TECHNICAL REPORT

ISO/TR 10809-2

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Cast irons —

Part 2: **Welding**

Fontes —

Partie 2: Soudage

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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 10809-2 was prepared by Technical Committee ISO/TC 25, *Cast irons and pig irons*.

ISO/TR 10809 consists of the following parts, under the general title *Cast irons*:

— *Part 1: Materials and properties for design*

— *Part 2: Welding*

Introduction

Cast irons can be successfully welded, see References [4], [9], [10], [16], [17] in the Bibliography. A precondition is that the welding is done professionally and with care.

It is intended that all welding of the different cast iron types and grades with themselves or with other ferrous materials should be done by trained personnel, in accordance with appropriate standards and approved procedures.

Technological advances in welding methods have contributed to a change of attitude with regard to welding iron castings.

The designer needs to understand that the conditions/parameters which might need to be considered if welding is to be carried out by a suitable welding process for either production or repair depend upon

— the cast iron material,

— the expected quality level of the weld,

— the casting shape and size,

— the welding application,

— the welded joint, and

— the filler metal(s), if required

Advancement of the state-of-the-art in welding of cast iron materials has been incorporated into International and European Standards [1], [2], [3], [5] in the Bibliography.

Economic considerations should be taken into account when deciding on the suitability of welding a casting.

As an important precondition, the weld of the casting or the constructive unit should satisfy the requirements to be agreed at the time of ordering between manufacturer and purchaser.

NOTE Currently, the best knowledge and most experience exist for malleable cast irons and spheroidal graphite cast irons.

This part of ISO/TR 10809 gives design engineers knowledge as to whether or not it is possible to weld the many types and grades of cast iron standardized in a number of international cast iron material standards

Cast irons —

Part 2:
Welding

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

The purpose of this part of ISO/TR 10809 is to assist the design engineer to understand and to acquire knowledge of how the family of cast iron materials can be welded and to utilize this technology to its full advantage in selecting the most appropriate technique for a particular cast iron. Because the application of welding technology and the metallurgical implications of welding are not scientific disciplines normally taught to engineering students, such users often have limited knowledge of the fundamentals underpinning welding technology for cast irons. This part of ISO/TR 10809 explains what can be achieved, what cannot be achieved and why. It is not designed to be a textbook of welding technology. It helps users to select the most appropriate welding process and conditions for a specific application.

This part of ISO/TR 10809 covers production (including finishing and joint welding) and repair welding.

2 Metallurgy

The temperatures which occur during welding dissolve the graphite present in the liquid metallic matrix. Depending on the carbon saturation of the melt and cooling rate of the weld, either martensite and/or ledeburite is formed. In the case of ledeburite, it is formed in the molten areas after a very short time interval ($\leq$ 40 ms). Therefore, it is practically impossible to avoid the formation of ledeburite.

Both martensite and ledeburite are very hard and brittle. They prevent deformation under load, impede machining of the weld and enhance the formation of welding cracks, unless suitable counter-measures are taken.

With the application of appropriate welding processes (e.g. pressure-welding processes), ledeburite can be removed totally from the welding groove, and the formation of martensite can be avoided by either preheating the welding area or the whole casting. They can be completely removed or minimized if appropriate post-weld annealing procedures are followed. To achieve these conditions, the material-specific interrelationships between the base material and the weld material should be converted into production parameters, so as to allow targeted and process-safe settings for the weld-seam characteristics.

The following major welding parameters/control variables are available.

a) Pre-heat temperature: To avoid martensite formation, the weld area should be pre-heated to temperatures above the start temperature of martensite transformation. Pre-heating will not prevent the formation of ledeburite.

b) Heat input: should be as low as possible during welding.

c) Welding speed: will vary depending upon the welding procedure applied and the chemical composition of the cast iron type and grade.

d) Cooling curve: In principle, the required cooling curve can be determined from the time-transition-temperature (TTT) diagram relevant to the cast iron material. For instance, continuously controlled cooling according to the appropriate TTT diagram can prevent the formation of martensite, e.g. in a flash-welding machine. When manual welding methods are used, the cooling rate is influenced by the selected pre-heating temperature.

e) Welding procedure/welding parameter: for automated procedures.

f) Filler metal: When manual or mechanized welding-arc processes are used, the filler metal is matched against the requirements of the weld or welded joint. This depends upon whether the welding process is carried out with homogeneous, semi-homogeneous or non-homogeneous filler metal. No filler metals are needed for the pressure-welding processes described later in the text.

g) Post-weld heat treatment: Measures can be undertaken to remove undesirable structures, such as:

— martensite which can be removed by a sub-critical anneal (tempering);

— ledeburite which can only be removed by a graphitization anneal at austenitizing temperature.

However, these control parameters are not independent of each other and have to be coordinated with the welding procedure applied.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
production welding
any welding carried out during manufacturing before final delivery to the end user

NOTE Production welding includes finishing welding and joint welding.

3.1.1
finishing welding
production welding carried out in order to ensure the agreed quality of the casting

EXAMPLE Finishing welding is the elimination of discontinuities at the surface, e.g. gas pores, sand/slag inclusions, unacceptable shrinkage cavities or cracks that impair the usability of the casting or substantially disturb the appearance of the casting, and which therefore have to be removed during production and before the casting is delivered to the customer.

3.1.2
joint welding
production welding used to assemble components together as an integral unit

EXAMPLE Joint welding is used when a casting is to be joined to another casting or component, e.g. sheet metal or steel profile, to form a complex constructive unit. Welding is part of the manufacturing process and can either be carried out in the foundry itself or at the facility of the processing subcontractor.

3.2
repair welding
welding carried out after final delivery of the casting to the end user

EXAMPLE A broken machine-column casting is causing substantial downtime and financial loss for the user. It would take too long to procure a new casting and delay production for an unacceptably long time period. Repair welding of the broken casting could solve the problem more quickly and economically.

4 Suitable welding processes

4.1 General

Five classes of welding process are described in the following subclauses:

- arc welding, see 4.3.2, 4.3.3, 4.4.2, 4.4.3, 4.4.4, 4.5, 4.6, 4.8.2;
- beam welding, see 4.7;
- resistance welding, see 4.8.1;
- oxy-acetylene gas welding, see 4.2;
- welding with pressure, see 4.8.1, 4.8.2, 4.8.3.

NOTE ISO 4063[54] categorizes the welding process by a number. In this part of ISO/TR 10809, the number relating to the welding-process follows the title of the clause.

4.2 Oxy-acetylene gas welding (311)

The oxy-acetylene gas welding process uses a manually operated flame as the heat source. The flame is energized by a gaseous fuel mix of oxygen and acetylene, the oxygen being mixed with the acetylene inside the burner. The flame is characterized by a two-stage combustion process which enhances the welding process, especially that of providing a protective shield against the ambient atmosphere.

Homogeneous welding rods should preferably be used for oxy-acetylene welding with large output burners having a neutral to slightly reduced flame setting. Fluxes designed to give a neutral atmosphere that prevent oxidation and re-dissolve the oxides formed during pre-heating are either integrated into the welding rods as grooves as a covering, or they are added separately. But also non-homogeneous filler metals are utilized. Data on mechanical properties of welds can be found in Reference [8] in the Bibliography.

4.3 Arc welding (1)

4.3.1 General

The process uses electrically generated welding heat with either homogeneous, semi-homogeneous or non-homogeneous filler rods to make the weld.

The electrical arc has a core temperature of between 5 300 K and 6 000 K. The arc is struck between the surface of the component to be welded and the consumable filler rod.

The coating on the electrode has several uses:

- protection against the atmosphere; the droplets of metal in the arc are protected by a cover of slag or protective gas;
- easier ignition of the arc;
- solid arc by ionization of the air column;
- alloying of the weld deposit;
- covering of the weld seam during cooling;
- increasing the deposition rate by adding iron powder;
- modification of the welding characteristic for such properties as current, polarity, weld shape, basicity and amperage.

Manual arc welding is the preferred procedure using covered electrodes (see ISO 1071[2]) with a pure nickel or nickel-iron core wire. Data on mechanical properties can be found in Reference [8] in the Bibliography. For certain applications, Ni-Cu, Cu-Al and Cu-Sn alloys have been used successfully.

The welding parameters chosen should ensure a narrow heat-affected zone with small amounts of hard structure. Interconnected martensitic and/or ledeburitic transition and heat-affected zones are particularly unfavourable as they induce residual stresses in the casting. Island-like distribution induces less stress in the welded area of the casting. Residual stress can be minimized by adopting some or all of the following measures, see Reference [15] in the Bibliography:

- using electrodes with the smallest possible core-wire diameter;
- using the lowest possible welding current to generate a short arc;
- depositing short stringer beads of 20 mm to 30 mm length with a low cross-section;
- allowing sufficient cooling time between the individual beads;
- changing the welding direction between the individual layers;
- holding the electrode vertically.

4.3.2 Metal arc welding with covered electrodes (111)

In order to fill the weld as quickly as possible and to maintain a constant pre-heating temperature as far as possible, metal arc welding with large-diameter covered electrodes in conjunction with a high current (up to 1 500 A) is chosen. For welding spheroidal graphite cast irons, the covered electrodes can consist of a cored rod of spheroidal graphite cast iron or steel. When a steel rod is used, carbon and silicon as well as elements required for spheroidal graphite formation, such as magnesium, cerium or other rare earths are added from the weld rod coating. Spheroidal graphite cast-iron rods used for oxy-acetylene welding can also be used. Since the magnesium contained in these rods, which is required for spheroidization, is prone to evaporate in the arc, covered electrodes or unalloyed core wires are preferred to reduce the susceptibility to graphite degeneration. An overview of the requirements for welding materials and the design of welding rods and covered electrodes can be found in Reference [2] in the Bibliography.

4.3.3 Self-shielded tubular-cored arc welding (114)

Due to the outside cover and the length of the electrodes, limits have to be set for manual metal arc welding concerning the degree of mechanization and, with it, the possible improved efficiency. Continuously fed electrodes offer essential increased efficiency.

Suitable welding processes are

- gas-shielded metal arc welding with bare electrodes, and
- submerged arc welding with bare electrodes.

The following self-shielded tubular-cored electrodes are the state-of-the-art:

- self-shielded tubular-cored wire electrodes used with or without gas protection. When welding without gas protection, the slag formers are positioned in the middle of the electrode wire. An excess of deoxidizer should be present;
- gas-shielded (CO_2) with bare wire electrodes.

Metal arc welding with flux-cored wire electrodes is gaining more and more in importance for economic reasons, because the process can be automated. The process has a high weld-metal recovery and provides numerous alloying possibilities. Since high pre-heating temperatures can cause thermal distortion, self-shielding flux-cored wires are used instead of shielding gas.

4.4 Gas-shielded metal arc welding (13/14)

4.4.1 General

The TIG (Tungsten Inert Gas), MIG (Metal Inert Gas) and MAG (Metal Active Gas) processes have special advantages by welding with non-homogeneous filler metal, due to the high energy density of their gas-shielded arcs and the associated narrow heat-affected zone.

4.4.2 Tungsten inert gas welding — (TIG welding) (141)

The arc burns between the unconsumed tungsten electrode and the work piece under the protection of an inert gas. This protective gas flows through a gas jet and protects the electrode and the weld against air ingress. Inert gases, such as Argon (Ar) and Helium (He), or mixtures of both gases, protect the tungsten electrode. Oxidizing protection gases, e.g. O_2 or CO_2, cannot be used. However, when welding certain metals, small percentages of H_2 are sometimes added. The process lends itself to part or full mechanization with or without filler metal welding. Welding rods or wire are normally added with the power off.

4.4.3 Metal inert gas welding — (MIG welding) (131/132/133)

As a general rule, the arc burns between a positive consumable welding wire and the work piece under a streaming inert gas inside an inert gas jacket. The protection gases are the same as those used for TIG welding. Inert gases, even with the high temperature of the arc, do not react with the weld. MIG welding is suitable for the welding of Aluminium (Al) and Magnesium (Mg) and their alloys.

The MIG/MAG processes can be used for joint welding, and when they are automated, it is possible to use them for large-scale joint-welding production. The MIG/MAG processes are increasingly used for hard facing (repair welding), finishing welding and general repair welding. By reducing the heat input through the adoption of short-arc and impulse technology, extremely narrow heat-affected zones result, with improved mechanical properties as shown in Reference [9] in the Bibliography. The main shielding gas used is argon. Today, only small amounts of CO_2 are recommended for MAG welding. A higher CO_2 content is considered problematic with regard to its oxidizing effect on magnesium and, as a possible consequence, the degeneration of graphite in cast iron.

4.4.4 Metal active gas welding — (MAG welding) (135/136/138)

Compared to MIG welding, the only difference in the welding process is that the inert gas is replaced by active gases such as CO_2, mixtures of either Ar and CO_2 or Ar, CO_2 and O_2. The same welding equipment is used for both MIG and MAG welding. The arc burns with the protection of an active gas between the consumable welding wire and the work piece. When using equal current and voltage, the protection gases have an effect on the arc shape, the length of the arc and the upper and lower welding beads.

Figure 1 illustrates the bending fatigue strength of un-welded and welded ferritic (left picture) and pearlitic (right picture) spheroidal graphite cast iron. These results are quite well in accordance with the results of blackheart malleable cast irons of the same strength category (References [10], [11] in the Bibliography).

4.5 Submerged arc welding (12)

Submerged arc welding is a masked arc welding process. The arc burns between the consumable wire electrode and the work piece. The arc is protected by a loosely (not fixed) filled granular, easily fluxed powder. Sparks and spatter are prevented by this technique. The powder protects the weld pool against air ingress, avoids abrupt cooling, shapes the weld and assists gas emission from the weld metal. It also has a metallurgical influence on the chemical composition of the weld metal.

Submerged arc welding, electro-slag welding with solid or flux-cored wire, cast welding or liquid metal welding are mainly used for repair welding of large castings.

