



3

Design and Mechanical Properties

Höganäs Handbook for Sintered Components

3

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PM-SCHOOL HANDBOOK 1

Material and Powder Properties

1. Material Science
2. Production of Iron and Steel Powders
3. Characteristics of Iron and Steel Powders

PM-SCHOOL HANDBOOK 2

Production of Sintered Components

4. Compacting of Metal Powder
5. Compacting Tools
6. Sintering
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Design and Mechanical Properties

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P/M processing offers unique design advantages, but certain P/M specific aspects have to be observed which are discussed in detail in this chapter.

Designing for P/M-processing

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8.1 General Aspects

Each method of producing structural parts offers specific advantages and has specific limitations. The great advantage of P/M-processing over other manufacturing methods is its capability to produce, without chip formation, complicated structural parts of high dimensional accuracy in large series at reasonably low costs. P/M-processing offers unique possibilities to create shapes which are not, or only with great difficulties and at high costs, achievable with other methods.

On the other hand, there are not only design advantages but also certain design restrictions specific to P/M-processing, which will be discussed in detail further below. Then, it will be seen that, in most cases, there are ways to adapt conventional designs to the specific requirements and unique possibilities of powder metallurgy without impairing and often improving the function of the structural part. The proper design of metal powder structural parts requires attention to the following points:

- Checking that the production quantity is sufficient to justify the necessary investment in tooling
- Examination of shape and dimensional specifications of the proposed part and suggestions for necessary changes
- Checking that given specifications on physical properties are within the limits of powder metallurgy
- Calculations to determine whether PM-processing is more economical than other possible methods

A decision for P/M-processing of a part is only on rare occasions a result of positive answers to all of the four points above. In powder metallurgy, more than in other engineering practice, the rule is that the final answer is the result of a series of compromises.

It should be noted that examples and figures presented in the following paragraphs are to be taken as guidelines rather than optimal answers to powder metallurgy designing problems. Clever design solutions call for long practice, skill and experience.

8.2 Dimensional Accuracy

The dimensional accuracy, which can be maintained on sintered structural parts depends partly on the directionality of the dimension and partly on the final processing step. On dimensions transverse to the pressing direction, narrower tolerances can be maintained than on dimensions in pressing direction. Narrow tolerances are applicable if the last processing step involves a sizing or coining operation. If, on the other hand, the final processing step comprises sintering or heat treatment – like hardening – the achievable accuracy is decreased. Roughly expressed, sizing tolerances can be compared with medium grinding or broaching tolerances as obtained by conventional machining methods. Tolerances for a part which is sintered, but not sized, can be compared with medium tolerances normally obtained when using common machining processes like turning, milling, drilling, etc.

The tolerances of carburized and hardened structural parts, finally, are in most cases comparable with wider machining tolerances, with the tolerances of die-cast light alloys and with the narrowest class tolerances of small items produced by investment casting methods. Approximate tolerances obtainable after sintering can be taken from *Table 8.1*.

Table 8.1. Tolerances Obtainable on Structural Parts after Sintering

Size (direction) mm	Diameter (horizontal) μm	Total Height (vertical) μm	Flatness (horizontal) μm	Parallelism (vertical) μm	⊥-angularity (vertical) μm
10	15	70	25	10	15
20	20	80	30	20	20
30	25	100	40	25	25
50	30	180	60	45	40
80	60	200	80	75	60
* Note: Figures vary (±) with powder composition and with sintering temperature and time					

How processing affects tolerances and physical properties is demonstrated schematically by Fig. 8.1.

