SUPPLEMENTARY OPERATIONS

Ferrous structural components, produced by powder metallurgy methods, are often subjected to supplementary operations in order to give them improved or special properties or to complete their final shaping.
10. SUPPLEMENTARY OPERATIONS

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10.1 Survey

For a variety of applications it is necessary to subject ferrous sintered components to supplementary operations, in order to give them improved or special properties, complete their final shaping, clean them, improve their appearance, etc.. These supplementary operations and their purpose are catalogued in Table 10.1.

Note: re-pressing/re-sintering, coining and sizing are not considered being supplementary operations but part of the powder metallurgy process; they have been described in detail in chapter 7.

<table>
<thead>
<tr>
<th>Table 10.1. Supplementary Operations</th>
</tr>
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<tbody>
<tr>
<td><strong>Operation</strong></td>
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<tr>
<td>Heat-treatment</td>
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<td>austenitizing, quenching,</td>
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<tr>
<td>tempering</td>
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<tr>
<td>Precipitation hardening</td>
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<tr>
<td>Case hardening:</td>
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<tr>
<td>carbonizing</td>
</tr>
<tr>
<td>carbonitriding</td>
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<td>nitriding</td>
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<td>plasma nitriding</td>
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<tr>
<td>Infiltration</td>
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<td>with metals</td>
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<td>Impregnation</td>
</tr>
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<td>with polymers</td>
</tr>
<tr>
<td>Impregnation</td>
</tr>
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<td>with oil</td>
</tr>
</tbody>
</table>
10. SUPPLEMENTARY OPERATIONS

Table 10.1. Supplementary Operations (continued)

<table>
<thead>
<tr>
<th>Operation</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining</td>
<td>• provide parts with threads, undercuts and traverse holes</td>
</tr>
<tr>
<td>Deburring and Cleaning:</td>
<td>• remove burrs</td>
</tr>
<tr>
<td>- barreling</td>
<td>• clean parts from shop soil, grease and other contamination</td>
</tr>
<tr>
<td>- vibratory deburring</td>
<td></td>
</tr>
<tr>
<td>- abrasive blasting</td>
<td></td>
</tr>
<tr>
<td>- ultrasound</td>
<td></td>
</tr>
<tr>
<td>- electrolytic alkaline</td>
<td></td>
</tr>
<tr>
<td>Joining:</td>
<td>• join different sintered parts together to achieve component of more shape</td>
</tr>
<tr>
<td>- brazing</td>
<td></td>
</tr>
<tr>
<td>- welding</td>
<td></td>
</tr>
<tr>
<td>- other methods</td>
<td></td>
</tr>
<tr>
<td>Peening and Plating:</td>
<td>• hardens surface and improves fatigue strength</td>
</tr>
<tr>
<td>- shot peening</td>
<td>• improve parts' appearance and corrosion resistance</td>
</tr>
<tr>
<td>- peen plating</td>
<td></td>
</tr>
<tr>
<td>- electroplating</td>
<td></td>
</tr>
<tr>
<td>Corrosion Protection:</td>
<td>• improve parts' corrosion- and wear-resistance</td>
</tr>
<tr>
<td>- Steam treatment</td>
<td></td>
</tr>
<tr>
<td>- Phosphatizing</td>
<td></td>
</tr>
</tbody>
</table>

Detailed descriptions of these supplementary operations are presented in the following paragraphs.

10.2 Heat-treatments

Sintered ferrous components can, in principle, be heat-treated like conventional steel parts. Thus, ferrous sintered parts can be through-hardened, case-hardened and precipitation-hardened. However, due to their porosity and their, in some cases, heterogeneous alloy composition, sintered ferrous materials respond in certain respects somewhat differently to heat-treatment than conventional steels.

10.2.1 Through-hardening

The basic mechanisms of steel hardening have been described in detail in chapter 1, §§ 1.5 and 1.6. We recapitulate here the essential features of the hardening procedure.
To be hardenable, a steel must contain between 0.1 and 1.4% carbon and be austenitic at higher but not at lower temperatures. The hardening procedure consists of the following three steps:

- austenitizing,
- quenching, and
- tempering

The involved temperature ranges are indicated in the diagram at Fig. 10.1.

**Austenitizing**
In a non-decarbonizing atmosphere, the parts are heated to and held at a temperature above \( A_3 \).

**Quenching**
From austenitizing temperature or from a somewhat lower temperature, but still above \( A_3 \), the parts are quenched in oil or water, whereby the austenite is transformed to hard and brittle martensite or bainite. Conventional steel parts are often quenched in plain water or water and brine for best results. Sintered parts, however, are better quenched in oil, because, due to their porosity, they may crack when quenched too rapidly. Besides, the quenching medium infiltrates the pore network, and brine retained in the pores after hardening would cause severe corrosion.
10. SUPPLEMENTARY OPERATIONS

**Tempering**

In order to eliminate the high internal stresses caused by the transformation of austenite to martensite and bainite, the parts are tempered at a temperature between 150 and 550°C. Hereby, the brittleness of the martensite and bainite is reduced, and the toughness of the parts increased.

The hardenability of conventional as well as sintered steels can be substantially improved by alloying them with certain other metals like e.g. copper, nickel and molybdenum. See Fig. 9.2b in the preceding chapter.