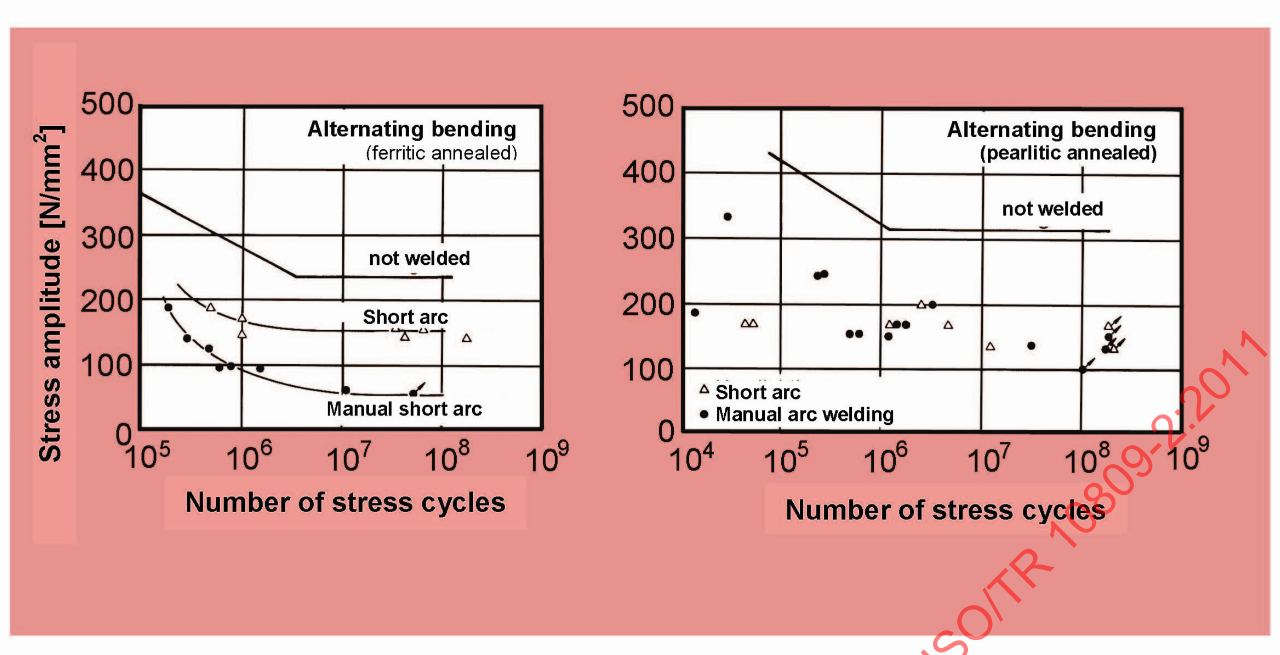


Figure 1 — Bending fatigue strength of un-welded and welded ferritic (left) and pearlitic (right) spheroidal graphite cast iron

Figure 1 is reproduced by permission of Bundesverband der Deutschen Giesserei-Industrie, Dusseldorf.

4.6 Plasma arc welding with or without filler metal (15)

Plasma welding is operated by a heavily heated gas consisting of molecules, atoms, ions and electrons. It is entirely electrically neutral.

Two different arc arrangements are used, an auxiliary arc and an assigned arc. The auxiliary arc is used to ignite the assigned arc. The auxiliary arc is induced by high-frequency current. If the assigned arc is ignited then the auxiliary arc extinguishes. The assigned arc burns between a non-consumptive thoriated tungsten electrode and the work piece. A water-cooled strangling copper injector is the anode and a Ti-electrode is the cathode. The plasma gas is blown into the annulus collector between the anode and the cathode. The Cu-injector effects a lateral contraction of the arc, thus an improvement of power density and accordingly an increase of temperature of the plasma beam. Adjustments allow the process to be used for either welding or cutting.

For plasma arc joint welding, in addition to the plasma gas, a second gas stream (99,95 % Ar) is used in order to protect the weld pool against atmospheric interference.

Most plasma arc welding equipment uses a third gas stream, the focussing gas (Ar + He, Ar + H_2, Ar + N_2) for additional compressing of the plasma stream outside the strangling injector.

Plasma welding with or without filler metal is mostly an application-orientated procedure, e.g. for pipe joints (see Figure 2).

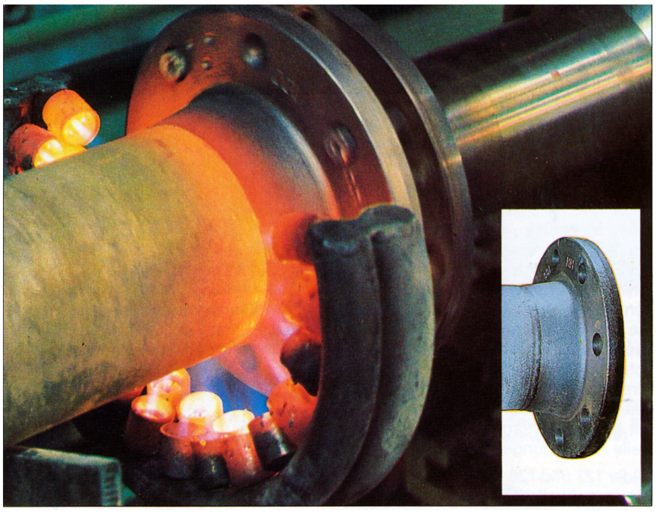


Figure 2 — Plasma welded joint between a centrifugal casting tube and a spheroidal graphite cast iron (JS) flange

Figure 2 is reproduced by permission of Bundesverband der Deutschen Giesserei-Industrie, Dusseldorf.

4.7 Electron beam welding (511)

When energy conservation is sought, electron beam welding should be considered as an alternative welding method (Reference [10] in the Bibliography). Electron beam welding has a very favourable heat input. Welding without filler metal showed unsatisfactory results. However, by adding a nickel inlay, the hardened zones in the area of parent metal were reduced to a minimum. Due to the procedural complexity, electron beam welding will very probably remain limited to certain special applications.

4.8 Pressure welding processes (4)

4.8.1 Flash welding (24)

Pressure welding processes use the application of heat and pressure to give macro-deformation and coalescence of the base material. Flash welding is a resistance pressure-welding process. The welding heat is generated by resistance heating directly in the welding unit by induced current. The parts are repeatedly pressed together, such that the contact faces are heated by the flashing (sometimes referred to as arcing) of the welding current. The process is reversed (repeated) until the energy at the contact faces is sufficient to achieve continuous flashing.

During the flashing phase, “fusing contacts” develop where the ends of the electrically charged parts are brought together. The extremely high current created in the transition zone quickly heats and melts the metal. The high resistance caused by insufficient compressing of the contact faces increases the deposition rate of the weld. Vapour pressure builds up on the weld surface as a result of metal evaporating in some areas. Due to vapour pressure, liquid metal is thrown out of the welding gap, creating a “shielding gas atmosphere” that keeps the atmospheric oxygen away from the weld. The flashing process is continued until the required welding temperature is reached. Then the machine control starts the upsetting process, followed by switching off the electric current.

Large, thick-walled castings are usually welded after pre-heating. Thin-walled castings do not normally require “reversing”. The process is then called flash welding without pre-heating, or “cold flash welding”.

Modern welding machines can provide a resistance post-weld heat treatment while the parts are still in the machine, thus avoiding intermediate cooling with the potential risk of creating martensitic structures prone to cracks.

The flash-welding process is divided into the following steps:

- initial flashing to produce parallel surfaces;
- flashing to generate sufficient heat for the upsetting operation;
- upsetting to compress two surfaces to form the joint and press out ledeburite from the weld zone;
- controlled cooling, post-weld, to prevent the formation of martensite and to produce the required structure (References [12], [13], [14] and [40] in the Bibliography).

Figures 12, 14 and 15 illustrate the process sequences and the process monitoring (see 6.1.2.2).

4.8.2 Magnetically impelled arc welding (185)

Welding with a magnetically impelled arc, sometimes referred to as Magnetarc™ welding, is an arc pressure-welding process that makes use of the fact that an arc can be deflected in various directions by a controlled magnetic field. Depending on the direction and intensity of the magnetic field, the arc can be rotated around its own axis, or programmed to take an elliptic shape of varying current density. In most cases, the electric arc moves between two tubes.

Welding is carried out with fully mechanized or automated welding equipment. The work pieces are centred and clamped in the machine, and the arc is struck as soon as the two faces to be joined touch. The arc is then rotated between the abutting faces with increasing speed, thereby melting them. Direct current is used for this welding process. The rotational speed is between 30 m/s and 150 m/s, depending on the strength of current, magnetic field and shielding gas used, which equals a rotational frequency of between 200 Hz and 2 000 Hz. After a predetermined period of time, the two components are pressed together, and then the welding current is switched off.

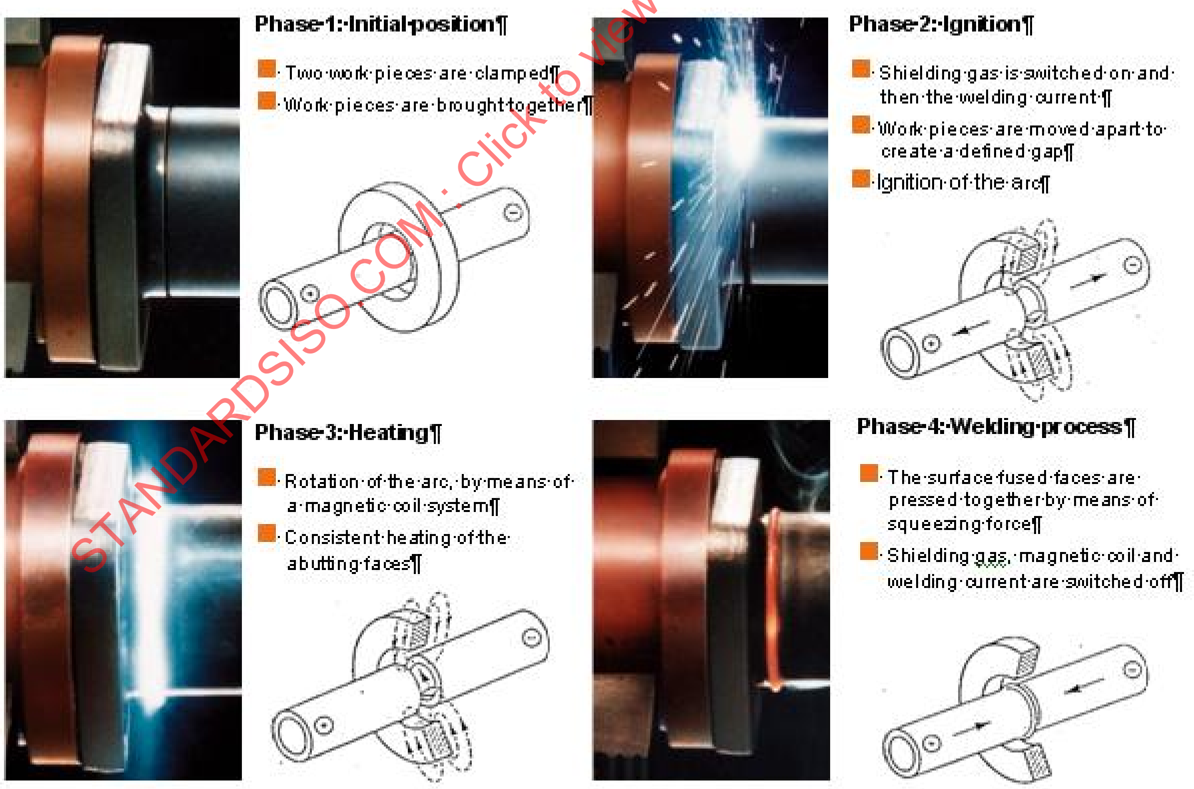


Figure 3 — Successive process steps of magnetically impelled arc welding

Figure 3 is reproduced by permission of KUKA Systems GmbH Industrial Solutions, Augsburg.

Examples of the ranges of the process parameters:

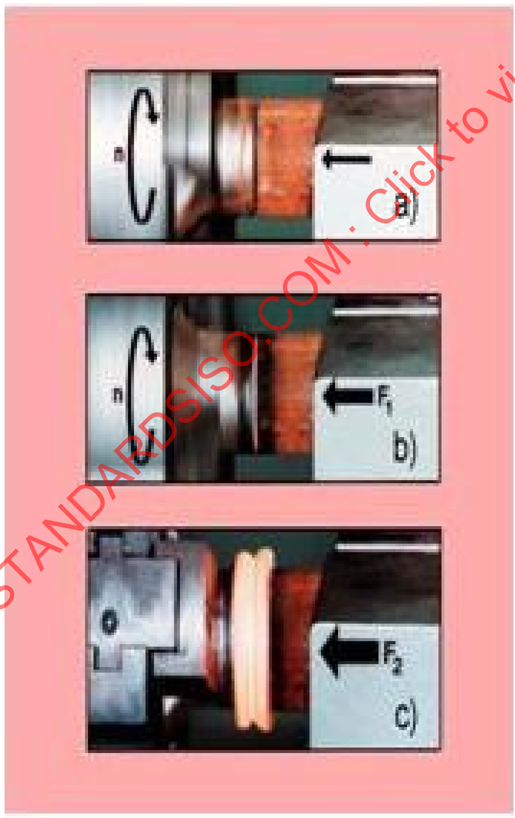
—	Strength of current:	200 A to 1 200 A	—	Upsetting force:	0,5 kN to 450 kN
—	Welding time:	0,3 s to 5 s	—	Magnetic field:	100 G to 500 G
—	Length of arc:	1,5 mm to 3 mm	—	Shielding gas:	Mainly CO_2

4.8.3 Friction welding (42)

Friction welding belongs to the group of hot pressure-welding processes. Heat generated by friction due to the relative motion of the contact faces allows joining under a compressive load. Here a distinction is necessary between conventional- and inertia-friction welding. During conventional-friction welding, powerful electric motors accelerate and stop the rotating component. During inertia-friction welding, the applied thermal energy is supplied by the mass and speed of the flywheel.

Friction welding can be successfully achieved by using the right combination and sequence of contact pressure and/or number of revolutions during welding. State-of-the-art control systems are used to provide a practically unlimited choice of pressure/speed curves. Changes in pressure or speed can be planned continuously or step by step. Typically, speeds range from approximately 500 to 3 000 r/min, with pressures varying between 20 N/mm^2 and 100 N/mm^2. When the joining faces have been heated sufficiently, the rotational movement of the friction spindle is decelerated abruptly to start the upsetting phase, and the two parts to be joined are forged together. Upsetting may be effected either while the spindle is still rotating with a defined speed, or into the spindle. The upsetting pressures applied are generally above the friction pressures needed to create the friction.

Figure 4 shows the successive process steps of friction welding.



Phase 1: Two pieces are clamped, rotation of one work piece

b) Phase 2: Heating: Two work pieces are pressed together with force F (friction force) Rotation n and force F_1 generate friction; the surfaces to be welded are heated

c) Phase 3: Welding: Rotation of the work piece is slowed down (selectable deceleration time), joining by increased force F_2, upsetting force

Figure 4 — Process phases of friction welding

Figure 4 is reproduced by permission of KUKA Systems GmbH Industrial Solutions, Augsburg.

Rotational symmetry is an important design consideration for friction welded components. Non-rotationally symmetrical parts can be joined with minimum angular deviation, but the process is not recommended.

