the Fe-C-Si ternary system at 2.4 % silicon suffices to describe the transition processes that occur (figure 9).

A distinction is made between two transformation stages (graphitisation stages) in the structure formation from the molten metal or the structure transformation in the solid state of aggregation. The first graphitisation phase lies between the liquidus temperature and the eutectoid transformation. This stage decides whether graphite crystals will be produced (grey solidification) during solidification of the cast iron or not (white solidification). Whether the molten metal solidifies to white or grey cast iron depends on its chemical composition and the rate of cooling during solidification. The second graphitisation stage lies in the area of the eutectoid transformation. Depending on the process conditions, this stage determines whether the matrix will be pearlitic or ferritic. A third possibility when it comes to influencing the outcome is to inoculate the molten metal, which promotes solidification to grey cast iron.

If the chemical composition is the same, the mechanical properties of the cast iron are dependent on the wall thickness of the casting – they are section sensitive. A small wall thickness means a fast rate of cooling, while a large wall thickness means a slow rate of cooling. This sensitivity of the mechanical properties to wall thickness is greater for grey iron than for SG iron.

The hardness (usually Brinell hardness) of cast iron materials is always mixed. Such materials have a hard, steel-like, metallic matrix in which graphite crystals of a lower hardness are embedded. The hardness of the metallic matrix can only be determined by means of microhardness measurements.

The density of cast iron materials is around 10 % lower than that of steels as a result of graphite crystals of very low density (approx. 10 % by volume) being embedded in the steel-like, metallic matrix. If the component geometry is kept the same, this difference in density means a weight saving, and therefore a lightweight effect, if cast iron is used instead of steel.
The machinability of cast iron materials is better than that of steels. Higher cutting speeds and bigger advances or longer tool lives are possible with cast iron. The graphite crystals in the cast iron act as both chip breaker and lubricant. The form and quantity of the graphite are of subsidiary importance. More important is the nature of the metallic matrix. Ferritic types are easier to machine than pearlitic types.

Cast iron materials are very suitable for gliding and rolling wear, that is to say the abrasion stress that occurs when machine elements move against each other. The graphite crystals provide additional lubrication. The winking of graphite crystals from the skin leaves small „pockets“, in which lubricant collects. This produces good anti-seizure performance. Of the normal types, varieties of cast iron with a pearlitic matrix offer the best wear resistance relatively speaking. Wear resistance can be greatly increased by means of surface hardening, thermomechanical treatment or isothermal austenite transformation.

The arguments in favour of ecologically sensible and therefore sustainable production are gaining ground. Cast iron materials are made from cast iron scrap, steel scrap and pig iron. In Germany in 2003 the proportion of pig iron, which takes a great deal of energy to manufacture, was 8.7 % of the total quantity of the aforementioned materials to be used. This means that more than 90 % of these metallic materials come from the secondary cycle.

Cast iron materials are therefore secondary materials and continuous cast iron is a secondary product. As materials, cast irons are virtually unbeatable from this point of view. They are also ecologically compatible to manufacture and use. They can be recycled in their entirety, with virtually nothing being left over. The recycling rate has been very high for many years and can scarcely be improved on. Production and product waste have always gone back into the material cycle. Recycling does not mean a reduction in quality – that is to say, there is no downcycling. But an improvement in quality, upcycling, is not a problem. It is possible, for example, to make grey iron with tenacity of 200 or 250 N/mm² from scrap grey iron with tenacity of 150 N/mm².

3.1 Grey iron (GJL)

Grey iron (GJL) is a traditional material that remains very successful today: global annual production of grey iron is more than all the other cast materials combined. Its cost effectiveness in terms of material, manufacturing, operating and disposal costs continues to be excellent. Attention can be drawn to its good mechanical, physical and technological properties, not to mention its good casting characteristics.

According to EN 1561, grey iron is an iron-carbon cast material in which the free carbon is largely present in the form of lamellar or flake graphite. The material designation is GJL (EN 1560). For sand casting the above standard offers material grades with tensile strength of 100 - 350 N/mm² and Brinell hardness of 155 - 265 units.

The graphite flakes form a cohesive structure of foliaceous components in a eutectic cell (figure 11). The arrangement of the graphite flakes can vary. It depends on the chemical composition of the cast iron, the cooling conditions and, to a large degree, also the nucleation behaviour of the molten metal, which can be strongly influenced by inoculation. With the right composition and inoculation to suit the casting process, flake graphite with a regular arrangement as per type A of the standard structure series (EN ISO 945) is produced. Depending on the process, not only A-graphite, but also B-graphite, is produced in continuous cast iron.