CCT-diagrams and related microstructures of a variety of sintered steels have been presented at Figs. 9.17 - 9.21 in the preceding chapter.

**10.2.2 Precipitation Hardening**

Precipitation hardening is possible in iron-copper and iron copper-carbon alloys, because copper is soluble up to about 9 wt.-% in austenite, but only up to 0.4 wt.-% in ferrite. See Fig. 10.2. When an iron-copper alloy, containing 0.4 - 9 wt.-% copper, is heated to 925 °C, all copper is dissolved in austenite. On rapid cooling, the copper-rich austenite transforms to a ferrite supersaturated with copper. When tempering the alloy at temperatures between 300 and 500°C, copper is precipitated in the form of finely dispersed particles embedded in ferrite. The lower the tempering temperature, the longer is the required tempering period, but the finer are the precipitated copper particles, and the harder is the alloy.

The precipitated copper particles obstruct the mobility of dislocations in the ferrite, and thus, increase its hardness and strength (ref. Chapter 1, § 1.2.4 and Fig.1.15).
10.2 HEAT-TREATMENTS

This hardening principle works for conventional as well as sintered iron-copper alloys. In fact, precipitation hardening may occur to a certain extent already when sintered iron-copper parts are cooled down from sintering temperature (1120°C). At the end of the sintering zone of a continuous sintering furnace, the temperature of the sintered parts drops first relatively fast, and then decreases more slowly. Thus, part of the copper may have time enough to precipitate from the supersaturated ferrite - at falling tempering temperature, so to speak.

10.2.3 Case Hardening

Case hardening is a relatively inexpensive and simple way of raising the wear resistance of structural components and improve their mechanical properties, especially their fatigue strength; - this goes for conventional as well as sintered parts.

As indicated in Table 10.1, several case hardening techniques are available. Note that salt bath hardening, a method frequently used for conventional (i.e. non-porous) steel parts, has been excluded from the table. This method is prohibitive for sintered parts, since corrosive salts entrapped in their pores are practically impossible to remove. Thus, sintered parts can only be case-hardened in gaseous media. The methods, most commonly used for sintered parts, are carbonizing and carbonitriding, and these two methods will, therefore, be especially emphasized in this paragraph.

Figure 10.2
Iron-rich corner of Fe-Cu phase diagram.
10. SUPPLEMENTARY OPERATIONS

Conventional case-hardening equipment can be used. Cleanliness is an important prerequisite for obtaining good results. Before heat treatment, the sintered parts must be free from sizing- or coining-lubricants, tumbling fluids and surface oxides.

Three specific problems arise in connection with the case-hardening of sintered parts:
- Controlling case depth.
- Measuring case hardness.
- Defining case depth.

Controlling case depth
The carbonizing or nitriding gases penetrate the interconnected pore system of the sintered parts, which leads to a faster pick-up of carbon or nitrogen. Thus, treating times for obtaining a given case depth are shorter for sintered than for conventional steel parts.

Generally, it is desirable to achieve a case of even depth and a narrow hardness transition zone. This can only be achieved when the majority of pores in the parts are not interconnected. Such is usually the case at sintered densities above 6.9 g/cm$^3$, or at lower densities when a pore-closing effect has been achieved during sintering by adding small amounts of sulfur and/or phosphorus to the powder mix before compacting.

Measuring case hardness
The porosity of the sintered parts presents a particular problem when measuring case hardness. According to the international standard ISO 4498, the so-called apparent hardness of sintered metals (except hard metals) is determined by means of either Vickers HV$_5$ (test load 5 kp) or Rockwell HR15N (test load 15 kp).

The reason for choosing relatively low test loads is the circumstance that, with sintered materials, the measured hardness values decrease with increasing test loads. See diagram at Fig. 10.3.

Figure 10.3 Influence of test load on the Vickers hardness number with surface-hardened sintered steel. [10.1]
The higher the test load and the lower the density of the sintered part, the greater is the risk that the Vickers pyramid (or Rockwell cone) breaks through the insufficiently supported hardened case. The true hardness of the case, independent of sintered density, can only be determined by means of microhardness tests, e.g. \( MHV_{0.05} \) (test load 50 p). See diagram at Fig. 10.4. The hardness values obtained with \( HV_5 \) reflect the density of the core rather than the hardness of the case.

Indentation marks are sometimes difficult to evaluate when their normal periphery is disturbed because the test pyramid (or cone) happened to break into a pore close to but invisible on the surface. Such indentation marks should, of course, be omitted from evaluation.

**Defining case depth**

The case depth in sintered steel parts is usually defined as the distance from the surface where the average microhardness has dropped to 550 \( MHV_{0.1} \) (or \( MHV_{0.05} \)). The emphasis here is on average microhardness. Sintered steel parts usually have a more heterogeneous microstructure than conventional steel parts.
10. SUPPLEMENTARY OPERATIONS

As a consequence, at any given distance below the hardened surface, microhardness values scatter more in sintered than in conventional steel parts. Occasionally, extreme stray values may occur when indentations are placed on sporadically present soft spots of ferrite, retained austenite, or pearlite in a matrix of martensite or bainite. See microstructure at Fig. 10.5. Such stray values should, of course, be excluded when calculating a representative average hardness value. It goes without saying that all microhardness measurements must be carried out on a well polished section through the component to be investigated.