The advantages of friction welding include the following:

— friction welding allows successful joining of most dissimilar materials;

— joining two identical materials is usually possible without any limitation in the wall thickness, i.e. up to the full cross-section;

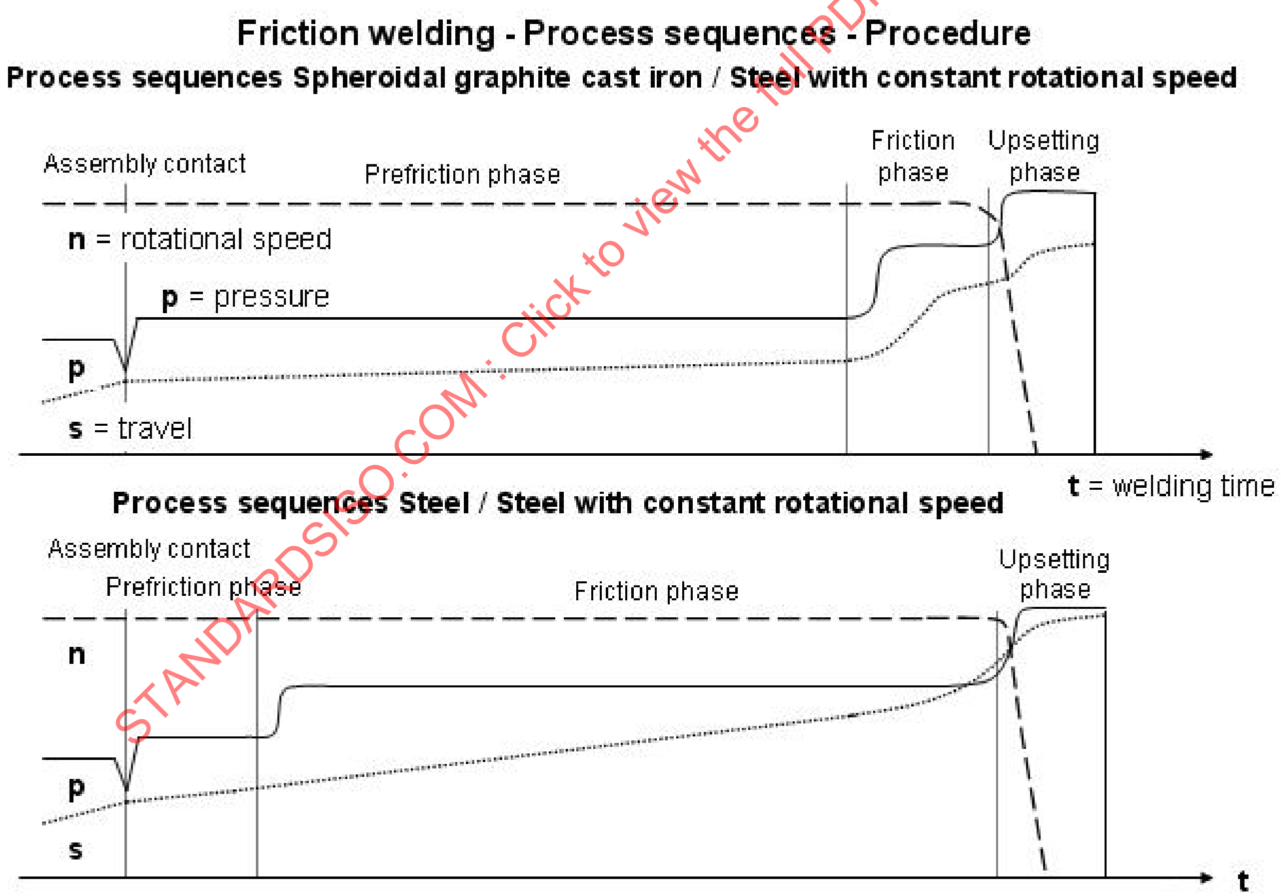
— the welding times are short and range between 10 s and 30 s;

— no filler metal is required for welding.

A significant restriction is that friction welding of dissimilar materials is often limited to hollow profiles. Other restrictions to friction welding include the following:

— for cast-iron materials, the wall thickness is limited by the need to squeeze out the ledeburite formed during the process, see 6.1 2.

Defining process parameters is more complex compared to welding with an input of electric energy. Parameters are based on carefully established, extensive data banks and experience gained over many years and through numerous trials. Machine and process reproducibility requires process parameters to be logged, evaluated and documented by appropriate control systems, which can range from simple analogue systems



as shown in Figure 5 to fully graphic, computer-based systems as shown in Figure 6.

Figure 5 — Time curve of process parameters of speed n, friction/upsetting pressure p, travel s

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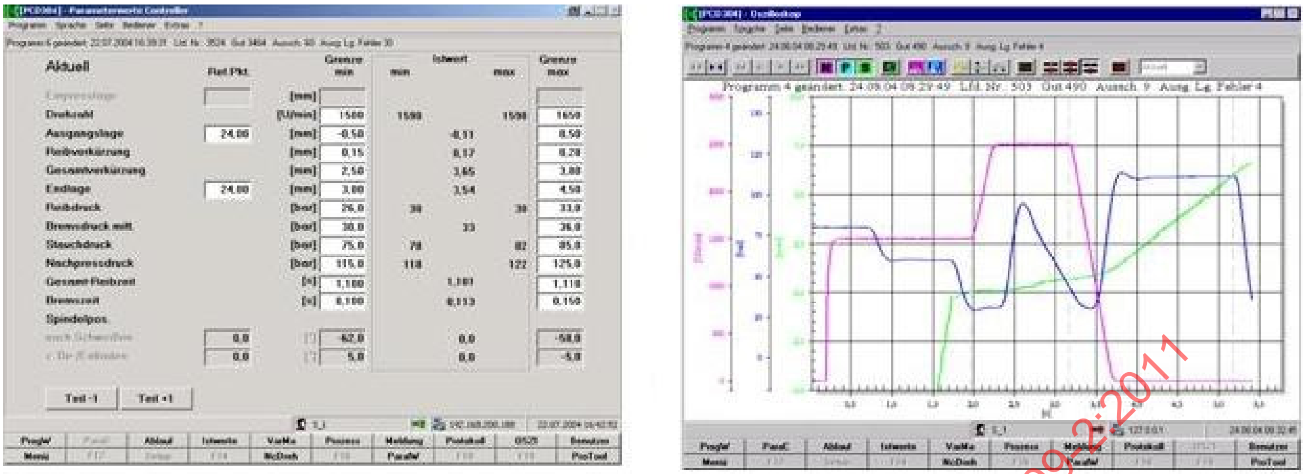


Figure 6 — Friction welding — Process monitoring with PC-based fully graphic systems

Figure 6 is reproduced by permission of KUKA Systems GmbH Industrial Solutions, Augsburg.

4.9 Other welding processes

Other welding processes are cast welding and liquid metal welding:

— cast welding: welding by pouring liquid metal into a specially prepared groove in a casting (Reference [1] in the Bibliography);

— liquid metal welding: welding with additional use of a metal arc welding process (Reference [1] in the Bibliography).

5 Suitable welding procedures

NOTE The specification of the requirement class and selection of the assessment group is the basis for the selection of the suitable welding procedure and any special conditions or considerations that apply (Reference [51] in the Bibliography). The following subclauses 5.1 to 5.4 give information on the suitable welding procedures and show examples related to the welding of cast irons.

5.1 Welding with homogeneous filler metal

Homogeneous filler metal comprises any filler which results in a deposited metal with the same type of microstructure as the parent metal (Reference [2] in the Bibliography).

Figure 7 shows an example of a cast-iron weldment produced with homogeneous filler metal, i.e. an iron matrix containing graphite.

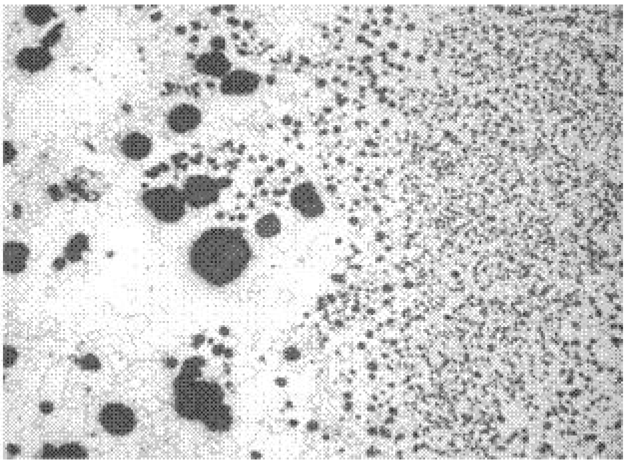


Figure 7 — Microstructure of the transition zone of a weld produced with a homogeneous Fe-C-Si filler metal (right side of photograph) on a JS/400-15 casting (left side of photograph)

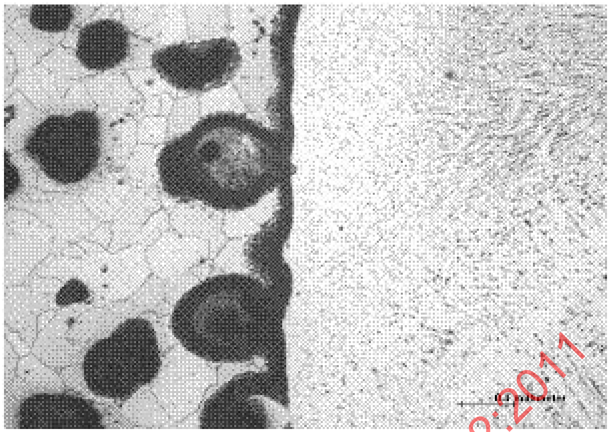


Figure 8 — Typical microstructure of a transition zone of a non-homogeneous weld of a spheroidal graphite cast-iron grade ISO1083/JS/400-15 (left) material with Ni-Fe filler metal (right) (see 5.3)

Figures 7 and 8 are reproduced by permission of Siempelkamp Giesserei GmbH, Krefeld.

To prevent the formation of martensite and/or bainite, the entire casting (in some cases just the weld) should be pre-heated. Pre-heating has the same effect as delayed cooling. The pre-heating temperature should range from 400 °C to 700 °C (References [6] and [7] in the Bibliography), depending on the type and grade of cast iron. During welding, the working temperature should be monitored and maintained within the limits given in the tables in Clause 7. An increased working temperature and the small solidification interval of cast irons form a much higher risk of the weld pool collapsing. In such circumstances, a weld-pool backing support needs to be used. If necessary, heat treatment can be carried out after welding to produce the required material structure and the casting should be sufficiently slow cooled to reduce residual stress.

Suitable welding processes used with homogeneous filler metals are

- self-shielded tubular-cored arc welding with wire electrodes without gas protection,
- manual metal arc welding with covered electrodes,
- oxy-acetylene gas welding,
- cast welding, and
- liquid metal welding.

In all five cases, welding should be carried out with the greatest possible heat input.

Suitable welding consumables should be chosen from those given in ISO 1071[2].

Homogeneous welding rods should be used for oxy-acetylene welding with large output burners having a neutral to slightly reduced flame setting. Fluxes designed to give a neutral atmosphere that prevent oxidation and re-dissolve the oxides formed during pre-heating are either integrated into the welding rods as grooves, as a covering, or they are added separately.

Solution annealing heat treatment can also then be necessary if additional elongation properties are required (Reference [7] in the Bibliography).

5.2 Welding with semi-homogeneous filler metal

Semi-homogeneous filler metal is any filler metal which results in a deposited metal with a steel-type microstructure, i.e. without any graphite being present (Reference [2] in the Bibliography). Welding with semi-homogeneous filler metal is only suitable for malleable cast irons and spheroidal graphite cast irons.

Some authors report on the use of steel electrodes for spheroidal graphite cast irons (Reference [28] in the Bibliography). To avoid cracks in the weld transition area, the weld temperature parameters need to be controlled and kept within close limits. Martensite should be removed by annealing to produce highly ductile welded joints. Pre-heating temperatures of 250 °C to 550 °C can considerably reduce the formation of martensite after welding. Reference [8] in the Bibliography contains typical mechanical properties.

5.3 Welding with non-homogeneous filler metal

A non-homogeneous filler metal is any filler metal which results in a deposited weld metal with a microstructure that differs from the parent metal (Reference [2] in the Bibliography).

Suitable welding processes are as follows:

— Manual metal arc welding with covered electrodes and filler metals with pure nickel or nickel/iron wire. (For certain applications Ni/Al, Cu/Al, Cu/Sn alloys have successfully been used);

— Tungsten Inert Gas welding (TIG);

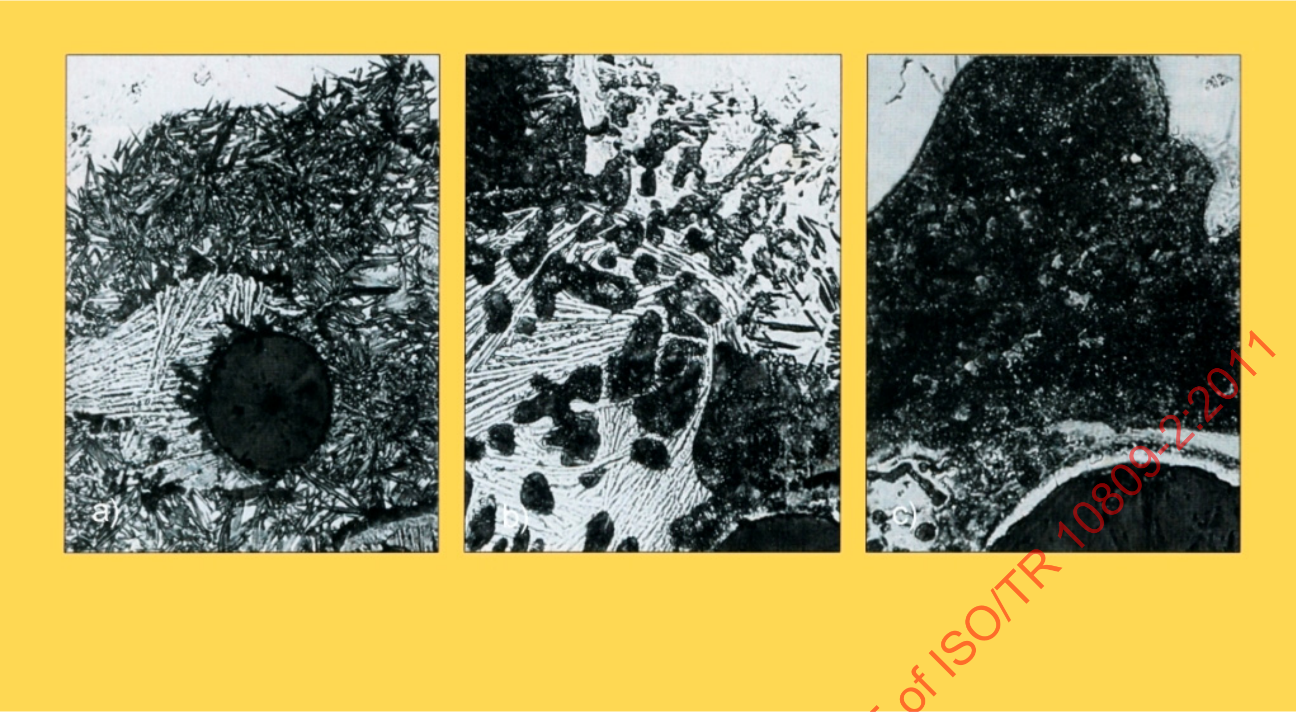
— Metal Inert Gas welding (MIG);

— Metal Active Gas welding (MAG).