The mechanical properties of grey iron are largely determined by the quantity and type of the graphite flakes. The nature of the essentially steel-like metallic matrix has only a limited impact. The graphite flakes weaken the bearing cross-section and cause stress concentration at the flake tips, which act like internal notches. These two circumstances are the reason for the relatively low strength values and low plasticity.

The mechanical properties of grey iron are manifestly dependent on the rate of cooling – which means for practical purposes the wall thickness of the casting. The dependence of mechanical properties on wall thickness is described in EN 1561 and must be taken into account when choosing a material.

Grey iron has a high damping capacity – in other words it is able to reduce externally imposed mechanical vibrations. The mechanical vibrations decay rapidly. The decay time for a vibration in grey iron is in a ratio of 1:4.3 to that for steel.

A detailed description of the properties of grey iron with details of its mechanical properties with regard to cyclical stress, its mechanical properties at high and low temperatures, its mechanical fracturing properties, its physical properties (density, coefficient of linear thermal expansion, thermal conductivity, specific thermal capacity, coercive field strength, hysteresis loss, specific electrical resistance) and its tribological properties (friction and wear) can be found in [3].

![Figure 11: Three-dimensional structure of lamellar graphite](image13)

![Figure 12: Using bars that have been rough-machined to his specification at the foundry (top), the customer can manufacture end-products quickly and economically (bottom). (Picture: K. Vollrath, Rees)](image13)
3.2 SG iron (GJS)

There has been industrial production of castings made from SG iron for 60 years. Compared with grey iron, SG iron is a relatively “recent” material. Graphite spheres were observed in cast iron for the first time ever in the foundry department of the Aachen University of Technology in 1937. At around the same time the British Cast Iron Research Institute succeeded in manufacturing SG iron by adding cerium to the molten iron. But it was not until International Nickel Inc. in the USA discovered that SG iron could be made by adding a nickel-magnesium master alloy that the foundations for the industrial production of this group of materials were laid. And so began the triumphal procession of the steel-like SG iron. In the years that followed, SG iron was substituted for steel and cast steel with great commercial success on numerous occasions. This substitution process is still going on.

According to EN 1563 and EN 1564 SG iron is an iron-carbon material in which the free carbon is largely present in spheroidal form (spheroidal graphite) as per forms V and VI in EN ISO 945 (figure 13). The material designation is GJS (EN 1569). The European standards lay down the following mechanical properties for sand casting:

- Normal grades: tensile strength 350 - 900 N/mm², 0.2 % permanent elongation limit 220 - 600 N/mm², elongation at rupture 2 - 22 %, Brinell hardness 130 - 330 units.

- High-tenacity grades: tensile strength 800 - 1400 N/mm², 0.2 % permanent elongation limit 500 - 1000 N/mm², elongation at rupture 1 - 8 %, Brinell hardness 130 - 330 units.

In EN 1564 the high-tenacity grades are designated as austempered ductile cast iron or ADI.

The presence of graphite spheres in a steel-like metallic matrix does away with the internal notch effect described above, minimising interruption of the metallic matrix. As with steel, the properties of the metallic matrix are shown to full advantage. The yield point/tensile strength ratio of SG iron is usually better than that of steels. For steel this ratio is 0.44 - 0.53, whereas for SG iron it is 0.6 - 0.7. SG iron has been used in place of steel (cast steel, forged steel, rolled steel) to great commercial advantage for more than 60 years and this trend is continuing.

With steel the elongation at rupture for comparable strength is greater than for SG iron. However, that is no disadvantage for these grades of cast iron, as has been demonstrated in numerous instances. An example from the past has been cited in this connection: the car crankshaft. The changeover from forged steel to SG iron for these crankshafts started in the sixties. For the same tensile strength and yield point (permanent elongation limit) in forged steel and SG iron the elongation at rupture of the grade of cast iron used was an order of magnitude smaller than that of the grade of steel (3 % as against 20 %). Today more than 90 % of all cars and vans have SG iron crankshafts that display perfectly adequate fatigue limits for flexion and torsion.

Elongation describes deformation (e. g. malleability) as a first approximation and so is a processing property rather than a usage property. Since cast parts are close to their final contours after solidifying and cooling, no forming process is necessary. Approximately 90 % of the fractures in machine elements are endurance fractures resulting from material fatigue. The residual fracture in such cases is always a brittle failure, even in steels with very high elongation at rupture.

The fatigue limits (fatigue strength under reversed bending stresses) for an unnotched sample is in the 180 - 320 N/mm² range for SG iron, including austempered ductile cast iron. SG iron is less notch sensitive than steel. As regards damping capacity for mechanical vibrations, the values for SG iron come between steel and grey iron. The advantages of SG iron over steel are summarised in table 2.