![Figure 10.5 Scattering of microhardness indentations (HV 0.05) in the microstructure near the surface of surface-hardened sintered low-alloyed steel (Distaloy AB) [10.1]](image)

Carbonizing

In a carbonaceous atmosphere, like endogas, the iron surface of the parts to be treated catalyzes two reversible chemical reactions:

\[
\text{CO} + \text{H}_2 \leftrightarrow \text{C}_6\text{Fe} + \text{H}_2\text{O} \quad \text{and (if methane is present)} \quad \text{CH}_4 \leftrightarrow \text{C}_6\text{Fe} + 2\text{H}_2
\]

Water vapor and excess hydrogen are flushed by a continuous stream of fresh carbonizing gas, and carbon is being picked up by the iron- or steel parts at a rate ruled by laws of diffusion and determined by temperature, time and carbon potential of the atmosphere.

As has been shown in chapter 1, § 1.3.2, the case depth of a steel specimen increases at a rate proportional to the square root of carbonizing time. This means, to double the case depth, the carbonizing time has to be increased fourfold.

1. A very flexible way of producing an endogas for carbonizing purposes is to crack methanol and dilute the obtained gas with nitrogen and hydrocarbons [10.10.1].

2. The carbon potential of a carbonaceous atmosphere is defined as the carbon content in an iron surface with which is in equilibrium. There are tables listing proper ratios of CO₂/CO as a function of carbonizing temperature for maintaining desired carbon potentials. The proper CO₂/CO-ratio can be checked conveniently by means of an infrared gas analyzer.
10.2 HEAT-TREATMENTS

Temperatures from 820 to 920°C can be used, and the higher the temperature, the shorter is the time for achieving a certain case depth. Common carbonizing conditions are 1 to 4 hours at 850 to 860°C. At higher temperatures, carbonizing times as short as 15 minutes may suffice.

After carbonizing, sintered parts can normally be quenched from 850°C in warm oil (50-60°C) without risk of distortion. When higher carbonizing temperatures are used, the temperature in the carbonizing furnace should be lowered to about 850°C before quenching.

The diagram at Fig. 10.6 shows typical microhardness profiles for two specimens of sintered plain iron with densities of 6.7 and 7.2 g/cm³ respectively, and for one specimen of wrought carbon steel (equivalent to SAE 1017), all carbonized for 2 hours at 850°C and quenched in oil.

![Diagram showing microhardness profiles](image)

Carbon has penetrated deepest into the sintered iron specimen with the lower density and least deep into the specimen of wrought carbon steel. Thus, the sintered iron specimen with the lower density shows a greater case depth and a higher core hardness than the sintered iron specimen with the higher density.

Although carbon has penetrated least deep into the wrought carbon steel specimen, this specimen exhibits the same high case hardness as the sintered iron specimen with the lower density, because of its higher initial carbon content and its higher hardenability.
10. SUPPLEMENTARY OPERATIONS

Fig. 10.7 shows microstructure and hardness profile of a specimen, compacted and sintered from Astaloy Mo + 0.2 wt.-% C, after carbonizing for 30 minutes at 920°C in endogas with a carbon potential of 0.8. Astaloy Mo is a water-atomized Fe+1.5%Mo-powder (ref. Chapter 3).
10.2 HEAT-TREATMENTS

Figure 10.7 Microstructure and microhardness profile of a low-alloyed sintered steel (Astaloy Mo + 0.2 wt.% C, sintered density 7.1 g/cm³), carbonized for 30 min at 950°C in endogas [10.2]
10. SUPPLEMENTARY OPERATIONS

Carbonitriding

In the carbonitriding process, ammonia is added to the carbonizing atmosphere. Catalyzed by the iron surface, ammonia dissociates according to the chemical reaction:

\[ 2\text{NH}_3 \leftrightarrow \text{N}_2 + 3\text{H}_2, \]

Carbon monoxide and methane (if present) dissociate according to the reactions stated further above. Nitrogen and carbon are being picked up by the iron or steel parts at their respective diffusion rates, while excessive hydrogen and water vapor are flushed by a continuous stream of fresh carbonitriding gas.

For surface hardening of low-alloyed and unalloyed sintered steel parts, carbonitriding is commonly preferred to carbonizing, because nitrogen increases hardenability and, thus, helps to achieve a greater case depth. On the other hand, carbonitriding has to be applied with some discretion.

Since nitrogen stabilizes austenite, undesirable amounts of retained austenite might occur in the hardened microstructure, in particular when alloying elements, like e.g. nickel, are present which have the same effect. In such cases, a straight carbonizing process should be preferred. Normally, carbonitrided or carbonized sintered steel parts are not tempered; but if necessary, tempering should be carried out at low temperatures, i.e. between 150 and 175°C.

The different effect of carbonizing and carbonitriding can be seen from the respective microhardness profiles shown at Fig. 10.8. In both cases, a sintered iron specimen with a density of 7.2 g/cm³ has been treated for 2 hours at 850°C and quenched in warm oil (50°C). Corresponding to its better hardenability, the case depth of the carbonitrided material is greater than for the carbonized material. The macrohardness (HV₅) on the surface is practically identical with both materials.