Welding with non-homogeneous filler metals, such as the high-nickel materials, produces a weld with a microstructure that differs from the parent metal (Reference [2] in the Bibliography) i.e. the matrix may be largely free from iron. In this case, the obvious distinguishing feature compared to that of a homogeneous filler metal is the difference in colour between the austenitic filler metal and the parent metal. In the dilution zone, the nickel-based filler metal picks up iron from the parent metal to form nickel martensite. During solidification, carbon precipitates in the form of small graphite spherulites, which results in a reduction of residual stress due to the increase in volume caused by the precipitation of graphite. The weld remains tough. Shot peening the weld while hot can even create advantageous compressive stresses that minimize the risk of residual stress from the welding procedure.

The typical microstructure of the transition zone of a non-homogeneous weld of an ISO1083/JS/400-15 material with Ni-Fe filler metal is shown in Figure 8, see 5.1.

For nickel-based weld metal, there is normally no need to pre-heat the casting. For welding procedures with a higher energy density, such as gas-shielded metal arc welding or manual arc welding with larger electrode diameters, pre-heating to 100 °C to 250 °C is recommended. The continuous martensitic seam caused by the higher specific heat input can thus be avoided but not the nickel martensite in the fusion zone or the ledeburite normally surrounding the graphite spherulites [see Figures 9 a), 9 b) and 9 c)].



a) Welding structure of a transition zone of spheroidal graphite cast iron welded with a Ni-Cu filler metal, not preheated: Transition zone with ledeburite and Ni-martensite

b) Welding structure of a transition zone of spheroidal graphite cast iron welded with a Fe-Ni filler metal, preheated to 350 °C: Transition zone with Ledeburite and Ni-Martensite

c) Welding structure of a multi-pass weld: Influenced by the welding heat the ledeburite isles of the lower layers have been transformed to pearlite and tiny spherulites with surrounding ferrite

Figure 9 — Welded structures with spheroidal graphite cast iron

Figure 9 is reproduced by permission of Georg Fischer Automotive AG, Schaffhausen.

The higher the heat input, the larger the ledeburite islands which, in extreme cases, can expand to form a continuous seam. Because ledeburite has practically no deformability and only decomposes at higher annealing temperatures and longer annealing times, the lowest possible heat input should be applied when welding graphite containing cast iron with non-homogeneous filler metal. For multi-layer welding, the upper layers can have a heat-treatment effect upon the lower ones [see Figure 9 c)].

The slower solidification rate of thick-walled cast irons results in fewer, but larger graphite inclusions. The increased distance between the graphite inclusions prevents the ledeburite islands from merging. The tendency to form a ductile melting line is therefore higher than in thin-walled castings, which consequently produces welds with a reduced risk of brittle fracture, even without post-heat treatment.

Cast iron with a ferritic matrix is easier to weld than cast iron with a pearlitic matrix. This is because, in a ferritic matrix, the carbon within the austenite responsible for hardening first has to be re-dissolved from the nodules, which takes time and thus makes the process less critical.

5.4 Welding without filler metal

Welding without filler metal involves the application of pressure to the welded joint. The usual processes are as follows:

— flash welding;

— magnetically impelled arc welding;

— friction welding.

These processes have proved to be successful for welding spheroidal graphite cast iron to spheroidal graphite cast iron or spheroidal graphite cast iron to steel. All three processes have the following three characteristics:

— They do not require the use of a filler metal. The weld is created by upsetting the joining surfaces at the end of the welding process, which results in a homogeneous or semi-homogeneous weldment.

— During the application of pressure, any unwanted ledeburite formed during welding is squeezed from the joint surface into the bulge, where it no longer affects the force progression. The ledeburite can be removed completely by machining the bulge before the welded component is processed.

— All three processes can be automated, which makes each of them suitable for high-volume production of safety critical parts, e.g. for the automotive industry. The process parameters can be monitored and the results recorded for process control purposes.

6 Examples of welding of cast irons

6.1 Welding of spheroidal graphite cast iron

6.1.1 Finishing welding

6.1.1.1 Finishing welding with homogeneous filler metal

Figure 10 shows an example of finishing welding with homogeneous filler metal on a 9-cylinder crankcase made of spheroidal graphite cast iron ISO1083/JS/450-10U.

The defect was situated in such a position that the housing had to be pre-heated in an upright position to a maximum temperature of 700 °C in the welding area. Electrical resistance annealing elements were positioned systematically by numerous control circuits. The difficulty was to guarantee a sufficiently high welding temperature and also to avoid distortion by the dead weight of the casting. The chosen welding process used was metal arc welding with a flux-cored wire electrode. The entire welding process was supervised by a third-party registered assessor.

Figure 7 (see 5.1) shows the typical structure of a spheroidal graphite cast iron ISO1083/JS/400-18 welded with a homogeneous filler metal.

Weight: ~53 t

Measures: 10 × 3 × 2,5 m

Figure 10 — Finishing welding of large iron castings 9-cylinder crankcase prepared for pre-heating and welding in an upright position at a height of 10 m

Figure 10 is reproduced by permission of Siempelkamp Giesserei GmbH, Krefeld.

6.1.1.2 Finishing welding with non-homogeneous filler metal

Figure 11 shows an example of finishing welding with non-homogeneous filler metal, viz. an 18-cylinder crankcase made of spheroidal graphite cast iron ISO1083/JS/400-18U. The casting weighs approximately. 23 tonnes, its size is 7 × 2 × 2 m.

A moulding sand inclusion through the casting wall was closed by MAG-welding. This process required a high degree of skill and technical expertise. Sound material was detected after surface inspection and radiographic testing demanded by the purchaser.

A typical microstructure of spheroidal graphite cast iron welded with non-homogeneous Ni-Fe filler metal is shown in Figure 8 (see 5.1).

Figure 11 — Finishing welding at the 18-cylinder engine block

Figure 11 is reproduced by permission of Siempelkamp Giesserei GmbH, Krefeld.

6.1.2 Joint welding

6.1.2.1 General

All welding processes and associated filler metals are suitable for joint welding of spheroidal graphite cast irons. To ensure satisfactory outcomes, the welding process, the wall thickness, the properties required by the purchaser, the structure of the weld, the welding conditions and parameters should be considered and agreed upon.

The following subclauses describe the application of joint-welding techniques to the welding of spheroidal graphite cast iron on examples taken from applications in the automotive industry in which specified process capability requirements have to be met. The three examples show that spheroidal graphite cast-iron castings can be joint welded and subjected to high loads in safety constructions and the process can be cost effective. The examples describe three separate joint-welding techniques: flash welding (bus axle), magnetically impelled arc welding (trailing arm) and friction welding (front axle body).

The following aspects should be taken into consideration when choosing a suitable joint-welding procedure for large-scale production:

— economy, i.e. mainly short process times (includes welding and post-welding heat treatment);

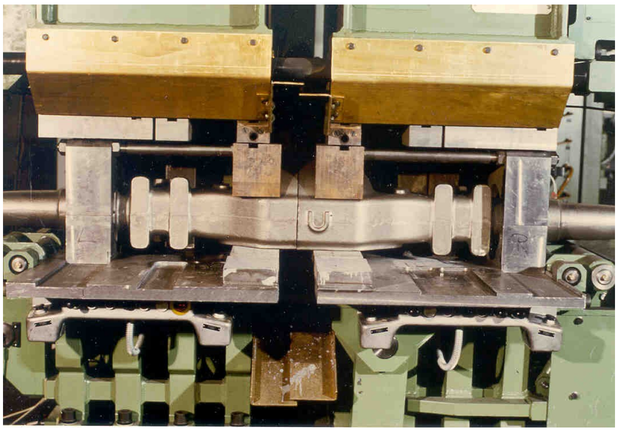
— process capability, i.e. mechanized or automated welding procedures such as these provide consistent weld quality of the components.

The long decomposition times of ledeburite oppose economic requirements. This means that squeezing the ledeburite out of the welding gap at the end of the so-called pressure-welding process has cost implications and that this process is especially cost effective and metallurgically suitable. Moreover, another benefit is that no filler metal is required, which additionally reduces costs and minimizes variation of all properties of the weld.

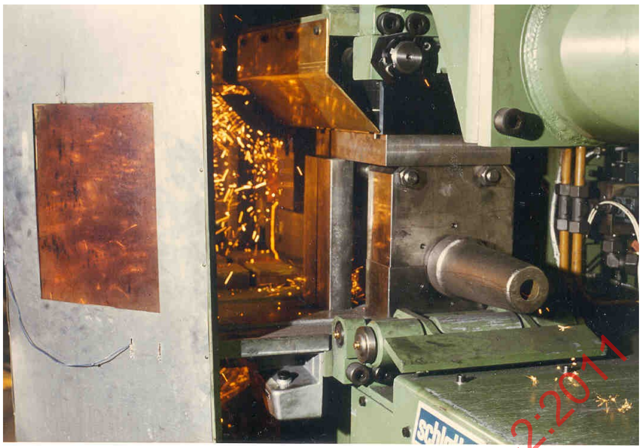
6.1.2.2 Flash welding

EXAMPLE Bus rear axle.

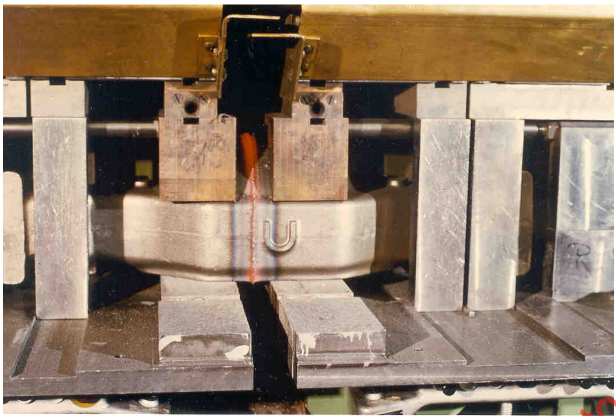
Figures 12 a), b), c), d) show selected sequences of the flash-welding process.



a) Fixing the axle beam halves in the welding machine



b) Typical formation of spatter during initial surface flashing, pre-heating and flashing



c) Post-annealing of the welding seam in the welding machine, cf. Figure 13

d) Heat-affected zone (temper colours) of the post-annealed rear axle beam in the welding machine

Figure 12 — Selected process steps of flash welding

Figure 12 is reproduced by permission of Georg Fischer Automotive AG, Schaffhausen.

6.1.2.3 Post-weld annealing in the welding machine

Figure 13 shows the TTT-diagram for continuous cooling for a typical composition of spheroidal graphite cast iron. It displays the cooling curves of the welded bus axles during post-annealing in the welding machine. Examination of the microstructure confirmed the expected values according to the diagram. No martensite, but only pearlite was formed. The ledeburite formed during flashing was completely squeezed into the weld bed.

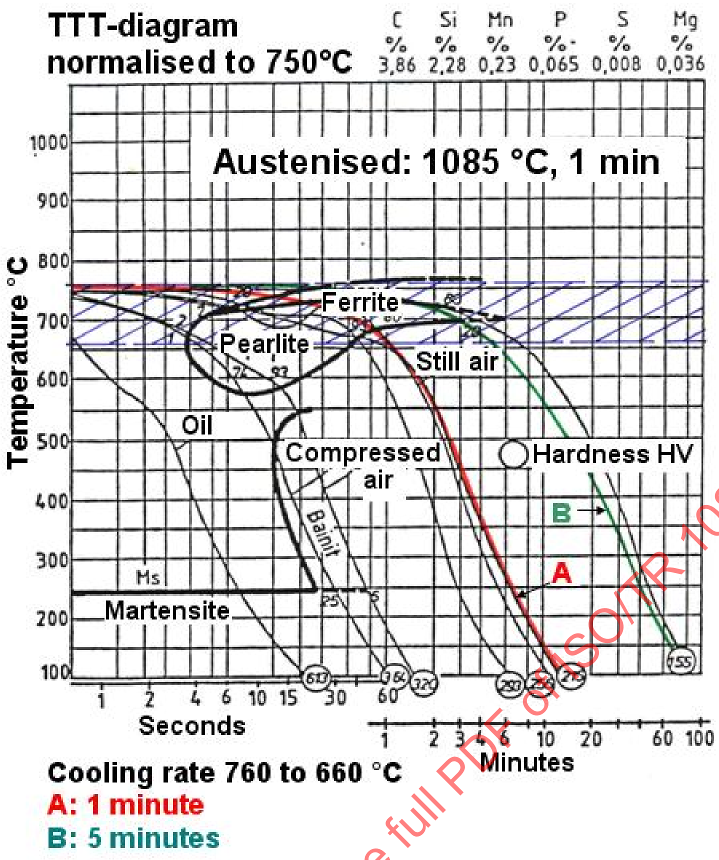


Figure 13 — TTT-Diagram (Time-Transition-Temperature) with cooling curves A and B

Figure 13 is reproduced by permission of Georg Fischer Automotive AG, Schaffhausen.

Advantages and restrictions of the process

Advantages:

— no special requirements on the shape of the weld contact area;

— wall thickness limited by the ability to squeeze out the ledeburite;

— saw cut sufficient for joint preparation;

— controlled post-weld cooling according to the TTT-diagram (Figure 13) prevents martensite formation;

— no filler metal required;

— reduced NDT requirement due to monitoring the welding parameters, see Figures 14 and 15;

— no pre- or additional post-weld heat treatment required.

State-of-the-art welding technology monitors the parameters of the welding process, and is able to accept or reject welded components automatically at the end of the welding cycle.

Restrictions:

— long processing times due to the post-weld cooling cycle;

— high equipment investment costs;

— current technology restricts flash welding to a maximum of 30 mm wall thickness.

6.1.2.4 Process monitoring

State-of-the-art welding technology monitors the parameters of the welding process, and is able to accept or reject welded components automatically at the end of the welding cycle, see Figures 14 and 15.

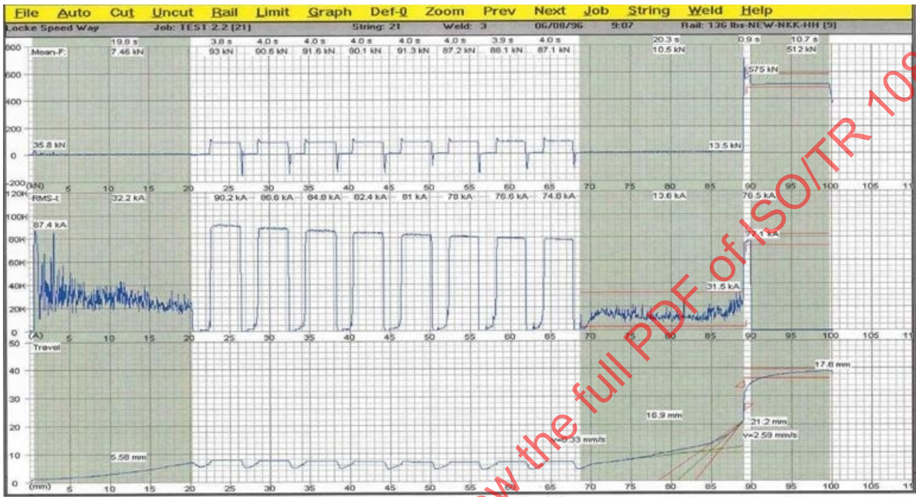


Figure 14 — Graph showing a welding process: all critical parameters are within the specification

Figures 14 is reproduced by permission of Schlatter Industries AG, Zurich.