Information on further static mechanical properties, fatigue limit, properties at high and low temperatures, machining, welding and wear behaviour can be found in [5].

Table 2: The advantages of SG iron over steel

<table>
<thead>
<tr>
<th>Advantage</th>
<th>SG Iron</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Its strength (tensile strength, permanent elongation limit) extends well into the range offered by steel.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>Its yield point/tensile strength ratio is better than for steel.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>Its smaller elongation at rupture (reduction in area at breaking) is not a disadvantage.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>Its hardness satisfies many requirements.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>Its fatigue limits extend well into the range offered by steel.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>Its density is about 10% lower.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>Its strength/weight ratio is higher.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>Lightweight construction is possible with cast iron.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>Its damping capacity for mechanical vibrations is better.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>It offers better machinability.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>It has good tribological properties.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>It can be almost completely recycled.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>Cast iron is a recycled material – cast iron parts are recycling products.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>There is no downcycling, but upcycling is always possible.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>Less energy is used for smelting.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>Cast iron is non-toxic.</td>
<td>✔</td>
<td>🔴</td>
</tr>
<tr>
<td>The use of cast iron instead of steel results in cost savings.</td>
<td>✔</td>
<td>🔴</td>
</tr>
</tbody>
</table>
4 Continuous cast iron

Various peculiarities have to be taken into account for continuous cast iron as opposed to sand casting. They are described in detail below.

4.1 Mechanical properties of continuous cast iron

The mechanical properties of grey iron (GJL) and SG iron (GJS) can be ordered in accordance with the European standards (EN 1561, EN 1563 and EN 1564 for sand casting) on the basis of either tensile strength or hardness (Brinell hardness) as the characteristic property. The manufacturing processes for the individual grades of cast iron, their chemical composition, the type of cast treatment and the heat treatment method are at the manufacturer’s discretion unless the customer specifies otherwise.

Table 3 shows chemical analyses for continuous cast iron for information purposes. These analysis values are in no way binding, however, as there is currently no national standard, no European standard (EN) and no international standard (ISO) for continuous cast iron. The foundries that supply continuous cast iron set out the mechanical properties of their products in brochures. The metallic matrix can be made ferritic, ferritic-pearlitic and pearlitic (figure 14).

The standardisation of grey and SG iron has long contained a number of specifications that are also reflected in the European standards (EN 1561, EN 1563 and EN 1564). In order to describe the mechanical properties of continuous cast iron, which differ from those for sand cast iron, however, depending on the process used, traditional specifications are adopted on the basis of the European standards for sand cast iron and adapted to the process-related peculiarities as

- The grades of continuous cast iron are identified in accordance with EN 1560.
- For SG iron the graphite structure must predominantly correspond to forms V and VI as per EN ISO 945.
- The manufacturing processes for grey and SG iron, cast treatment, chemical composition and heat treatment

![Figure 14: Microstructure of continuous cast alloys (pictures: Gontermann-Peipers, Siegen (D))](image)
are at the manufacturer’s discretion. Chemical analyses for grey and SG iron are given in table 4, but they are not standardised and therefore not binding.

- The grades of cast iron can be ordered on the basis of both tensile strength and hardness as the characteristic property.

- The mechanical properties are classified according to the controlling wall thickness. The controlling wall thickness is twice the modulus or ratio of volume to surface area. To provide a simplified overview, the mechanical properties for continuous cast iron are also specified as a function of diameter in the case of round bars.

- There are traditionally three sampling variants:
  • separately cast test pieces (designation S),
  • attached test pieces (designation U),
  • test pieces removed from casting (designation C).

These designations are defined in EN 1560. Separately cast test pieces are not used for continuous cast iron in practice. Attached test pieces are not possible owing to the process used. In the case of continuous cast iron, therefore, the test pieces are removed from the strand and the expected values in the casting (strand) taken consistently as the basis for the mechanical properties.

- The specifications in EN 1561, EN 1563 and EN 1564 apply to tensile testing, hardness testing and repeat testing.

Extensive statistical analyses have been carried out by the four firms involved with a view to laying down real values for the mechanical properties of continuous cast iron (see appendix). The results of these statistical analyses showed that the aforementioned expected values were the minimum values for tensile strength or Brinell hardness.

The mechanical properties for continuous cast iron are set out in tables 4 to 7. In the case of grey iron, four grades of cast iron covering a tensile strength range of 80 to 220 N/mm² are offered. Brinell hardness is in the 110 - 290 units range. In the case of SG iron the four grades offered cover a tensile strength range of 370 to 600 N/mm². The tensile strength, permanent elongation limit, elongation at rupture and hardness are dependent on the strand diameter or controlling wall thickness. This sensitivity of the mechanical properties to wall thickness is much more pronounced for grey iron than for SG iron.