![Microhardness profiles of sintered iron (ASC100.29) carbonized respectively carbonitrided for 2 hours at 850°C and quenched in oil of 50°C. (10.1)](image)
10.2 HEAT-TREATMENTS

When sintered iron parts have lower densities, the carbonizing and nitriding gases may penetrate too deep into the interconnected pore system and produce a case of undesired thickness. See diagram at Fig. 10.9.

This can be prevented very efficiently by adding sulfur in elemental form or as iron-sulfide to the iron powder. See diagram at Fig. 10.10.

Due to the presence of sulfur in the iron powder compact, a liquid phase is forming during sintering with the effect that the interconnected porosity is reduced substantially, while the total porosity is practically unaffected.
10. SUPPLEMENTARY OPERATIONS

See diagrams at Fig. 10.11 and sections through case-hardened specimens at Fig. 10.12.

Figure 10.11 Influence of sulfur additions on total and interconnected porosity for (a) sintered iron and (b) sintered iron + 2.5% copper [10.3]
As can be seen from the diagram at Fig. 10.13, carbonizing and carbonitriding have a very beneficial effect on the bending fatigue strength of sintered steel parts. This effect is due to the circumstance that the martensite in the hardened case of the parts has provoked compressive stresses which reduce the effective bending stresses in the case.
Nitriding

In the nitriding process, the steel parts are heated in a nitrogenous atmosphere, like ammonia or a mixture of ammonia and nitrogen. Catalyzed by the iron surface, ammonia dissociates according to the chemical reaction:

$$2NH_3 \leftrightarrow N_2 + 3H_2.$$ 

Nitrogen is being picked up by the surface of the steel parts, and excessive hydrogen is flushed by a continuous stream of fresh nitrogenous gas.

The nitriding process comprises three steps:

1. The parts are through-hardened and tempered before nitriding, and the tempering temperature must be at least 30°C above the nitriding temperature.
2. The parts are thoroughly cleaned and sometimes given a phosphate coating.
3. The parts are nitrided at a temperature of approx. 495 - 565°C.

Unlike in carbonizing and carbonitriding, the parts need not to be quenched and may cool normally.
10.2 HEAT-TREATMENTS

Because of the lower temperatures and the absence of quenching which involves drastic volume changes, nitriding causes less distortion than other surface hardening methods. There is, however, a small growth in dimensions after nitriding.

**Plasma-Nitriding**

In this process, a plasma consisting of nitrogen-ions and electrons is created between two electrodes in a vacuum chamber containing low-pressure nitrogen gas. The positive charged nitrogen-ions bombard the steel parts (which form the cathode), heating them to a temperature varying between 470 and 570°C, cleaning their surface by dislodging surface atoms, and depositing active nitrogen.

Fig. 10.14 shows the microstructure and the microhardness profile of a plasma-nitrided specimen of sintered steel made of Astaloy-Mo + 0.5 % C, having a sintered density of 7.1 g/cm³. Comparing microstructure and hardness profile shown here with those shown at Fig. 10.7, it can be seen that, for the same material, plasma-nitriding has yielded a much smaller case than carbonizing.
10. SUPPLEMENTARY OPERATIONS

Nitrocarbonizing
In this process, the emphasis is put on nitriding, but some carbonizing takes place also. The parts are treated for 1 - 2 hours at a temperature of approx. 570°C in a mixture of
equal parts of endogas and ammonia. Then, the parts are quenched in warm oil. The hardened surface layer is very thin and consists of iron nitrides with a small amount of dissolved carbon. It makes the parts highly resistant to wear and galling. Due to the low temperatures involved in this process, distortions are small; but the formation of the nitrided surface is connected with a small dimensional growth.

**Induction Hardening**

When only certain surface areas of a structural component are to be hardened, induction hardening is the most convenient method to choose, provided the carbon content of these areas is at a proper level. The required carbon local content can be achieved either by adding graphite to the powder mix, resulting, after sintering, in an even carbon level throughout the entire component, or by gas carbonizing of the surface of the component without subsequent quenching.

In both cases, the components are then heated for a few seconds in an induction coil and rapidly quenched with a spray of water or oil. The frequency of the alternating current in the induction coil determines the depth of the heated zone - the higher the frequency, the smaller is the heated zone and, thus, the depth of the hardened case. The design of the coil has to be specially adapted to the particular shape of the components - which can be a tricky business when the components are of unsymmetrical shape and to be hardened at areas difficult to access. Fig. 10.15 shows a section through an induction-hardened chain sprocket made of Distaloy AB + 0.7 % C, having a sintered density of 7.1 g/cm³.

![Fig. 10.15 Section of an induction-hardened chain sprocket. (Distaloy AB + 0.7 wt.% C, density 7.1 g/cm³). The hardened area appears dark on the photomicrograph.](image)

More information about surface hardening can be found in [10.1] - [10.4].
10. SUPPLEMENTARY OPERATIONS

10.3 Infiltration and Impregnation

10.3.1 Infiltration with Metals

The interconnected pore system of sintered iron parts can be infiltrated with copper or copper alloys. To this effect, the infiltrate in the form of small disks (conveniently pressed of powder) is placed below or on top of the sintered parts which then are passed through a belt furnace at a temperature just above the melting point of the infiltrate. Provided the amount of infiltrate has been carefully adapted to the pore volume to be filled, the sintered iron parts suck up the infiltrate completely, and the entire interconnected pore volume is being filled.