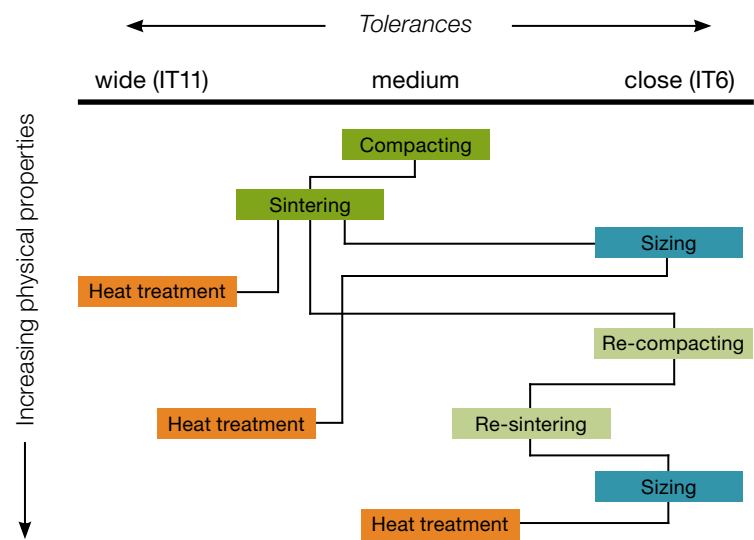


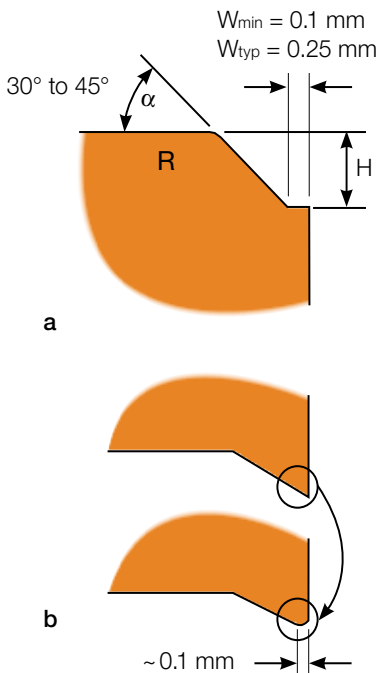
Fig. 8.1 How processing influences tolerances and physical properties of P/M-parts. Also depending on material, geometry and processing.

8.3 Examples of Design Features to be Preferred and to be Avoided

The examples presented in the following may help the designer of machine components to avoid shapes impossible to be compacted or requiring unnecessarily complex and costly compacting tools, or impairing tool life.

8.3.1 Chamfers, Fillets and Tapers

Fig. 8.2 Chamfers.

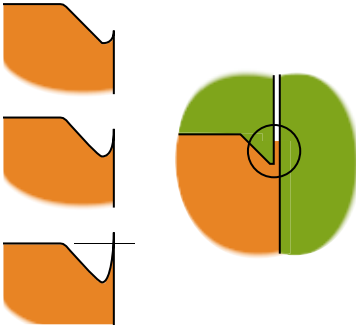


Sharp edges between face and side walls of the component should be excluded in order to reduce burring and increase tool life.

As shown in sketch (a), the chamfer is composed of a slope with an angle and a flat zone of width W . The greater the chamfer's angle α , the larger the compression force required to produce this angle.

Usually, the chamfer's angle is 45°, but any angle less than 45° is acceptable. Because of the force required to compress the powder, angles greater than 45° relative to the horizontal are to be avoided. This will aid in preventing die and core rod breakage. The height H should not reduce the parts thickness by more than 30% because of the variation in density this will produce.

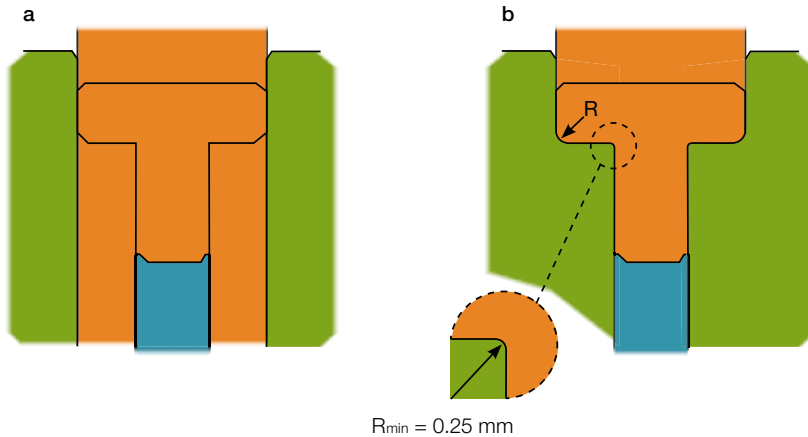
The minimum width of the flat zone is 0.1 mm, but a value of 0.2 - 0.3 mm is recommended. Also, a typical value for the radius R would be 0.2 - 0.3 mm. As shown in sketch (b), if no flat zone is considered, the punch's life will be affected and it will eventually break to form its own flat with a dimension in the order of 0.1 mm.