In the case of SG iron this high rate of cooling in the skin leads to a clear increase in the sphere count compared with the centre of a cast iron strand (figure 17). Y. S. Lerner [14] gives the distribution of the sphere count over the cross-section for a continuous cast round bar of SG iron with a diameter of 110 mm (figure 18). The sphere count of 450/mm² near the surface declines towards the centre of the bar. It achieves a value of 115/mm² at a distance of approximately 30 mm from the surface and remains constant to the centre of the strand.

Table 3: Chemical composition of continuous cast iron, reference values

<table>
<thead>
<tr>
<th>Chemical element</th>
<th>Grey iron GJL [%]</th>
<th>SG iron GJS [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>2.80 – 3.70</td>
<td>3.00 – 3.85</td>
</tr>
<tr>
<td>Si</td>
<td>2.25 – 3.99</td>
<td>2.00 – 3.00</td>
</tr>
<tr>
<td>Mn</td>
<td>0.40 – 1.00</td>
<td>0.10 – 0.80</td>
</tr>
<tr>
<td>P</td>
<td>0.08 – 0.25</td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>S</td>
<td>&gt; 0.03</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Cr</td>
<td>0.05 – 0.50</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Cu</td>
<td>0.05 – 0.60</td>
<td>0.05 – 1.20</td>
</tr>
<tr>
<td>Ni</td>
<td>0.05 – 0.80</td>
<td>0.05 – 1.00</td>
</tr>
<tr>
<td>Mg</td>
<td>0.025 – 0.080</td>
<td>0.025 – 0.080</td>
</tr>
</tbody>
</table>

Table 8 sets out the existing continuous cast iron materials of the four firms involved (trade names, registered trademarks) for the aforementioned grades of cast iron with the material designations brought into line with European standardisation. This means that customers know where they stand, the existing names that are familiar on the market are not lost and the manufacturers’ rights are protected. Figure 15 shows the position of the test pieces taken from the strand for round, square and rectangular cross-sections.

Process-related peculiarities occur in the skin of grey iron. A very high rate of cooling occurs during solidification of the skin owing to the influence of the water-cooled, open-ended die. This produces grey iron with graphite structure type D and also some type E as per EN ISO 945. This very feathery, interdendritically structured graphite gives rise to a completely ferritic metallic matrix as a result of very short diffusion paths (figure 16). The thickness of the skin with graphite structure type D and type E is dependent on strand diameter and is greater than 25 % for 25 to 50 mm, approximately 15 % for >50 to 200 mm and approximately 10 % for >200 to 350 mm. The data for the thickness of this skin are not binding, but for information purposes only. Free carbides are also present in this skin.
The proposed values contained in tables 4, 5, 6, 7, and 8 provide a comprehensive overview of continuous cast iron properties, including tensile strength, Brinell hardness, and machining tolerances. These tables are essential for understanding the performance characteristics of grey iron, SG iron, and grades of continuous cast iron with trade names.

### 4.2 Machining allowances, straightness

For the manufacture of static cast iron using sand casting processes, the general tolerances and machining allowances have been standardised as a function of linear size for grey and SG iron (compare DIN 1685-1 and DIN ISO 8062). As things stand, there is no such standardisation for continuous cast iron. The firms involved in this project have proposed the values contained in tables 9 and 10 for the machining tolerances and straightness of the strand lengths as a function of strand dimensions for grey and SG iron. Figures 19 and 20 illustrate the machining allowances and straightness.

### Table 4: Continuous cast iron, GJL, characteristic property: tensile strength

<table>
<thead>
<tr>
<th>Strand diameter [mm]</th>
<th>Controlling wall thickness [mm]</th>
<th>Tensile strength Approximate value min. [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GJL-150C, ferritic, annealed</td>
<td>30 - &gt; 40</td>
<td>15 - &gt; 20</td>
</tr>
<tr>
<td></td>
<td>40 - &gt; 160</td>
<td>20 - &gt; 80</td>
</tr>
<tr>
<td></td>
<td>160 - &gt; 300</td>
<td>80 - &gt; 150</td>
</tr>
<tr>
<td>GJL-200C, predominantly ferritic</td>
<td>30 - &gt; 40</td>
<td>15 - &gt; 20</td>
</tr>
<tr>
<td></td>
<td>40 - &gt; 160</td>
<td>20 - &gt; 80</td>
</tr>
<tr>
<td></td>
<td>160 - &gt; 300</td>
<td>80 - &gt; 150</td>
</tr>
<tr>
<td>GJL-250C, ferritic-pearlitic</td>
<td>30 - &gt; 40</td>
<td>15 - &gt; 20</td>
</tr>
<tr>
<td></td>
<td>40 - &gt; 160</td>
<td>20 - &gt; 80</td>
</tr>
<tr>
<td></td>
<td>160 - &gt; 300</td>
<td>80 - &gt; 150</td>
</tr>
<tr>
<td>GJL-300C, predominantly pearlitic</td>
<td>30 - &gt; 40</td>
<td>15 - &gt; 20</td>
</tr>
<tr>
<td></td>
<td>40 - &gt; 160</td>
<td>20 - &gt; 80</td>
</tr>
<tr>
<td></td>
<td>160 - &gt; 300</td>
<td>80 - &gt; 100</td>
</tr>
</tbody>
</table>