Advantages of infiltration:
• Increased density and strength properties.
• Infiltrated sintered parts are impermeable and pressure-tight.

Disadvantages of infiltration:
• Inferior dimensional accuracy.
• Higher material- and production costs.

More information about copper infiltration can be found in [10.5].

10.3.2 Impregnation with Polymers

When sintered parts are to be made impermeable to gases or fluids, they can be impregnated with thermosetting liquid polymers. The sintered parts and the liquid polymer are, separated from one another, placed in a low-pressure chamber. Here, the air is evacuated from the pores of the sintered parts which then are immersed in the liquid polymer. After immersion, the pressure in the chamber is raised to normal again. By this procedure, the pores are very efficiently filled with liquid polymer. After leaving the chamber, the parts are heated for setting of the polymer.

Advantages of polymer impregnation:
• Impregnated parts are impermeable to gases and fluids which expands their range of applications (e.g. as components in hydraulic pumps).
• Impregnated parts are ready for chemical surface finishing operations like electroplating.
• Impregnated parts exhibit improved machinability (less interrupted cutting).
Polymer impregnation is relatively costly but indispensable when low-density parts are to be used in applications as listed above. Information on impregnation equipment and suppliers of suitable polymers can be found in reference [10.6] - [10.8].

### 10.3.3 Oil Impregnation

The purpose of oil impregnation is to give sintered parts self-lubricating properties. The impregnation process is, in principle, the same as described above for polymer impregnation. Under reduced atmospheric pressure, the pores of the parts are evacuated from air, and the parts are then dropped into a bath of hot or cold oil.

For self-lubricating bearings, it is important that their pore system is completely filled with oil. The rotating shaft in the bearing acts like a rotary pump sucking the oil out of the pore system at one place and pressing it back into the pore system at another place, thus creating a continuous oil film that prevents direct contact between shaft and bearing. If the pore system of the bearing is only poorly filled with oil, the protecting oil film may be interrupted, and galling will occur between shaft and bearing.

Oil impregnation is often used also for sintered components that are subjected to wear, like cams and gears. In these cases, however, evacuation of the pores is not necessary, and the parts can simply be dipped in oil.

Some typical oils commonly used in self-lubricating bearings are listed in Table 10.2.

**Table 10.2. Oils for self-lubricating bearings**

<table>
<thead>
<tr>
<th>Type of oil</th>
<th>Characteristics and fields of application</th>
<th>Range of operating temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral Oils</td>
<td>Very economic lubricants for medium loads and speed at moderate temperatures.</td>
<td>-20 °C - +90 °C</td>
</tr>
<tr>
<td>Synthetic Oils</td>
<td>Good long-time behavior at medium loads. Suitable for higher speeds and higher temperatures.</td>
<td>-40 °C - +120 °C</td>
</tr>
<tr>
<td>Silicon Oils</td>
<td>Suitable at high temperatures and low loads. Insufficient long-time behavior.</td>
<td>-60 °C - +200 °C</td>
</tr>
</tbody>
</table>
10. SUPPLEMENTARY OPERATIONS

10.4 Machining and other Operations

10.4.1 Machining

General aspects
Generally, sintered structural parts are produced to final shape and high dimensional accuracy, and do not require subsequent machining. There are exceptions, however. Cross bores, threads and slots or groves transverse to pressing direction, for instance, cannot be provided by the powder metallurgy technique, and have to be machined afterwards. In certain cases, as e.g. with rotationally symmetrical multiple-level parts, it may even be more economical to generate some of the levels in a subsequent turning operation, instead of using a compacting tool with delicate multiple punches (ref. Chapter 8, Fig. 8.32).

In the machining of sintered ferrous materials, specific problems arise, not encountered with wrought materials of similar composition. The most typical ones are listed below:

- Due to the porosity of the material, the cutting action of the tool is constantly interrupted which causes accelerated wear of the cutting edge.
- Due to the porosity of the material, normal chip formation is prevented. Chips disintegrate immediately into fine particles which, in drilling or tapping operations, may clog the outlet.
- Cutting fluids will enter the open pores of sintered materials, and the parts must be thoroughly cleaned after machining. The use of cutting fluids is prohibitive when components are machined that are, or are to be, oil-impregnated. If the parts are already oil-impregnated before machining, cutting fluids will contaminate the oil in the pores. If the parts are to be oil-impregnated after machining, cutting fluids retained in the pores impair the oil-impregnation.
- Some operations, like reaming or grinding, may seal the pores by smearing the surface of the parts. This would destroy the self-lubricating properties of bearings and other oil-impregnated parts.
- Debris from abrasive operations like grinding, honing and lapping tends to collect in surface pores. Thorough subsequent cleaning operations are necessary.