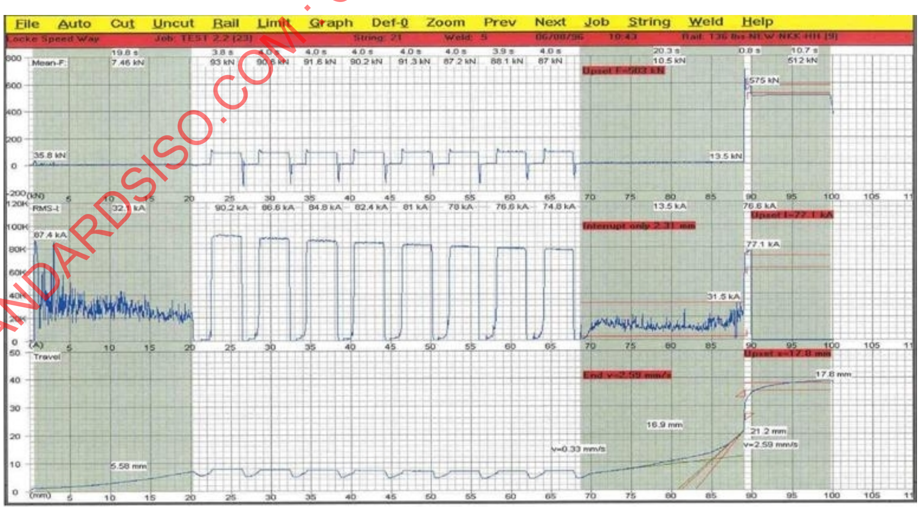


Figure 15 — Graph showing a welding process: welding parameters shown in red are outside the tolerance band

Figures 15 is reproduced by permission of Schlatter Industries AG, Zurich.

6.1.2.5 Test results

Fatigue strength tests were carried out with the bus axles under pulsating bending stress. Comparative tests included the serial steel axle beams, as well as two-piece welded axle beams, or cast as one piece, made of spheroidal graphite cast iron (ISO1083/JS/600-03). The test rig is shown in Figure 16 and the results are shown in Figure 17.

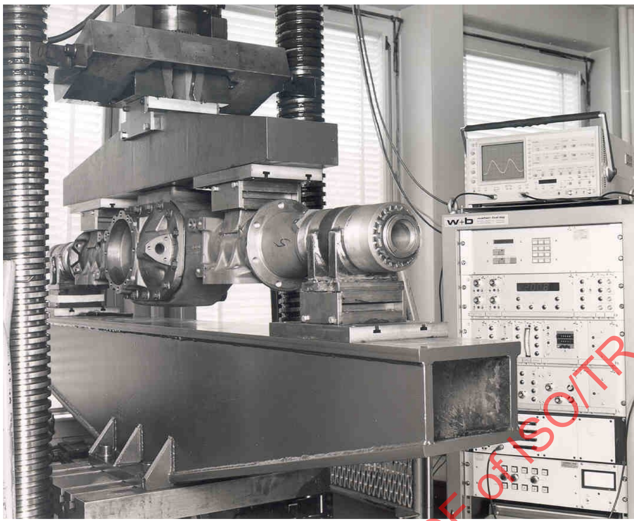


Figure 16 — 10 tonnes axle beam of spheroidal graphite cast iron ISO1083/JS/600-3 on the servo-controlled 600 kN universal testing machine

Figure 16 is reproduced by permission of Georg Fischer Automotive AG, Schaffhausen.

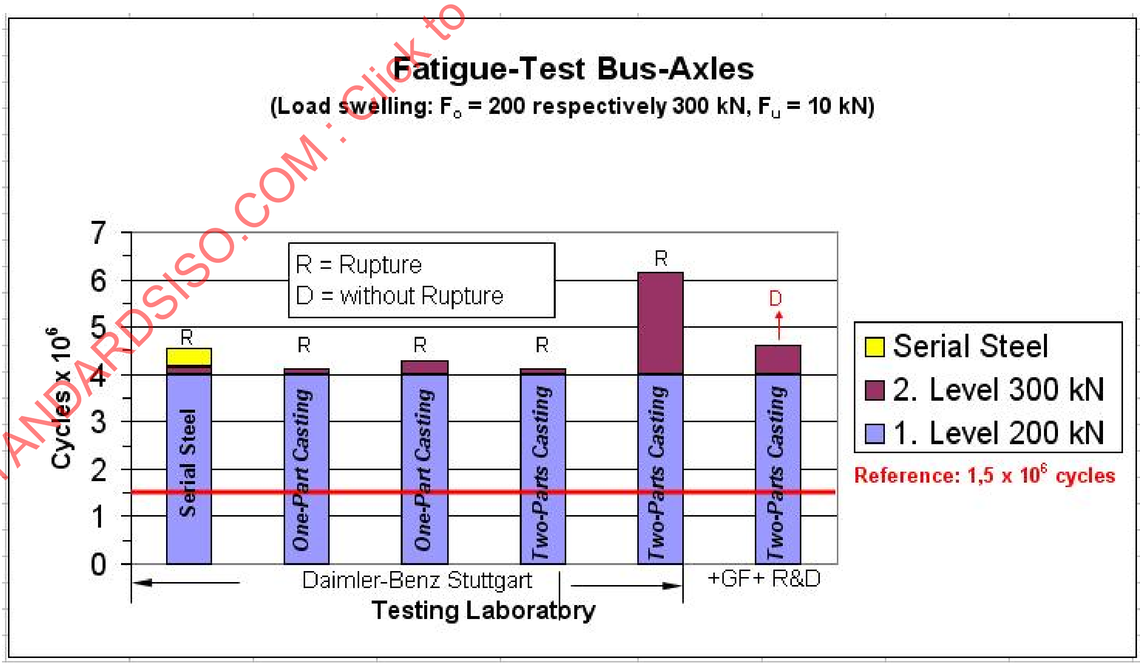


Figure 17 — Fatigue strength test of bus axle beams — Results

Figure 17 is reproduced by permission of Georg Fischer Automotive AG, Schaffhausen.

Figure 18 illustrates the freedom in component profile design for flash welding.

EXAMPLE Flash-welded bus axle.

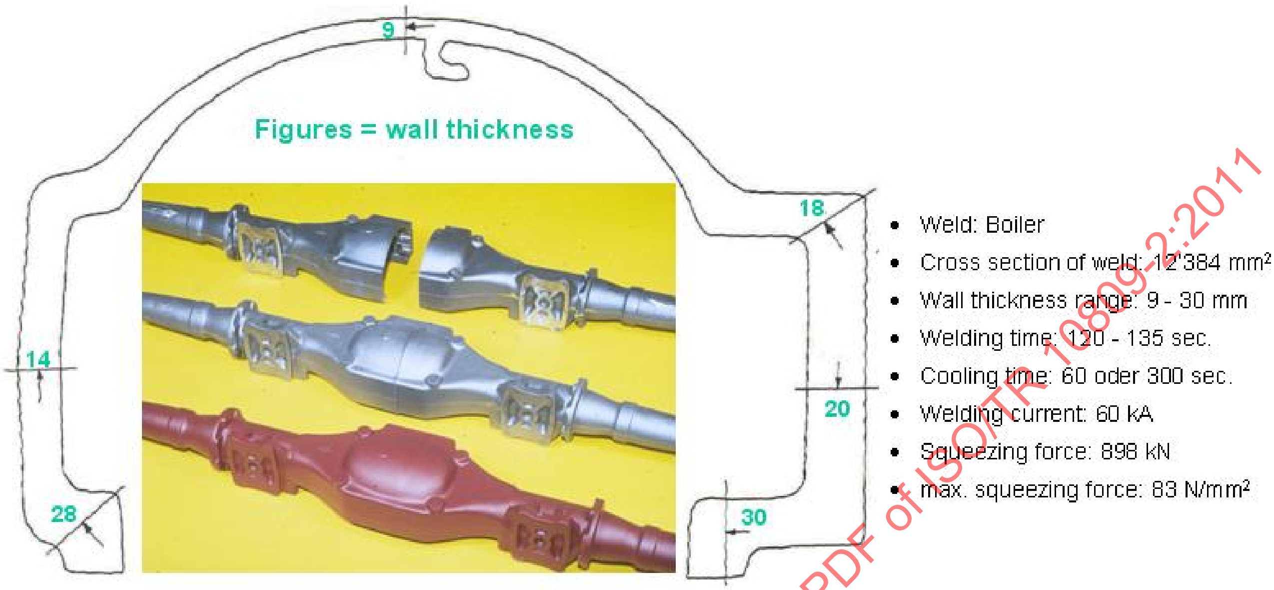


Figure 18 — Overview of the freedom of profile design of the welding surface for components that can be flash-welded

Figure 18 is reproduced by permission of Georg Fischer Automotive AG, Schaffhausen.

6.1.2.6 Magnetically impelled arc welding

EXAMPLE Rear axle trailing arm.

Contrary to flash welding, magnetically impelled arc welding (magnetarc welding) requires

— enclosed geometries, and

— preferably rotationally symmetric parts; deviations, e.g. oval profiles.

Advantages and restrictions

Advantages:

— cost-effective welding process: welding times ≈10 s;

— no filler metal required;

— reliable welding process, process stability in practice million fold verified (up to now, over 6 million rear-axle control arms for front-driven ASTRA and ZAFIRA compact van).

Restrictions:

— Casting wall thickness is limited to a maximum of 6 mm. (Current research aims at increasing the feasibility to 8 mm to 10 mm wall thickness by pre-heating the weld.)

Figure 19 illustrates a trailing arm for the Astra/Zafira rear axle made from spheroidal graphite cast iron ISO1083/JS/400-15 material and Figure 3 (see 4.8.2) shows the magnetically impelled arc welding procedure being performed.

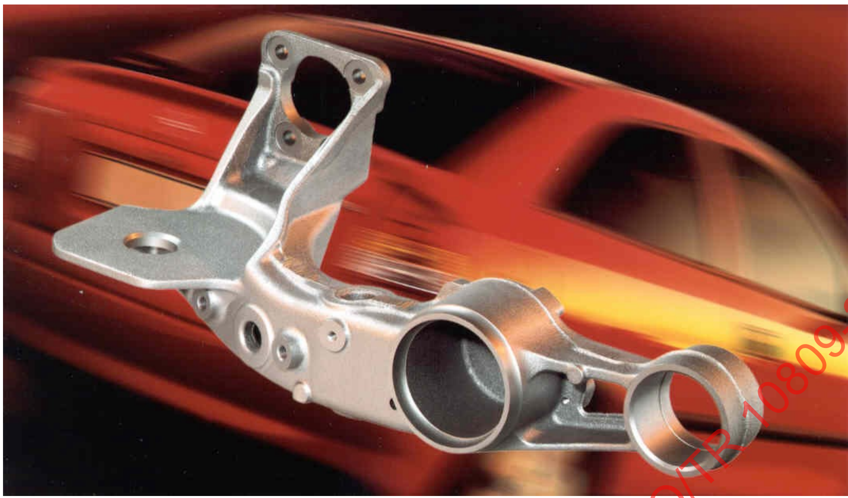


Figure 19 — Trailing arm for the Astra-Zafira

Figure 19 is reproduced by permission of Opel, Russelsheim and Georg Fischer Automotive AG, Schaffhausen.

6.1.2.7 Process monitoring

Current welding technology allows the parameters of the welding process to be monitored, and to accept or reject welded components automatically at the end of the welding cycle (Figure 20).

Valve housings, axle control arms, etc. are well-tried practical examples. Figure 24 shows the welded rear axle of the General Motors ASTRA and ZAFIRA models. Two trailing arms (Figure 19) of spheroidal graphite cast iron ISO1083/JS/400-15 are welded to a steel torsion profile grade 22MnB5 modified (Reference [53] in the Bibliography). To date, more than 6 million axles, i.e. over 12 million welds, have been produced, and no field failure has been reported. Such usage shows that the joining of safety parts made of spheroidal graphite cast iron and steel with the magnetarc welding process is both process capable and suitable for large-scale production.

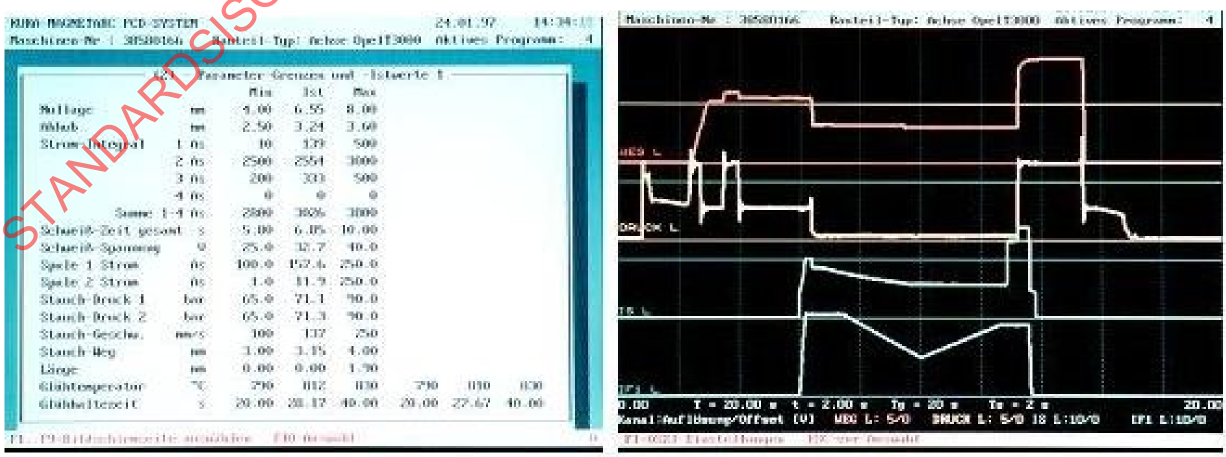


Figure 20 — The latest generation of process monitoring with digital parameter display and sequence

Figure 20 is reproduced by permission of KUKA Systems GmbH Industrial Solutions, Augsburg.

6.1.2.8 Thermal secondary treatment

Because the weld cools down rapidly as soon as the welding current is switched off, the formation of martensite can only be avoided either by pre-heating the complete casting or the welded area only. Existing martensite can be eliminated by post-weld heat treating/tempering of only the welded area. Thus, a finishing treatment (post-weld heat treatment/tempering) is indispensable for large-scale production of automotive safety components.

Intensive trials carried out with trailing-arm rear axles have shown that inductive tempering (Figure 21) with a heating rate of 13 s to 750 °C and a holding time of 30 s within the cycle time of the welding machine, is sufficient to destroy any unwanted martensite.