C – test piece taken from casting (DIN EN 1560)

### Table 5: Continuous cast iron, GJS, characteristic property: tensile strength

<table>
<thead>
<tr>
<th>Strand diameter [mm]</th>
<th>Controlling wall thickness [mm]</th>
<th>Tensile strength Approximate value min. [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GJS-400-15C, ferritic, annealed</td>
<td>30 - &gt; 60</td>
<td>15 - &gt; 30</td>
</tr>
<tr>
<td></td>
<td>60 - &gt; 200</td>
<td>30 - &gt; 100</td>
</tr>
<tr>
<td></td>
<td>200 - &gt; 370</td>
<td>100 - &gt; 200</td>
</tr>
<tr>
<td>GJS-400-7C, ferritic-pearlitic</td>
<td>30 - &gt; 60</td>
<td>15 - &gt; 30</td>
</tr>
<tr>
<td></td>
<td>60 - &gt; 200</td>
<td>30 - &gt; 100</td>
</tr>
<tr>
<td></td>
<td>200 - &gt; 400</td>
<td>100 - &gt; 200</td>
</tr>
<tr>
<td>GJS-500-7C, pearlitic-ferritic</td>
<td>30 - &gt; 60</td>
<td>15 - &gt; 30</td>
</tr>
<tr>
<td></td>
<td>60 - &gt; 200</td>
<td>30 - &gt; 100</td>
</tr>
<tr>
<td></td>
<td>200 - &gt; 400</td>
<td>100 - &gt; 200</td>
</tr>
<tr>
<td>GJS-600-3C, predominantly pearlitic</td>
<td>30 - &gt; 60</td>
<td>15 - &gt; 30</td>
</tr>
<tr>
<td></td>
<td>60 - &gt; 200</td>
<td>30 - &gt; 100</td>
</tr>
<tr>
<td></td>
<td>200 - &gt; 400</td>
<td>100 - &gt; 200</td>
</tr>
</tbody>
</table>

1 Depending on the process, these material grades contain small quantities of free carbides, which can be removed by heat treatment.

C – test piece taken from casting (DIN EN 1560)
5 Heat treatment of cast iron

The heat treatment of metallic materials divides into
- thermal treatment
- thermochemical treatment
- thermomechanical treatment

The properties of cast iron can be positively influenced to a large extent using thermal and thermochemical heat treatment. Thermomechanical treatments are not relevant in the case of cast iron because, apart from surface reforming, reforming is not part of the manufacturing sequence.

The structural transformations possible with heat treatment, and the resulting changes in properties, are more extensive and varied with cast iron materials than with steel. The higher silicon content of 2.0 to 3.5 % that is always present in the unalloyed materials, for example, means that the eutectoid temperature in the Fe-C diagram becomes a eutectoid area in the Fe-C-Si diagram. There is, of course, an „internal“ carbon source in the form of the graphite crystals, which means that the austenite can always be carburised until saturated with carbon. As with solidification, the silicon content delays the formation of iron carbides. The interactions between the stable and metastable Fe-C-Si can also be put to good use.

5.1 Thermal treatments

Fundamental changes in microstructure and consequently in properties can be achieved using thermal heat treatment. Figure 21 shows the temperature-time sequences of important heat treatment variants in the form of a schematic diagram.

5.1.1 Stress-relief annealing

It is not practically possible to manufacture a cast product without internal stresses owing to the different rates of cooling within the product. The size and direction of these internal stresses are dependent on the geometry of the cast components, their design and the process conditions during casting. Stress-relief annealing is a heat treatment that is used specifically to reduce internal stresses. The annealing temperatures of between 500 and 550 °C are below the area of eutectoid transformation, so an unwanted change in structure and therefore a change in the mechanical properties during the annealing process is avoided. To prevent new internal stresses developing during stress-relief annealing as a result of heating and cooling, rates of heating of between 10 and 50 K/h and rates of cooling of between 25 and 35 K/h up to at least 300 °C must be ensured. Stress-relief annealing is only used on continuous cast iron in special cases.