Due to its specific capabilities on the one hand, and its specific limitations on the other hand, ferrous powder metallurgy operates with a great variety of material compositions partly uncommon or not even feasible in conventional iron metallurgy. Since powder metallurgy typically produces structural parts of high dimensional accuracy, requiring no or only very little subsequent machining, its primary aim in choosing material compositions is achieving optimal physical properties. Considerations about the machinability of the chosen material, therefore, play often a secondary roll.
Unlike with conventional materials, the properties of sintered materials can be varied not only by chemical composition and conventional heat treatment, but also by additional parameters like sintering conditions and sintered density (or porosity). Thus, the number of actually or potentially available sintered ferrous materials is correspondingly great, and the combined effect of the involved variables on machinability is very complex.

At the present state of the art, it is, therefore, impossible to formulate universally applicable relationships between the specifications of a sintered material and its machinability. Besides, the definition of "machinability" is a problem of its own. Numerous empirical data on the machining behavior of various sintered materials are available, but the frame of this paragraph is too limited to present them all. However, as of particular interest, we present here the results of an investigation about machinability-enhancing additives to a selected variety of ferrous sintered materials, determined by means of the so-called drill-life test.

**The Drill-Life Test**

This test is fast and relatively inexpensive, the results are reproducible, and the shape of the test specimen is not a limiting factor. Choosing the drill-life test is motivated also because drilling is the most frequently utilized machining operation on sintered components. In the drill-life test, machinability is rated by the number of holes that can be drilled under conditions as specified below:

- **Drill:** High speed steel, SKF-Malcus List No. 100, Ø 3.5 mm.
- **Speed:** 3000 rpm (33 m/min at the periphery of the drill used).
- **Feed:** 235 mm/min (0.08 mm/rev at the speed used).
- **Coolant:** None.
- **Test specimen:** Sintered disc Ø 80 mm, height: 12 mm.
- **Type of holes:** Through holes.
- **Wear criterion:** Totally worn drill.

The test is repeated five times with separate drills taken from the same batch, and the average number of holes obtained is calculated. This number is referred to as the machinability index.

**Machinability-enhancing additives**

Several machinability-enhancing additives, comprising S, Se, Te, MnS, MoS2, and MnX3, have been investigated by means of above described drill-life test. It was found that MnS and MnX had the most beneficial effect on machinability, without impairing strength properties and dimensional changes of the materials tested [10.12].

3 Chemical composition not disclosed because of pending patent applications.
10. SUPPLEMENTARY OPERATIONS

The beneficial influence of MnS and MnX on machinability emerges from the diagrams at Figs. 10.16 - 10.18.

Figure 10.16 Influence of machinability-enhancing additives upon machinability index, hardness, tensile strength, density and dimensional change of sintered steel (Distaloy AE + 0.5 wt.% C, density between 7.08 and 7.13 g/cm³) [10.10]
10.4 MACHINING AND OTHER OPERATIONS

Figure 10.17 Influence of machinability-enhancing additives upon machinability index of sintered steel (SC100.26 + 0.3 to 0.7 wt.% C, density 7.1 g/cm³) [10.11]

Figure 10.18 Influence of machinability-enhancing additives upon machinability index of sintered steel (SC100.26 + 2 wt.% Cu + 0.3 to 0.7 wt.% C, density 7.1 g/cm³) [10.11]
10. SUPPLEMENTARY OPERATIONS

Machining Parameters
Some general guidelines to suitable machining parameters for drilling and turning are presented in Tables 10.3 and 10.4.

Table 10.3. Recommended Machining Parameters for Drilling of Sintered Iron Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Cutting speed m/min</th>
<th>Diameter of the drill, mm Feed, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Most types of sintered materials</td>
<td>10-15</td>
<td>0.05</td>
</tr>
<tr>
<td>Carbon containing materials</td>
<td>15-20</td>
<td>0.04</td>
</tr>
<tr>
<td>Sulfur containing materials</td>
<td>30-40</td>
<td>0.04</td>
</tr>
</tbody>
</table>

The data in this table are a compromise between productivity, tool life and edge break outs. The cutting speeds are relevant for an helix angle of 28°. When drilling in relatively soft (usually carbon-free) materials, tool life can be more than doubled with an helix angle of 40°.

Table 10.4. Recommended Machining Parameters for Turning Sintered Iron Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Carbide grade</th>
<th>Cutting speed m/min</th>
<th>Feed rate mm</th>
<th>Depth of cut mm</th>
<th>Angle of attack°</th>
<th>Rake angle°</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sintered materials</td>
<td>K01</td>
<td>min. 150</td>
<td>max. 0.3</td>
<td>max. 0.1</td>
<td>max. 3</td>
<td>max. 0.3</td>
</tr>
<tr>
<td>K10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* For soft materials, the higher angle of attack within the stated limits is recommended.

More information on the machining behavior of sintered ferrous materials can be found in [10.10] - [10.14].
10.4.2 Deburring and Cleaning

Sintered parts usually show some burr at their edges, arising from powder extruded into the gaps between compacting die and punches (ref. Chapter, Fig. 8.3), or generated in a subsequent machining operation. Surface and pores of sintered parts may also be contaminated with shop soil and grease, or with oil and lubricants from sizing or coining. Therefore, the parts have to be deburred and cleaned.