Fig. 8.3 Chamfers and Burrs.

Because a certain free space or clearance between the tooling elements is necessary, a small amount of powder is being extruded into this gap during compaction and each compact will end up having burrs.

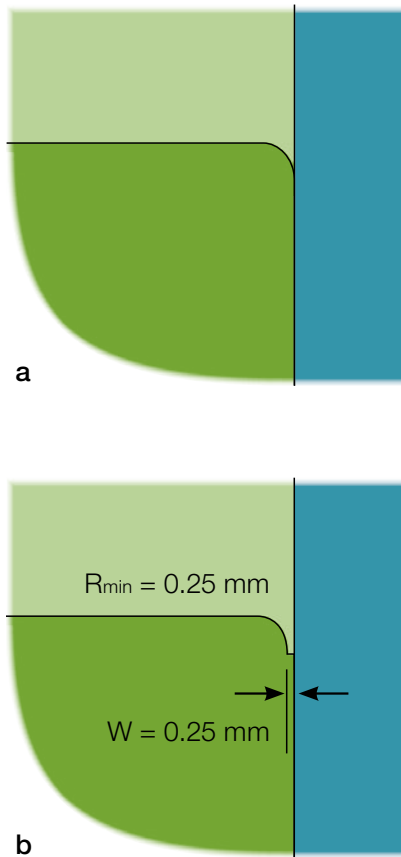
The design of a chamfer will help reduce the production of burrs. However, as shown in the sketch, the size of burrs will increase with time along with the wearing of the pressing elements.

It is therefore important to reface the punches before the burrs exceed the chamfer's height.

Fig. 8.4 Fillets.

When a part of this type is formed by two lower punches, as shown in sketch (a), it is not essential to design a fillet radius where the flange and the hub intersect. One must remember however to include a chamfer at the flange periphery. If, however, the flange is formed by a shelf die, as shown in sketch (b), the addition of a radius should be considered in order to avoid cracks during the part's ejection (see also Fig. 5.8 in chapter 5). The larger the radius, the better the outcome. Usually, the minimum acceptable radius is 0.2 mm.

Fig. 8.5 Rounded-off Edges.



It is possible to round off edges. However, a perfect radius, as shown in sketch (a), is not really practical because of the tip generated at the bottom end of the punch.

This tip is almost bound to break at the beginning of the pressing operation. It is then advisable to add a flat zone as illustrated in the chamfers example (see Fig. 8.3).

Sketch (b) shows how this flat zone must be produced. A typical size is 0.2 - 0.3 mm. Here, the radius of the curve is not mentioned, any size will fit, the larger the better, providing that the tip of the rounded part does not decrease the compact's height by more than 30%.

However, producing a radius less than 0.2 mm is not recommended. The flat zone may then be almost entirely removed by deburring (tumbling operation).

Fig. 8.6 Corners and Edges Facing the Die.

Top View



Possible



Preferred

Theoretically, sharp corners and edges facing outward can be produced. In practice, however, it would be preferable to round them off.

The die will then be easier to design and will also be less susceptible to cracking. If the die is designed in one single piece, a minimum radius will always be present.

This radius is generated by the tools used to carve the die.

Fig. 8.7 Corners and Edges Facing the Core Rod.