Figure 16: Microstructure of GJL in rim area (picture: Gontermann-Peipers, Siegen)

a) fine D-graphite, outside  
 b) transition from D- to E-graphite  
 c) predominantly E-graphite inside

Figure 17: Sphere count for continuous cast GJS (picture: ACO Guss, Kaiserslautern (D))

a) - in rim area  
 b) - in centre
5.1.2 Soft annealing at high temperature

If cast parts that have solidified to grey cast iron are to display their typical mechanical properties, they must not as a rule have any structure content that has solidified to white cast iron. If there is any content of eutectic (ledeburitic) carbides or even primary carbides during casting and solidification, an annealing temperature well in excess of the eutectoid interval between 900 and 950 °C must be chosen in order to remove it. The rate of cooling is chosen on the basis of whether a pearlitic or ferritic basic structure is wanted.

5.1.3 Soft annealing at low temperature

This heat treatment is used to turn pearlite into ferrite. Whereas the soft annealing of steel only coalesces lamellar pearlite into granular pearlite, the soft annealing of cast iron results in a completely ferritic basic structure without any eutectic iron carbide content. The annealing temperature in this case is just below the eutectoid interval at around 700 °C. The rate of cooling is 50 K/h. In the manufacture of the GJL-150C and GJS-400-15C grades of continuous cast iron heat treatment generally forms part of the manufacturing chain in the foundry.

5.1.4 Two-stage soft annealing

If SG iron has to satisfy the highest tenacity requirements, the necessary properties can only be achieved in unalloyed grades by means of two-stage heat treatment. This consists of austenising at 850 - 920 °C, followed by furnace or air cooling and then holding (5 to 10 h) at the eutectoid interval between 650 and 740 °C. Quenching is followed by tempering in a coolant.

5.1.5 Isothermal annealing

Isothermal annealing aims to set a completely or partially pearlitic structure with a view to achieving certain strength properties or homogenising the structure in different wall thickness areas. This process is also called normalisation based on the heat treatment of steel. In isothermal annealing the component is heated to temperatures between 900 and 920°C, reaching the austenite region above the eutectoid. Then accelerated cooling is carried out in order to suppress ferrite formation. Depending on the component size, the optimum rate of cooling is achieved using still air or water spray. This heat treatment variant is also used in the foundry’s manufacturing chain for continuous cast iron.

5.1.6 Hardening

As an iron-carbon-silicon material, cast iron can be hardened just like steel. The hardening of cast iron is either aimed at forming a wear-resistant skin (surface hardening) or used as the first stage of the combined hardening and tempering process. It gives the cast iron high hardness values of 45 to 60 HRC and therefore high wear resistance.
With hardening, the component is heated above the eutectoid interval at temperatures of 850 - 950 °C. During austenising the austenite is carburised until saturated. The sources of carbon for this are the eutectoid carbide of the pearlite and the graphite crystals. The rapid cooling (quenching) that follows prevents the formation of ferrite or pearlite and leads to transformation into martensite and residual austenite. The high rates of cooling required are achieved by immersing the component in oil, emulsions or water. Hardening the entire volume of the component is the first stage in the combined hardening and tempering process.

Using special technologies, it is also possible to harden just a thin skin on the component in order to improve wear resistance. With this surface hardening the skin is heated to a temperature in the austenite region with a flame, induction current or laser and quenched rapidly. Laser remelting is a special process used to change the skin with the aim of improving wear or corrosion resistance. To do this, the skin is melted with the laser. Owing to the high thermal conductivity of the material below the skin, solidification takes place at a high rate of cooling. In the case of cast iron this produces a very hard skin that has solidified to white cast iron. Using this remelting technology, it is also possible to add alloying elements to the molten metal in order to achieve special properties in the skin.

5.1.7 Combined hardening and tempering

In this process hardening is followed by tempering (reheating). The tempering results in further optimisation of properties. In the case of SG iron combined hardening and tempering can be used to achieve mechanical properties similar to those for heat-treatable steels, but plasticity and tenacity remain below the values achievable for the steels. Tempering dismantles the quenching structure produced by hardening (martensite and residual austenite). Depending on the properties to be achieved, the tempering temperature is between 150 and 650 °C. As the tempering temperature goes up, the tensile strength, 0.2 % permanent elongation limit and hardness decline, while elongation at rupture and notched-bar impact strength increase. Several tempering stages are passed through before the higher tempering temperatures are reached and, unlike with steels, can result in a carbide-free state in the case of cast iron owing to the silicon content.

Tempering at high temperatures also causes secondary graphite to form in a ferritic basic structure.