**Barreling**
In this deburring operation, the parts are tumbled in a revolving barrel, together with an abrasive or alone, dry or in an aqueous medium.

**Vibratory deburring**
This operation is similar to barreling, but the barrel is not only rotating but also vibrating. The process is faster and yields more uniform results.

**Abrasive blasting/Shot blasting**
In this deburring process, the parts are hit by abrasive media propelled by compressed air or centrifugal forces.

**Ultra-sound cleaning**
In this operation, the parts are placed in a tank containing a medium that can carry ultrasound waves generated by a transducer. The medium, agitated by the transducer, shakes loose all contaminants adhering to the surface and trapped in the pores of the parts.

**Electrolytic-alkaline cleaning**
This process involves electrolysis in a strongly alkaline solution by which the parts are thoroughly cleaned, deoxidized, and stripped of none-metallic coatings. Due to the alkaline character of the solution, there is very little risk of corrosion.

More information about deburring and cleaning of sintered ferrous parts can be found in [10.15] - [10.21].

10.4.3 Joining

One typical advantage of the powder metallurgy technique is its capability to produce parts of very complex shape not feasible with conventional techniques. There are, however, some limitations, as undercuts, grooves and holes transverse to compacting direction cannot be generated.

In many cases, these limitations can be overcome by means of joining one sintered part with another or with a conventionally produced part. Methods suitable for this...
10. SUPPLEMENTARY OPERATIONS

Purpose are mainly brazing and spot welding, but other methods, like shrink-fitting, riveting or gluing, may also be successful in certain cases.

Brazing
Observing certain preconditions, brazing is a convenient method of joining ferrous structural parts during or after sintering. However, their interconnected porosity may constitute a problem, because the capillary forces in the pores tend to drain the gap from the solder. This effect can be reduced or prevented by the following precautions:

- For brazing during sintering, the parts should have a green density higher than 6.7 g/cm³; for brazing after sintering, the parts should have a sintered density higher than 6.5 g/cm³.
- Use Sinter Braze 90, a special brazing powder mix consisting of 80% of an alloy containing Cu, Ni, Mn, Si, and B, and to 20% of iron powder. On melting, the alloy dissolves the iron powder so rapidly that it solidifies again before being drained into the pores.
- Iron powder compacts to be brazed must not contain sulfur additions, because sulfur reacts with the manganese in the brazing alloy, forming MnS which spoils the wetting property of the solder entailing insufficient filling of the joint.

The most practical way of applying the brazing powder is in the form of small compacts of suitable shape and weight. The two parts to be joined are assembled in the desired position, and the brazing powder compacts are applied as fits. See schematic example at Fig. 10.19. To warrant good results, the entrance to the gap between the two parts to be joint should be sufficiently wide.

This can be achieved e.g. by putting a chamfer on the edge of one of the parts as shown schematically at Fig. 10.20.

Sinter Braze 90 is a Höganäs product. Ask for special Höganäs brochure PM 90-9.
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Approximately 0.2 - 0.5 grams of solder per cm² joint area are needed; but the exact amount must be determined empirically from case to case. The tensile strength of a joint, brazed with Sinter Braz 90, is approx. 400 N/mm².

Two interesting examples of brazed assemblies of sintered iron parts, mass-produced for the automobile industry, are shown at Figs. 10.21 and 10.22.

Fig. 10.21 Planetary carrier for transfer case, assembly of two brazed sintered iron parts, manufactured by Toyota Motor Company. [10.22]
10. SUPPLEMENTARY OPERATIONS

More information about brazing of sintered iron parts can be found in [10.22] - [10.28].

Welding
Arc welding and oxyacetylene welding techniques are unsuitable for joining sintered ferrous parts because they would heavily oxidize their porous structure. But sintered ferrous parts can successfully be joined by means of so-called projection welding. A ring-shaped projection or several small projections on the face of the part are formed in the compacting operation and provide the necessary welding material. Two (or several) parts with such projections (usually 0.5 to 1.0 mm high) are placed on top of each other in a fixture and pressed together between two electrodes. The electrical current passing through the projections melts them down and produces spot welds.

To warrant a good welding result, the sintered material should not contain greater amounts of copper, and the carbon content should not exceed 0.2 wt.-% carbon. Nickel contents in the sintered material have no adverse effect on the welding result.

More information about welding of sintered iron parts can be found in [10.29] - [10.33].

Other Joining Methods
Shrink-fitting is a joining method ideally suited for sintered parts of annular shape. One of the two parts to be joint is pressed from a powder mix that shrinks and the other one from a powder mix that grows during sintering. The growing part is pressed with an OD that fits exactly into the ID of the shrinking part. The two green parts are stack together and passed through the sintering furnace.

The strength of the so obtained joint is relatively high, in particular if one or both parts contain some amount of copper which melts during sintering and acts as a braze in the joint.
Riveting techniques (cold or hot) can also be utilized. One of the two parts to be joint is pressed with small bosses serving as rivets, and the other part is pressed with the corresponding holes. The parts are usually sintered separately and assembled and riveted afterwards.

Adhesive techniques have to be used with discretion as the pores of the sintered parts may drain the adhesive from the joint. More information on adhesive joining of sintered parts can be found in [10.34].