EXAMPLE Medium frequency annealing — passenger car rear axles.

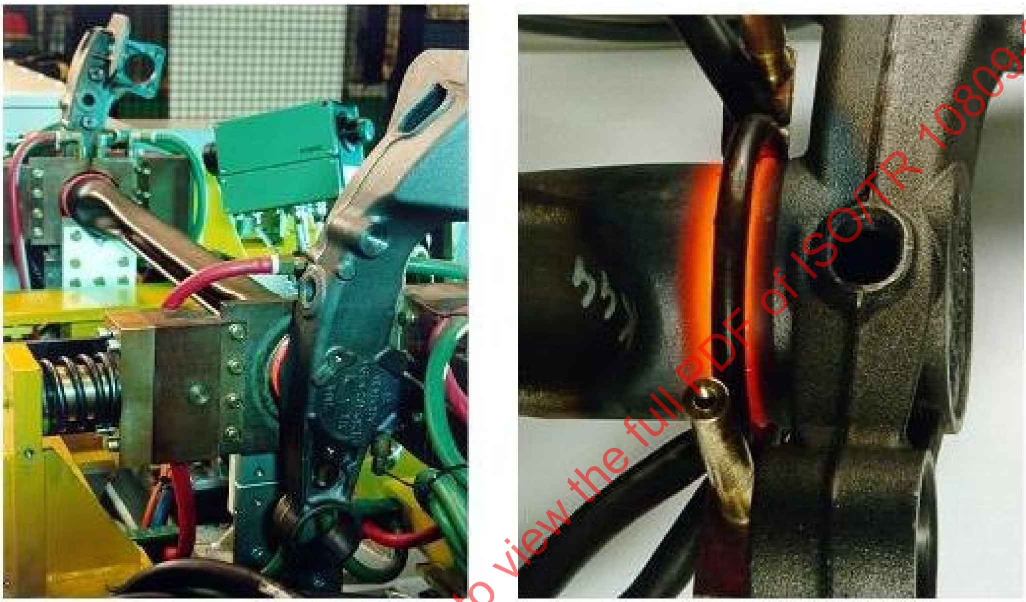


Figure 21 — Inductive tempering of the welded joint of spheroidal graphite cast iron ISO1083/JS/400-15 trailing arm to a steel tube centre-piece

Figure 21 is reproduced by permission of KUKA Systems GmbH Industrial Solutions, Augsburg.

Figures 22 and 23 show the hardness distribution, with no heat treatment and with inductive tempering, respectively, and the results of this post-weld heat treatment by comparing the hardness distribution unannealed and heat-treated.

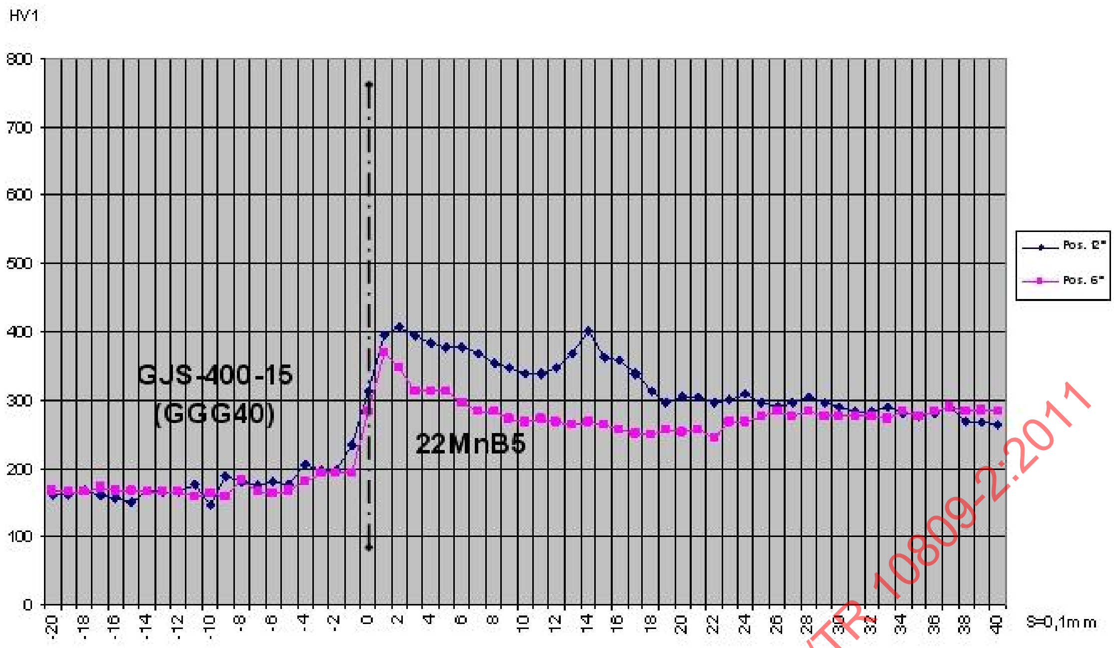


Figure 22 — Hardness distribution, no heat treatment

Figure 22 is reproduced by permission of KUKA Systems GmbH Industrial Solutions, Augsburg.

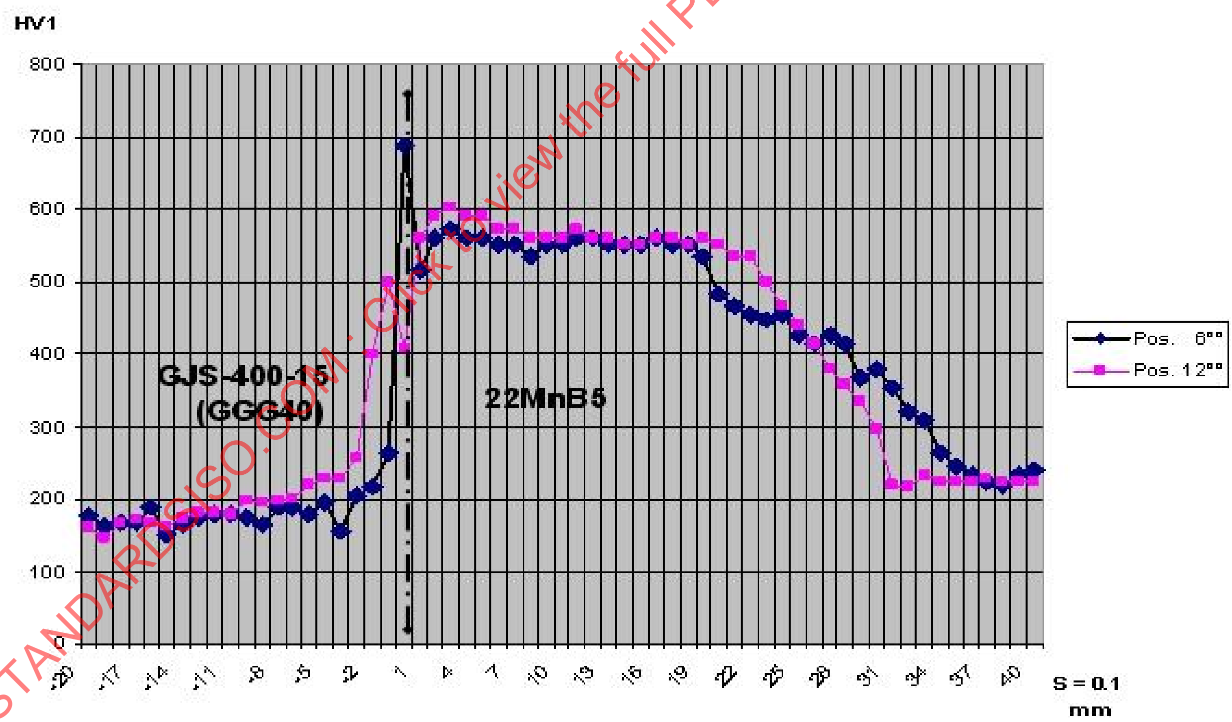


Figure 23 — Hardness distribution, inductive tempering

Figure 23 is reproduced by permission of KUKA Systems GmbH Industrial Solutions, Augsburg.

6.1.2.9 Additional requirements

To meet additional requirements for the maximum pearlite content of the trailing arms after welding, the foundry had to adapt the silicon content of the normal chemical composition of the material.

Production details: Figure 24 shows a magnetarc-welded rear axle and Figure 25 shows the welding line, respectively.

Figure 24 — Magnetarc-welded rear axle

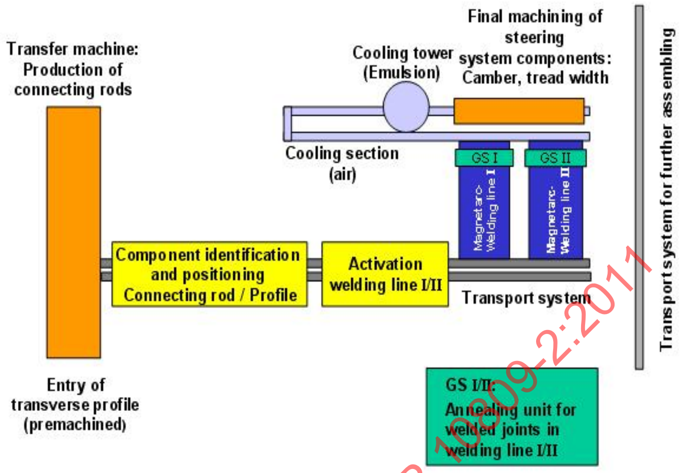


Figure 25 — Magnetarc-welding line

Figures 24 and 25 are reproduced by permission of Opel, Russelsheim.

Figures 26 and 27 show examples of other magnetarc-welded components.

1

2

3

Key

1 axle with differential housing
2 axle with differential housing
3 various rear axles

Figure 26 — Magnetic arc welded axles

Figure 26 is reproduced by permission of KUKA Systems GmbH Industrial Solutions, Augsburg.

Key

1 rear axle
2 valve housing
3 driving cab bearing
4 axle control arm

Figure 27 — Magnetic arc welded components

Figure 27 is reproduced by permission of KUKA Systems GmbH Industrial Solutions, Augsburg.

6.1.2.10 Friction welding

EXAMPLE Friction welding of a front axle body.

A German foundry has developed a composite construction forming a front axle housing made of ferritic spheroidal graphite cast iron ISO1083/JS/400-18 and axle tubes made of steel S 355J0, joined to the housing by friction welding (Figure 28). The accuracy of positioning of the drive trains is a point of interest: for such large components it is less than ±1°. With smaller components, the positioning accuracy is said to be around ±30 min.

Figure 28 — Front axle body of spheroidal graphite cast iron (ISO1083/JS/400-18) friction welded to steel (S355J0) wrists

Figure 28 is reproduced by permission of Bundesverband der Deutschen Giesserei-Industrie, Dusseldorf.

6.1.3 Repair welding

6.1.3.1 General

Repair welding can be carried out on all unalloyed and alloyed grades of spheroidal graphite cast irons.

Castings that contain fractures, particularly in large components, cannot, as a rule, be replaced by the manufacturer on call. Thus, the down time to replace the damaged casting can be prohibitive. In such circumstances, the economic decision to repair-weld the casting is sensible. Repair welding can be used to mend broken half castings, broken component segments and to replace metal where there has been extreme wear and tear.

The purchaser should only agree to the repair if the properties after welding are the same as before welding. Thus, repair-welding firms need to be specialized and have the necessary welding equipment, heat treatment facilities, skilled and supervised personnel, and quality management systems to enable a successful repair.

The requirements for repair welding mostly demanded by the purchaser are as follows:

— identical static and dynamic material characteristics;

— colour and corrosion consistency between the base metal and the filler material;

— compliance with the delivery date for the “repaired” casting(s).

In the majority of cases, a repair weld would be carried out using a homogeneous filler metal.

Prior to welding, the component needs to be sufficiently disassembled to allow access for the welding operations. It should also be possible to place the component or the sub-component needing repair in a pre-heating furnace. Welding should always be carried out by qualified welders.

The filler metal should be selected either from a suitable standard filler metal or from one produced by the repair shop which might need to be adjusted to the composition of the parent metal by adding alloying and trace elements. Detailed and recorded planning for the welding process should be made. This planning should include: analysing the parent metal, identifying the equipment to be used, use of qualified personnel, the pre-heating parameters, the welding process, the post-weld treatment and a working procedure for each sequence of the operations that are to be carried out.

6.1.3.2 Examples

EXAMPLE Finishing welding of a large cylinder block.

The following figures show the pictured details of the welding procedure with its different steps, and are given with more details in Reference [41] in the Bibliography.

Figure 29 shows an example of repair welding on an 18-cylinder block for a ship's diesel engine, the technical details of which are:

- — Number of cylinders: 18
- — Mass of casting: 120 t
- — Cast-iron grade: ISO1083/JS/400-18
- — Length of casting: ~12 000 mm
- — Width of casting: ~2 000 mm
- — Height of casting: ~3 000 mm

Figure 29 — Large cylinder block to be repair welded

Figure 29 is reproduced by permission of Caspar Hahn GmbH & Co KG, Remscheid.

Figure 30 shows the defective spot detected by ultrasonic testing after blast cleaning and after first-process machining.

Figure 30 — Defective spot detected by ultrasonic testing after blast cleaning and after first-process machining

Figure 30 is reproduced by permission of Caspar Hahn GmbH & Co KG, Remscheid.

It is important to know that finishing welding with homogeneous filler metal on large castings may comply with repair welding to some extent. For safety and warranty reasons, it is necessary that the prepared weld location area be inspected for possible cracks; all detected discontinuities need to be removed before placing the component in an annealing furnace. When pre-heating the repair-welding location, it should be in a flat position for welding. Homogeneous welding of cast-iron materials should not be carried out on a casting in the upright or overhead welding position.

The component is then positioned such that the welding area is easily accessible when the segment cover is opened (see Figure 31). For this example, the annealing furnace is heated at a rate of 30 °K/h up to the pre-heating temperature of 550 °C to 650 °C. The furnace temperature is controlled by measuring the temperature of the casting to maintain the pre-heating temperature constant in the vicinity of the welding area.

Figure 31 — Annealing furnace with cylinder block

Figure 31 is reproduced by permission of Caspar Hahn GmbH & Co KG, Remscheid.

Sometimes repair welding has to be carried out on machined components, therefore the pre-heating has to be performed with special heating rates depending upon the size, wall thickness, condition of machining and material grade of the casting to be repaired. The preheating and working temperatures need to be kept in a low temperature range.

For successful repairs, normally the liquid arc welding process is used. That means that a casting electrode is used to liquefy the peripheral zone of the parent metal. Depending on the volume of the weld, the diameter of the electrodes is 8 to 25 mm and the welding current is up to 1 700 A (see Figure 32).

Liquid iron with a chemical composition of the casting is used (Figure 33), and this liquid iron is inoculated and if necessary treated in small ladles (e.g. with FeSi and/or Mg depending on the material to be welded).