Combined hardening and tempering can be a good way of improving the strength values of SG iron in many cases. It does not produce very good values for plasticity and tenacity, however.
5.1.8 Isothermal austenite transformation

Isothermal austenite transformation at temperatures below the pearlite stage and above the martensite stage is otherwise known as austempering (DIN 17014). In the case of cast iron this treatment with complete bainitic transformation did not produce particularly good properties. However, a special heat treatment variant with incomplete isothermal austenite transformation has come about in this area and offers an excellent combination of mechanical properties.

In isothermal austenite transformation the cast iron is first completely austenised at 875-920 °C. If the cast iron parts are then quickly transferred to a salt bath at a temperature of between 300 and 400 °C, austenite transformation commences with the formation of ferrite needles and saturation of the remaining austenite content with carbon, which leads to stabilisation of this residual austenite. Carbide formation does not happen and austenite transformation virtually stops. This is incomplete isothermal austenite transformation. Once the cast iron has cooled to room temperature, it has a basic structure of needle ferrite and a high residual austenite content of up to 40 %.

Isothermal austenite transformation has gained in importance for SG iron. In the case of parts manufacture it leads to high strength values combined with favourable values for plasticity and tenacity [6 to 8]. This means that it can be substituted for heat-treatable steels.

5.2 Thermochemical treatments

Thermochemical treatments are heat treatments in which the chemical composition of a material is deliberately changed by diffusing one or more elements in or out. These thermochemical treatments include nitriding, alumising, siliconising, boronising and chromising, which produce positive changes in properties in cast iron as well as steel.

5.2.1 Nitriding

Nitriding is a thermochemical treatment that produces the diffusion saturation of the surface layer of a grade of steel or cast iron with nitrogen by heating in a suitable medium. The purpose of nitriding is to enhance the hardness, wear resistance, fatigue strength and also the corrosion resistance of a workpiece through the absorption of nitrogen into the surface.

The processes involved in nitriding are based on the iron-nitrogen phase diagram. In the case of nitriding below the eutectoid temperature the α mixed crystal is saturated with nitrogen first. Then the nitride Fe₄N (γ-phase) forms. Once it has been saturated, the nitride Fe₄N forms as a further phase, known as the ε-phase. The outcome of the prolonged operation of atomic nitrogen on the surface of a steel or cast iron component is the formation of the following layers from the skin to the core: ε-phase, γ-phase, α mixed crystal. If the nitrided component is slowly cooled to room temperature, the nitrogen solubility of the ε- and α-phases declines and the γ-phase is eliminated from these layers.

5.2.2 Nitriding and other alloying elements

If iron materials are nitrided with alloying elements that form special nitrides, the structure of the nitride layer is more complicated. Alloying elements, such as Cr, Al, Mo or V, that have a great affinity with nitrogen form very hard special nitrides. Cast iron always has higher silicon contents, which lead to an increase in hardness, with this being ascribed to the presence of aluminium in the ferrosilicon used.

A distinction is made between the compound layer and the diffusion zone in a nitrided component. The hardness characteristic from the surface to the core of the nitrided component is shown in figure 24. This characteristic, which shows hardness as a function of the distance from the surface, is used to determine the effective case depth after nitriding. The effective case depth after nitriding is the vertical distance from the surface of a nitrided workpiece to the point at which the hardness corresponds to a limit value that has been set for the purpose. The limit value within the meaning of this standard is the hardness number, which is referred to as the limit hardness. The limit hardness refers to the state specified in the manufacturing documentation for the nitrided component. The limit hardness should be defined as Vickers hardness HV.

Limit hardness = (actual core hardness + 50) HV (1) (rounded to 10 HV)

The hardness HV₀.₅ measured at approximately three times the effective case depth after hardening should be used as the core hardness. The limit hardness is generally specified as Vickers hardness HV₀.₅.

5.2.3 The nitriding process

Nitriding is carried out in salt baths or the gas phase. Bath nitriding is done in cyanide baths and is really carbonitriding because of the carburisation that takes place at the same time. The salt baths used consist of either sodium cyanide or calcium cyanide with chlorides added in small quantities.

Gas nitriding is based on the use of ammonia, which dissociates thermally at the temperatures of between 500 and 560 °C that are used. This makes the necessary atomic nitrogen available at the surface of the component. The degree of dissociation for the ammonia depends on the pressure and temperature in the nitriding furnace. Nitriding takes a relatively long time. For a normal nitriding steel and a nitriding depth of 0.6 mm it takes 100 hours, for example. The nitriding time can be reduced by using glow discharges and adding oxidising gases (particularly oxygen for the ammonia).