10.4.4 Peening and Plating

Shot peening is an operation in which the surface of the parts is blasted with steel shot. The impact of the steel shot creates high internal stresses within a thin plastically deformed surface layer of the parts, thus improving their fatigue strength and wear resistance. A further effect of shot peening is that surface pores of sintered are closed by plastic deformation. Closed surface pores reduce the risk of electrolyte penetrating the pore system of the sintered where it would cause corrosion.

Peen-plating is a process in which the sintered parts are barreled in a mixture of glass beads, water and a metal plating powder. The impact of the glass beads continuously creates a fresh metallic surface on the parts, simultaneous hammering particles of the plating metal upon it. In this way, the particles of the plating metal are successively cold-welded to the surface of the parts.

Electroplating is a process in which the parts are coated with a thin layer of metal created by electrolytic decomposition of an aqueous solution of a metal salt. The parts to be coated form the cathode in the electrolyte, and the anode consists either of the metal to be deposited on the parts (consumable anode) or of a chemically inert electrical conductor. Typical electroplating metals are nickel, chromium, zinc and cadmium.

The porosity of sintered parts constitute a problem in electroplating, as the electrolyte can penetrate the pores causing immediate or delayed corrosion. It is therefore necessary, prior to electroplating, to close the pores by means of infiltration with metal (see § 10.3.1), impregnation with plastics (see § 10.3.2), shot peening or steam treatment (see next paragraph).
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10.4.5 Corrosion Protection

Due to their porosity, sintered iron and steel parts are especially susceptible to corrosion. When working in corrosive environments, they have to be adequately protected. Two classical methods of corrosion protection have proven very successful also with sintered ferrous materials: steam treatment and phosphatizing.

Steam treatment

In this treatment, the parts are placed in a closed furnace chamber where they are exposed to superheated steam (H\textsubscript{2}O) at a temperature close to but below 550°C. Under these conditions, the following oxidizing reaction takes place at the surface of the parts:

\[ 3\text{Fe} + 4\text{H}_2\text{O} \rightarrow \text{Fe}_3\text{O}_4 + 4\text{H}_2 \] \hspace{1cm} (10.1)

The Fe\textsubscript{3}O\textsubscript{4} (magnetite) forms a brownish-black, strongly adhering and highly wear-resistant, layer on the surface of the parts as well as inside their surface-connected pores. The so obtained tight magnetite coating is not only extremely hard but also highly corrosion resistant. The thickness of the coating grows with the square root of treating time (ref. Chapter 1, § 1.3.2).

The hydrogen (H\textsubscript{2}) emerging from above reaction is constantly diluting the steam (H\textsubscript{2}O). If the H\textsubscript{2}-concentration in the steam near the surface of the parts increases too much, the reaction (10.1) is reverted, and the oxide layer is reduced again. In order to prevent this, three measures are important:

1. Maintain a sufficiently high turbulence in the steam.
2. Arrange the parts in the chamber in such a way that “dead corners” are avoided.
3. Bleed controlled amounts of air or oxygen into the furnace chamber to keep the H\textsubscript{2}-concentration down to an acceptable level.

It is also very important that neither the steam temperature nor the temperature of the parts exceed 550°C because above this temperature, the reaction (10.1) is more and more superseded by the reaction:

\[ \text{Fe} + \text{H}_2\text{O} \rightarrow \text{FeO} + \text{H}_2 \] \hspace{1cm} (10.2)

which forms a gray, flaky and loosely adhering, layer of FeO (wüstite) on the surface of the parts. It gives the surface of the parts an ugly appearance and provides no corrosion protection at all.
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The various conditions just described are illustrated in the diagram at Fig. 10.23.

![Diagram showing % H₂ and Temperature relationship](image)

Figure 10.23 Suitable and unsuitable conditions for the steam treatment of iron parts.

The influence of steam treatment upon the mechanical properties of plain sintered iron parts is illustrated in the diagrams at Fig. 10.24. As can be seen, the hardness of the parts is significantly increased - particularly with parts of low density, tensile strength is practically unaffected, and elongation is decreased with parts of densities below 7.4 g/cm³.
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Figure 10.24 Influence of steam treatment upon the properties of plain sintered iron parts.
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Phosphatizing
This treatment is used to coat sintered iron parts with a thin rust-preventing film of iron phosphates. The parts are dipped into an aqueous solution composed primarily of phosphoric acid, and catalyzed by the iron, the following reactions take place at their surface:

\[
\begin{align*}
\text{Fe}^{II} + \text{H}_3\text{PO}_4 &\rightarrow \text{Fe}^{II}\text{HPO}_4 + \text{H}_2 \\
2\text{Fe}^{III} + 2\text{H}_3\text{PO}_4 &\rightarrow 2\text{Fe}^{III}\text{PO}_4 + 3\text{H}_2
\end{align*}
\]

(10.3)

(10.4)

The hydrogen escapes as gas, and the phosphates adhere strongly to the surface of the parts and, to a certain extend, fill their pores.

More information about corrosion protection of sintered ferrous parts can be found in \[10.35\] - \[10.38\].
10. SUPPLEMENTARY OPERATIONS

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