Figure 32 — A casting electrode is used to liquefy the peripheral zone of the parent metal

Figure 33 — Both the electrode and the homogeneous cast-iron melt are added carefully to the welding bath

Figures 32 and 33 are reproduced by permission of Caspar Hahn GmbH & Co KG, Remscheid.

For the duration of the welding process, the periphery is continuously liquefied by electrode arc to guarantee a safe joint between the filler material added and the parent metal. The process is continued until the mould is filled completely.

As soon as the bath stabilizes, the annealing furnace is closed. The entire component is then stress-relieved at approximately 550 °C. After a specified holding time, the casting is cooled down to 200 °C at a rate of 30 °K/h, then cooled to ambient temperature in still air.

The microstructure of the weld should match the requirements of the customer but mostly it is much finer and more even than the parent metal. This is visible in the micrograph shown in Figure 34.

At the end of the welding procedure, the weld should be prepared for crack and pore detection, and the finished weld is given a surface crack and porosity inspection prior to acceptance by the purchaser to guarantee freedom from welding porosity, gas inclusions and/or underbead cracks below the surface or in the joint zone between the parent metal and weld.

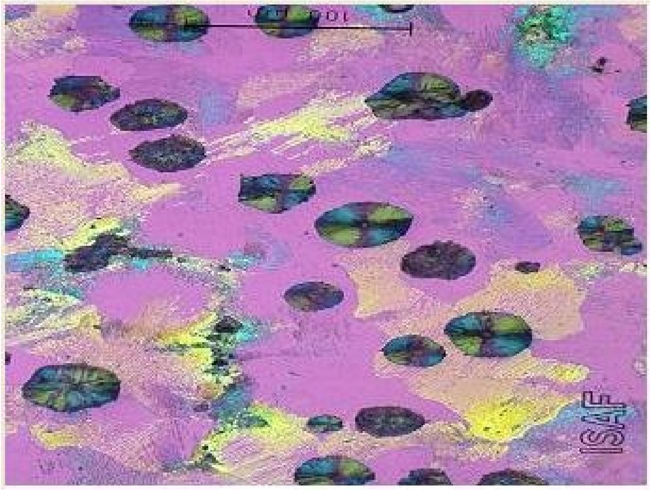


Figure 34 — Microstructure in the weld area — Graphite precipitation in the weld seam with perfect graphite spherulites

Figure 34 is reproduced by permission of Caspar Hahn GmbH & Co KG, Remscheid.

Repair welding is a reliable procedure which is accepted by Accreditation Bodies. It is advantageous in that it is possible to adjust the welding area microstructure to that of the parent metal, and as the component is stress relieved after welding, there is less likelihood of distortion during subsequent finishing process.

EXAMPLE Repair welding of a spheroidal graphite cast-iron machine table.

Figure 35 shows the two ruptured pieces of a four-post press machine table as delivered, and Figure 36 shows the component after repair welding, immediately prior to reassembly into the machine column. A total of 320 kg of homogeneous filler metal were needed for this repair job.

Figure 35 — Machine table as delivered

Figure 36 — Machine table after repair

Figures 35 and 36 are reproduced by permission of Caspar Hahn GmbH & Co KG, Remscheid.

The technical details of the machine table are

- Mass: ~4 000 kg
- Width: ~1 800 mm
- Length: ~5 000 mm
- Material grade: Spheroidal graphite cast iron ISO1083/JS/400-15

6.2 Welding of grey cast iron

6.2.1 General

There is a common misconception that grey cast irons cannot be welded, and in many user specifications and standards it is specifically disallowed in the belief that a weld will act as a stress raiser that promotes failure of the part.

These concerns need to be understood. Welding grey cast iron to a dissimilar material is not recommended, as the weldment is normally unfit for purpose.

6.2.2 Finishing welding

Finishing welding can be carried out, provided that the internal surface defects are not too large, and provided that a competent person carries out the procedure.

The difficulty with finishing welding grey cast iron is that the material within the weld pool normally solidifies very quickly and the resultant structure comprises hard iron carbide (ledeburite) in a pearlitic matrix, particularly the case where arc welding is used and consequently there is a large heat input into the weld pool. The surrounding heat-affected zone usually becomes martensitic due to the rapid cooling rate and thus there is a complex mixture of undesirable structures in the weldment. This situation can be overcome in two ways.

First, a powder welding technique can be chosen, in which a gas welding process is used, that provides a low heat input into the surrounding material, minimising or avoiding the formation of martensite (Reference [42] in the Bibliography). Research has been carried out on this technique by breaking grey iron tensile bars and recording the properties. The broken halves of the bars were then powder welded in a jig to ensure straightness, and re-tested. All of the results showed that the tensile bars broke away from the weld and that the weldment had a higher tensile strength than the parent metal. Using this technique it is advisable to preheat the casting to about 300 °C to 400 °C prior to starting. A normalising heat treatment might also be advisable if the repair is large.

Second, the casting can be gas welded utilising cast-iron welding rods and an appropriate flux. The welding rods require a silicon content about 0,5 % higher than that in the casting, to take into account the loss of silicon in the weld pool. The casting should be preheated as previously described, allowed to cool slowly following finishing welding and if the welding area is large, normalized.

For very minor surface defects, arc welding is sometimes used as a cosmetic maintenance. This procedure is normally undesirable for the reasons previously mentioned, and because the wire is normally a high-nickel material, the undesirability of welding becomes clearly evident when the surrounding metal begins to tarnish.

6.2.3 Joint welding

There is very little experience of this method. Therefore, at this time, it is not recommended; additional development is necessary.

6.2.4 Repair welding

Repair welding is a common procedure.

EXAMPLE Repair of a cracked press column.

The column piece of a screw press had cracked. It was successfully repair welded and thus minimized the down time of the machine which would have occurred if there had been the need to make, machine and assemble the new component in the existing machine.

Figures 37 and 38 document the successful repair welding of a column piece from a screw press made of grey cast iron (lamellar graphite cast iron) ISO185/JL/250. The ruptured pieces, shown as delivered in Figure 37, were joined by repair welding with a homogeneous filler metal and returned to an intact column, shown in Figure 38. A total of 410 kg of filler metal were needed for this repair job.

Figure 37 — Screw press column before repair welding

Figure 38 — Screw press column after repair welding

Figures 37 and 38 are reproduced by permission of Caspar Hahn GmbH & Co KG, Remscheid.

Technical details of the column are:

— Mass of the repaired column: 120 t

— Material grade: Grey cast iron ISO185/JL/250

— Length of casting: ~3 120 mm

— Width of casting: ~1 750 mm

— Height of casting: ~860 mm

6.3 Welding of compacted graphite cast irons

Compacted graphite cast iron is not suitable for joint welding but finishing and repair welding can be undertaken utilising the methods outlined for grey and spheroidal graphite cast irons.

6.4 Welding of malleable cast iron

6.4.1 General

Whiteheart malleable cast irons can be readily welded, provided that the material has been efficiently decarburized. The decarburization process removes all of the carbon from the casting surface, resulting in a matrix of ferrite. This allows whiteheart malleable cast iron to be welded to plain carbon steels.

In order to weld successfully low carbon ferritic steels to whiteheart malleable cast iron, the ideal microstructure of the whiteheart malleable cast iron should be a fully decarburized material comprising ferrite, usually containing 'vacant sites': very small holes that once contained the temper carbon nodules. These holes have no adverse influence on material properties, as the original carbon nodule that inhabited the site had little inherent strength. Sometimes the vacant sites can actually 'heal', or close, such that they are not visible under the microscope. In materials that are less efficiently decarburized it is possible to have a surface structure of ferrite and vacant sites, with an inner core containing temper carbon nodules, possibly even with remnant pearlite in the core centre. Under these circumstances welding success depends on the depth of the weld pool. If it extends into areas where temper carbon nodules are present, then carbides may subsequently form due to the solution of carbon, to the detriment of the weld. In general terms, it is preferable to ensure that a completely decarburized whiteheart malleable cast iron is used for assembly welding operations.

With the addition of pearlite stabilising elements or adjustments to the heat treatment cycle, it is possible to decarburize the material such that no temper carbon nodules are present but a pearlitic matrix is obtained. During welding there is the probability of transformation products adjacent to the weldment, which would require additional heat treatment to minimize this probability.

Because of the decarburizing annealing in an oxidizing furnace atmosphere, whiteheart malleable cast iron has a structure which is dependent upon the wall thickness with a carbon content increasing from outside to inside (see Figure 39).

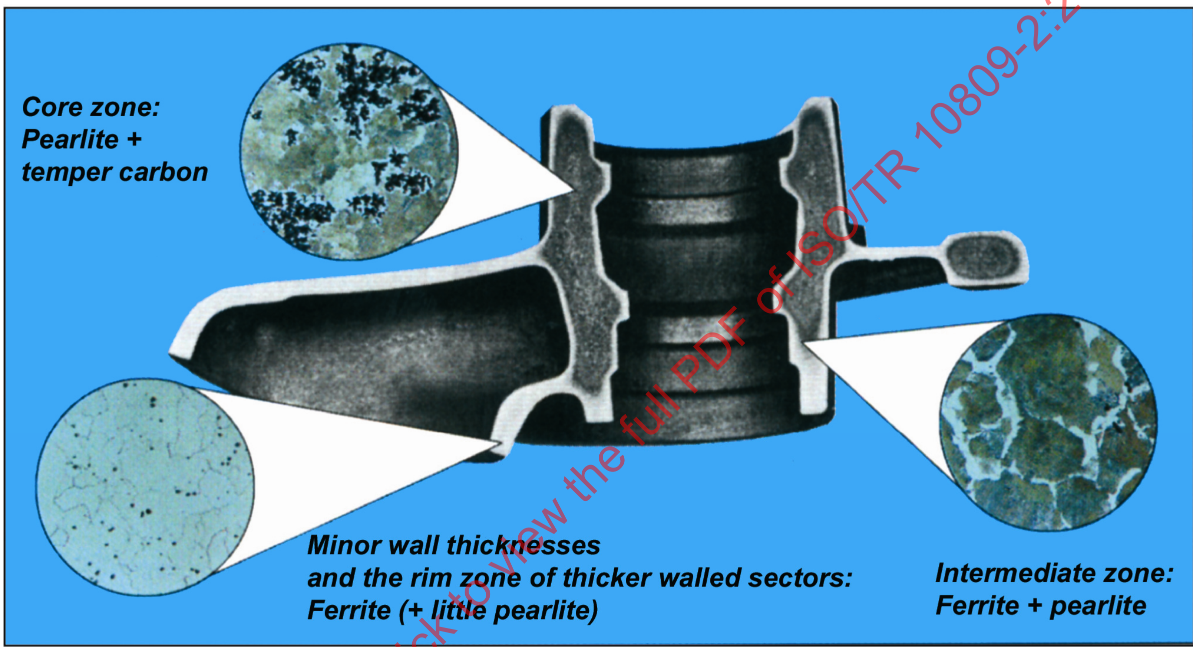


Figure 39 — Microstructure of a whiteheart malleable cast-iron casting

Figure 39 is reproduced by permission of Bundesverband der Deutschen Giesserei-Industrie, Dusseldorf.

Blackheart malleable cast irons always contain temper carbon nodules and thus carbides will always form during the welding process. The same welding techniques as those described for spheroidal graphite cast iron can be adopted, however, utilising either a powder welding technique or gas welding with specially cast rods to replicate the properties of the parent metal. It should be remembered that the temper carbon nodules in blackheart malleable cast iron are produced by heat treatment and it is not possible to replicate this structure in metal that has solidified from a liquid weld pool. This problem might concern some users who might consider this a stress raiser in service, and careful decision making is needed under these circumstances.

6.4.2 Finishing welding

Finishing welding is rarely carried out because of the size of the traditional malleable castings. In the majority of cases it is less expensive to cast a new casting than to eliminate the undesired imperfection by preparing the weld, finishing welding, and heat treating the welded casting.

6.4.3 Joint welding

EXAMPLE Valve housing.

By lengthening the decarburization process, weldable malleable cast irons are decarburized to a maximum residual carbon content of 0,3 % in wall thicknesses of ≤ 8 mm, to guarantee unrestricted weldability. Thus, compared with normal whiteheart malleable grade ISO5922/JMW/400-5, the mechanical properties of the weldable malleable grade ISO5922/JMW/360-12 shows slightly lower tensile strength, but enhanced elongation and toughness properties.

Figure 40 shows a forming test on weldable malleable cast-iron valve housings grade ISO5922/JMW/360-12. There are many examples of joint welds of weldable, whiteheart and blackheart malleable cast irons to malleable cast iron and malleable cast iron to steel (References [51], [52], [55] and [56] in the Bibliography).

Figure 40 — Valve housings after forming test

Figure 40 is reproduced by permission of Bundesverband der Deutschen Giesserei-Industrie, Dusseldorf.

6.4.4 Repair welding

Malleable cast irons can be repair welded. But normally it is not used for the same reasons described with finishing welding (see 6.4.2). There are no examples to illustrate in this part of ISO/TR 10809.

6.5 Welding of abrasion resisting cast irons

Welding of abrasion resistant cast irons is generally not recommended.

6.6 Welding of austenitic cast irons

6.6.1 General

The austenitic cast irons can be welded (References [18], [19] and [20] in the Bibliography) by any of the methods described in 6.1 although high-nickel filler materials are commonly used because of the nickel content of the casting material and their good colour matching. Some of these filler materials are prone to micro-cracking in the heat-affected zone. Welding research has resulted in the addition of niobium to obviate this problem. Only one grade has a specified niobium addition, but this element can be added to any grade, if welding is likely to be a problem. There are no adverse effects of niobium, provided that it is added in the quantity required at a level within the specified range.

Welding of austenitic cast irons is important in terms of finishing welding and joint welding. Common finishing welding of grades with lamellar graphite presents no major problems. Spheroidal graphite (ductile iron) grades are more difficult to weld due to the higher demands on the weld seam and the heat-affected zone. They are, however, the more important materials in regard to their fields of application.

Many austenitic cast-iron grades with spheroidal graphite have a crack forming tendency in the heat-affected zone that is crucially dependent on the chemical composition. The relationships were scrutinized for the most important grade austenitic spheroidal graphite cast iron ISO2879/JSA-XNiCr20-2 (References [22], [23] in the Bibliography). Phosphorous and sulfur have a very detrimental effect, while manganese and, above all, chromium reduce the crack forming tendency; see Figure 41.

Figure 42 shows the influence of alloying elements on the affinity for formation of cracks during welding of spheroidal austenitic cast iron ISO2892/JSA/NiCr/20-2[27].