In this case SG was nitried in the flow of ammonia gas. The relevant hardness gradient curves are shown in figure 25 for material grade GJS-400-15C. A nitriding temperature of 510 °C and nitriding time of 36 hours produced an effective case depth after hardening of 0.2 mm (curve a), while a nitriding temperature of 580 °C and a nitriding time of 5 hours produced an effective case depth after hardening of 0.1 mm (curve b).

These investigations show that SG iron can be successfully nitried in the same way as steel. Gas nitriding was used for a gear rim made of SG iron in grade GJS-400-15C (figure 26). This gear rim has the following characteristics: module 3.5, 20 teeth, base circle 63 mm, 44 units minimum hardness on nitrided tooth profiles (effective case depth after hardening 400 HVₐ), inside and outside diameter plus sides ground after nitriding. The nitrided gear rim satisfied all the requirements in full, just like a steel gear rim.
6 Coating continuous cast parts

Coating is the conscious creation of serviceable layers on pre-treated surfaces without essentially changing the macrostructure of the components. Coating includes both the application of amorphous or foil-like substances and the chemical or electrolytic application of layers. All the numerous coating processes aim to protect components against corrosion and wear, or to achieve a decorative effect.

A wide variety of coatings are also used on cast iron, including painting, enamelling, chromium plating and nickel plating.

7 Surface reforming (deep rolling, shot peening)

In surface reforming only the skin of a component is compacted with a ball or roller tool, which is moved over a surface with a specific vertical force and a defined speed, or by blasting with spherical shot (shot peening). This causes compressive stresses.

Such surface reforming has been successfully used on the transition radii of crankshaft castings made from SG iron, for example. The internal compressive stresses thus created increased compressive strength noticeably.

8 Use of continuous cast iron

Unlike static cast iron, where use is unequivocally fixed by the manufacture of cast parts that are close to final dimensions, continuous cast iron is a semi-finished cast product that can be used for all sorts of applications. Continuous cast iron is therefore extremely versatile. It can be used to manufacture a wide variety of components for every branch of industry.

Important areas of application are illustrated by figures 8, 10, 12, 22, 23 and 27, for example. These pictures demonstrate the diversity of possible uses.

9 Concluding remarks

An ad hoc working party under the German Foundry Association (DGV) in Düsseldorf has assessed and described the current manufacturing status of continuous cast grey and SG iron. This also represents a first attempt with a view to future standardisation.

The firms involved are thanked for their expertise and constructive cooperation. Thanks go to the following individuals in particular: Dipl.-Ing. Klaus Reif (leader of ad hoc working party (DK)), Marco Antes and Dipl.-Ing. Wolfgang Giese (ACO guss (D)), Dipl.-Ing. Christophe Ancel, Bernard Linder, Dipl.-Ing. Hans Sattel and Dipl.-Ing. Franck Kootz (Contifonte (F)), Dipl.-Ing. Klaus Beute (Gontermann-Peipers (D)) and Dipl.-Ing. Henrik Elmkvist (TASSO (DK)).

Literature

Appendix: Statistical analysis for mechanical properties

The firms involved in this article measured and statistically analysed mechanical properties as a function of strand diameter/modulus over an extended period of production.

Tensile strength and Brinell hardness were measured for grey iron, while tensile strength, 0.2 % permanent elongation limit, elongation at rupture and Brinell hardness were measured for SG iron. The familiar sensitivity of mechanical properties to wall thickness was also clearly apparent for continuous cast iron. This sensitivity is much more pronounced for grey iron than for SG iron.

Figure 27: Various components made from grey and SG iron that clearly demonstrate the varied use of continuous castings. (Picture: ACO Guss, Kaiserslautern (D))

The data contained in tables 5 to 8 was collated on the basis of the results obtained in this way. Some selected examples of the statistical analysis are presented in figures I and III to V for material grades GJL-250C and GJS-400-15C.

Figure II shows the correlation between tensile strength and Brinell hardness for grey iron. Based on the testing of the mechanical properties of grey iron, for which mostly separately sand cast test pieces (round samples with a diameter of 30 mm) are used, the possible tensile strength for a strand diameter of 30 mm was fixed as the reference quantity for continuous casting. Please note in this respect that the tensile strength values are for test pieces removed from the casting.

Figure I: Tensile strength in relation to strand diameter for GJL-250C, round bars, sample position D/4
Figure II: Tensile strength in relation to hardness for GJL, tensile strength = f(hardness) for sample position D/4
Figure III: Tensile strength in relation to strand diameter for GJS-400-7C over modulus (D/4), unannealed
Figure IV: 0.2 % permanent elongation limit in relation to strand diameter for GJS-400-7C over modulus (D/4), unannealed
Figure V: Elongation at rupture in relation to strand diameter for GJS-400-7C over modulus (D/4), unannealed