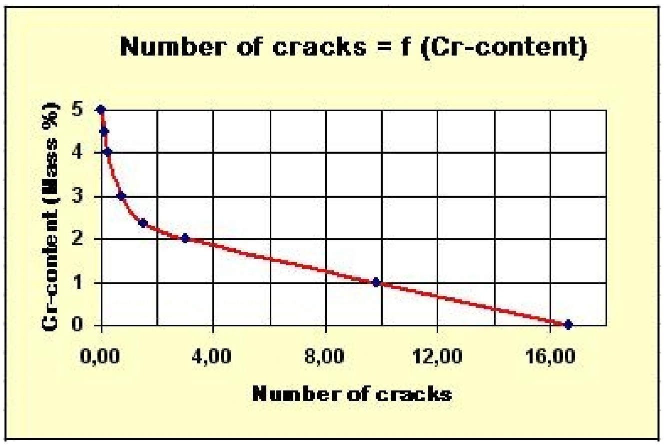


Figure 41 — Effect of chromium on crack forming tendency

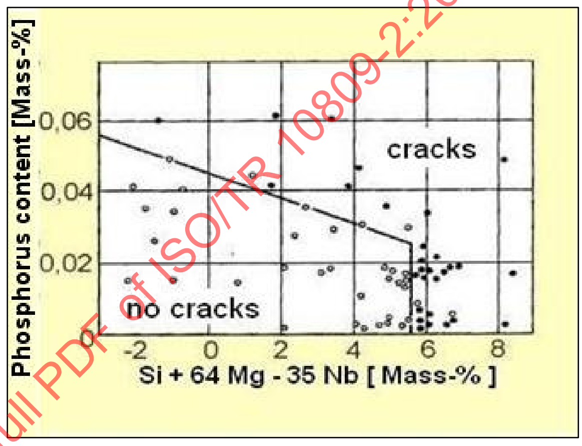


Figure 42 — Influence of phosphorus, silicon, magnesium and niobium on crack forming tendency

Figures 41 and 42 are reproduced by permission of Bundesverband der Deutschen Giesserei-Industrie, Dusseldorf.

The higher chromium content is certainly adverse to the requirements on a good feeding behaviour and high toughness. The combined effect of silicon and magnesium is unfavourable and needs to be limited. The formula (Reference [32] in the Bibliography) is:

$$\% \text{ Si} + 75 \% \text{ Mg} \leq 6{,}3 \quad \text{(Reference [18] and [19] in the Bibliography)} \qquad (5)$$

The suitability for welding can be further improved by adding niobium. The optimum niobium content depends on the phosphorous, silicon, and magnesium contents. Based on the favourable effect of niobium, a weldable grade ISO2892/JSA-XNiCrNb20-2 was developed.

Table 7 contains recommendations for material compositions to obtain crack-free welds with this grade. To avoid problems during finishing welding, many foundries as a matter of routine control perform a limitation of composition and alloying with niobium for larger castings, i.e. instead of delivering grade ISO2892/JSA/XNiCr/20-2, grade ISO2892/JSA/XNiCrNb20-2 is supplied, which is otherwise equivalent.

Table 1 — Recommended chemical composition for crack-free welds for Grade ISO2892/JSA/XNiCrNb20-2

ISO2892/JSA/XNiCrNb20-2		
Chemical element	**Low P mass fraction %**	**Normal P mass fraction %**
C_{total}	2,5 to 3,0	
Si	1,5 to 2,2	
Mn	1,0 to 1,5	
Cr	2,0 to 2,5	
Ni	19,0 to 22,0	
Mg	≤ 0,080	≤ 0,05
P	≤ 0,025	≤ 0,04
Nb	0,06 to 0,11	0,12 to 0,17

6.6.2 Finishing welding

Manual arc welding is the method mainly used for finishing welding.

In principle, heat input should be as low as possible to avoid embrittlement of the heat-affected zone by carbide formation, shrinkage porosity and cracks or fractures (Reference [23] in the Bibliography). This means that welding is carried out without preheating, and it may be necessary to cool down each layer of weld to below 50 °C. Following these instructions, for instance, a number of cracked pump housings of a sea water desalination plant were successfully repaired by welding. After welding, the housings were subjected to stress relieving.

Commercial nickel-iron electrodes with a nickel content of 60 % are the preferred welding consumables. Sometimes homogeneous or pure nickel electrodes are used. The latter show the highest strength values, but there is also maximum danger of crack formation (Reference [22] in the Bibliography). To some extent, the welding consumables of various different manufacturers showed considerable differences in their behaviour and the quality of the welds.

For all other grades, with lowest phosphorous and magnesium contents, the following applies to manual arc welding with a suitable NiFe electrode. For the grades with lamellar graphite as well as grades ISO2892/JSA/XNiMn13-7, ISO2892/JSA/XNiSiCr30-5-5, and ISO2892/JSA-XNiSiCr-35-5-2, preheating to 300 °C to 350 °C is recommended (Reference [2] in the Bibliography). Keeping the furnace temperatures within this range prevents the formation of cold cracks. However, for exhaust manifolds made of ISO2879/JSA-XNiSiCr/35-5-2 it was shown (References [24] and [25] in the Bibliography) that it is possible to produce crack-free welds reproducibly even without preheating.

It is virtually impossible to obtain crack-free welds with the chromium-free or low-chromium grades ISO2892/JSA/XNi22, ISO2892/JSA/XNiMn23-4, and ISO2892/JSA/XNi35. The limitations that apply to ISO2892/JSA/XNiCrNb20-2 in regard to the chemical composition and addition of niobium are also beneficial here, but it will not be possible in all cases to obtain completely crack-free welds. These grades should be welded without preheating.

For major welding jobs, a buffer layer at the joint sides is recommended to prevent cracking.

Other suitable welding procedures are TIG and MIG welding, while gas welding is less recommended due to the high heat input. After welding, depending on the kind of casting and extent of welding, heat treatment is recommended between 650 °C and 680 °C, or even normalizing or graphitization annealing between 950 °C and 1 050 °C. The latter process is to dissolve the carbides formed in the melt and heat-affected zone.

When austenitic cast iron is joined to stainless steel, diffusion of carbon from the cast iron into the steel can occur, leading to the precipitation of chromium carbides. This can produce embrittlement of the microstructure, and a reduction in corrosion resistance due to the segregation of chromium. Heat treatment further exacerbates this situation by increased carbon diffusion. For heat resistant components, such as exhaust manifolds, such combinations have proved to be successful, because their scaling resistance is sufficient (References [28] and [29] in the Bibliography). Expansion elements have been welded into exhaust manifolds, cast flanges joined to stainless steel tubes to form exhaust manifolds, and interfaces made between cast exhaust manifolds or turbocharger housings and catalyst housings made of ferritic steels.

6.6.3 Joint welding

The welding consumables and procedures used for joint welding need to be carefully chosen and monitored. The above mentioned limitations regarding the adjustment of the chemical composition need to be taken into account, and alloying with niobium needs to be performed. Graphitization annealing should be carried out whenever possible after welding to decompose any brittle carbides. If annealing is not feasible, for instance in the field, a buffer layer with nickel-iron electrodes at the joint sides and a subsequent annealing of the individual components prior to welding is a feasible solution. Strength, however, is lower than when similar electrodes are used. Make sure that the castings show a dense microstructure free from inclusions around the weld seams, since cracks tend to propagate from pores and inclusions.

EXAMPLE Manifold.

Figure 43 shows a manifold assembled of steel pipes and austenitic spheroidal graphite cast-iron flanges using joint welding of grade ISO2892/JSA/XNiCrNb20-2.

Figure 43 — Manifold

Figure 43 is reproduced by permission of Bundesverband der Deutschen Giesserei-Industrie, Dusseldorf.

Trials performed to produce homogeneous friction welding joints were successful (Reference [26] in the Bibliography) with austenitic spheroidal graphite cast-iron grades ISO2892/JSA/XNiSiCr35-5-2, ISO2892/JSA/XNi35, ISO2892/JSA/XNiMn23-4, ISO2892/JSA/XNiCr20-2 and austenitic lamellar graphite cast-iron grade ISO2892/JLSA/XNiCuCr15-6-2, and joints with good to sufficiently good mechanical properties and good corrosion resistance were achieved with tubes and solid bodies. Plastic deformability could be further improved by subsequent heat treatment. It is also possible to produce welded joints between various different cast-iron grades. Friction welding joints with stainless steel, however, showed problems similar to the usual fusion welding joints, despite the short welding time.

6.6.4 Repair welding

No experience is available.

6.7 Welding of ausferritic spheroidal graphite cast irons

6.7.1 General

Sometimes welding of austempered spheroidal graphite cast-iron castings is necessary. This needs adapted welding procedures. By controlling the composition and cooling rate of the weld metal, an austenitic-bainitic micro-structure can be directly obtained under as-welded conditions.

Although since 1996 several papers (References [31] to [39] in the Bibliography) about the welding of ausferritic spheroidal graphite cast iron have been published, no practical application can be seen till now.

As ausferritic spheroidal graphite cast iron is mainly used for applications where high strength and toughness are required, welding operations should always be done prior to the austemper heat treatment.

In order to maintain this hierarchy, the poor toughness of the heat-affected zone can be greatly improved, even reaching the properties of the parent material, if the proper welding consumables are used (References [37] and [38] in the Bibliography). However these welding consumables are not readily available.

In a previous study, the welding electrodes used were studied and the microstructure of the weld metal was analyzed (Reference [35] in the Bibliography). During the welding procedure the base metal near the weld would be heated to high temperature to form a heat-affected zone. The compositions of the heat-affected zone are the same with the ausferritic spheroidal graphite cast-iron base metal and cannot be adjusted by adding alloying elements. Therefore its as-welded microstructure and mechanical properties can be different with weld metal and ausferritic spheroidal graphite cast-iron base metal.

Commonly the toughness of the heat-affected zone is poor and welding crack is liable to arise in the zone, which can greatly reduce the mechanical properties of the whole weld joint. The effect of the welding heating cycle on the microstructure and mechanical properties of the heat-affected zone, the microstructures of the weld joint are observed under the optical microscope and electron microscope. The phase transformation and characteristics in the weld joint are analyzed.

Ausferritic spheroidal graphite cast-iron test plates 140 × 80 × 15 mm were used. The plates were austenitized at 900 °C, then austempered at 375 °C. A test hole 40 mm in diameter and 10 mm in depth was machined at the centre of the plate, a thermo-couple was installed into each test hole and several were drilled at different locations of the welding hole. The hole was filled with test electrodes (alloying elements = Ni, Mo) and the temperatures were measured and recorded.

Table 2 shows the composition of weld metal used to weld ausferritic spheroidal graphite cast-iron test plates.

Table 2 — Composition of weld metal

C %	Si %	Mn %	Ca %	Ba %	Al %	Bi %	S %	P %	Ce %	Ni %	Mo %
3,54	3,3	0,35	0,002	0,006	0,45	0,004	≤ 0,015	≤ 0,015	0,016	8,10	0,20

The cooling rate could be affected by the diameter of the whole, also by the welding input, while the welding process parameters needed to hold constant during the welding procedure: welding current was about 190 A, voltage about 24 V.

The test plate was cut off at the centre of the test hole and the microstructure of the weld joint was observed with an optical microscope and electron microscope.

The welding joint is divided into 5 zones. The listing shows the observed microstructure(s):

— Zone 1: Weld zone: austenite, bainite (ausferrite);

— Zone 2: Partial fusion zone: nodular graphite, pearlite and a little of martensite;

- Zone 3: Austenite transformation zone: nodular graphite, pearlite or sorbite;
- Zone 4: Repeated transformation zone: pearlite, bainite;
- Zone 5: Base metal: bainite (ausferrite), austenite.

The “as-welded” microstructure of the weld metal is bainite (ausferrite) plus austenite.

The specimens for tensile test were taken across the joint. It has been found, that the specimens fractured in the austenite transformation zone. The ultimate strength of the joint was of 695 MPa and the elongation of the whole joint was 2 %.

6.7.2 Finishing welding

When interpreting the results of this work finishing welding and joint welding should be possible with manual metal arc welding by using homogeneous and semi-homogeneous filler metal. There is no information in this publication about pre-heating and post-weld annealing, but it seems, that the cooling rate can be controlled by the diameter of the hole and/or the heat input.

Finishing welding is not recommended for castings with an ausferritic structure, i.e. for castings after final austempering heat treatment.

There is limited experience with this material and a lot of development is necessary to reach the state of the art of welding spheroidal graphite cast iron or malleable cast irons.

6.7.3 Joint welding

When analysing the sequence of work steps of the production process of ausferritic cast iron, the ausferritising anneal always is the last step. Therefore it seems useful to transfer this knowledge to the joint-welding process. Then the wide experience of welding of unalloyed or low alloyed spheroidal cast iron could be used for welding ausferritic cast iron too, and all welding methods suitable for spheroidal cast iron could be used. Joint welding could be a good example. Then the ausferritising process of the assembly and/or unwanted discontinuity to be finishing welded with a basis structure of unalloyed or low alloyed GJS would be the last step after welding, viz. the post-weld heat treatment would be the transformation anneal to ausferrite.

However the suitability of this procedure has not been proven at the time of the publication of this part of ISO/TR 10809.

6.7.4 Repair welding

No experience, but the procedure would be more complicated than the process described for joint welding and would be very similar to the finishing process (see Reference [28] in the Bibliography).

7 Summary data for the welding of cast irons

The basis of these tables is Table B.1 of EN 1011-8:2004[1].

The tables give information on the welding procedures, methods and filler metal types for most cast iron castings using either homogeneous, semi-homogeneous or non-homogeneous filler metals. This edition of the report does not cover those cases where insufficient data is available.

NOTE 1 At the time of the publication of this part of ISO/TR 10809 most information is available for spheroidal graphite cast irons, all types of malleable cast irons (whiteheart, weldable and blackheart), lamellar graphite (grey) cast irons and austenitic lamellar, respectively spheroidal graphite cast irons.

NOTE 2 Best knowledge and most experience on successful welding applications exist with spheroidal graphite cast irons, lamellar graphite (grey) cast irons, malleable cast irons and austenitic lamellar and spheroidal graphite cast irons either as assembly of cast iron against cast iron or cast iron against steel.

Table 3 shows recommendations for welding of spheroidal graphite cast irons (ISO 1083[45]). Table 4 shows recommendations for welding of lamellar graphite cast irons/grey cast iron (ISO 185[44]). Table 5 shows recommendations for welding of compacted (vermicular) graphite cast irons (ISO 16122[48]). Table 6 shows recommendations for welding of whiteheart malleable cast irons (ISO 5922[47]). Table 7 shows recommendations for welding of weldable malleable cast irons (ISO 5922[47]). Table 8 shows recommendations for welding of blackheart malleable cast irons (ISO 5922[47]). Table 9 shows recommendations for welding of austenitic grey (lamellar)/austenitic spheroidal graphite cast irons (ISO 2892[46]).

NOTE 3 We need to be aware that the recommendations depend on knowledge of and experience with the appropriate welding procedures used for welding of the different types of cast irons, of the metallurgical reactions of the different cast-iron materials dependent upon special welding conditions necessary for sufficient material properties of the weldings of the accordant cast-iron materials, their structures, and possible post-weld annealing treatments, etc.

NOTE 4 There might be a lot more experience in the literature as collected in this part of ISO/TR 10809. The question marks in the tables point to the necessity for further research and development on welding of cast irons in the future. Especially, new welding procedures can lead to unexpected success and new technologies for welding cast irons.