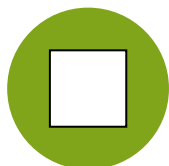
Top View



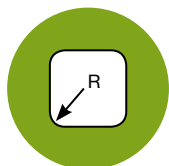
Possible



Preferred



Possible



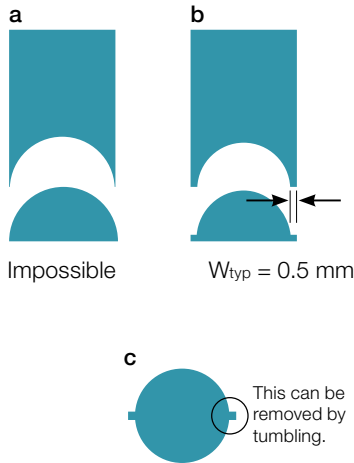
Preferred

Theoretically, sharp edges and corners facing inward can easily be produced, but one has to remember that where a sharp edge is present, the part will be more susceptible to cracking. These cracks are produced during the part's ejection.

Here, the core rod's withdrawal leads to an elastic shrinkage of the hole left by the rod passage, causing extremely high shearing stresses in the part.

Finally, rounded off corners allow for a more uniform filling, resulting in improved parts while extending the tool's life.

Fig. 8.8 Spherical End.

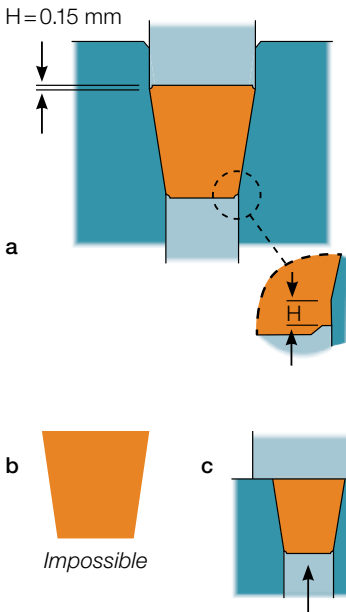


A perfect hemisphere, as shown in sketch (a), cannot directly be obtained during pressing. A punch with a feather edge will not support the compacting pressures and will break almost immediately.

A small flat surface having a width W , as in sketch (b), must be considered in order to strengthen the punch. A typical width of this surface is at least 0.5 mm, but a larger width is also possible depending on the overall height of the part. The pressure applied to the punch is higher at its tip than at its center and a uniform density in the part is therefore not achievable.

The flat surface around the hemisphere can be removed by machining or aggressive tumbling. See sketch (c).

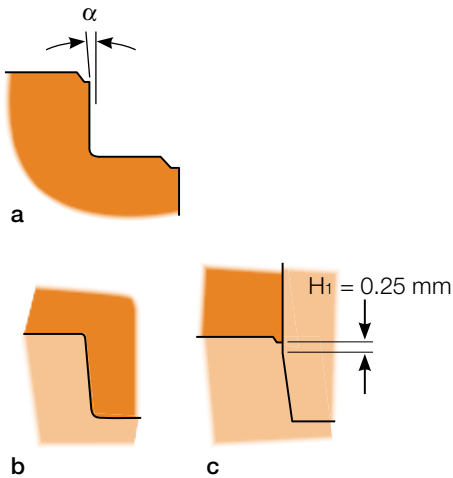
Fig. 8.9 Tapered Sides Formed by the Die.



A perfect conical part cannot be produced without machining. Two flat zones have to be added at each end as shown in sketch (a). These flat zones (height H) are essential.

The upper flat helps prevent the top punch from crashing into the die, while the lower flat helps eliminate the risk of burring and powder jamming between the die and the bottom punch. The typical height H is 0.1 - 0.2 mm. This, however, may vary according to the accuracy of the press.

The part shown in sketch (b) is impossible to produce due to the fact that the top punch will eventually collide with the die during pressing. However, if a perfect taper is required at the top, this can be made with the help of an anvil top punch, as shown in sketch (c).

Fig. 8.10 Tapered Sides Formed by Upper Punches.

A shape as the one shown in sketch (a) would be very difficult to produce. If the taper is to be obtained by one and only one upper punch, as shown in sketch (b), then the minimum angle α has to have a value of 2° .

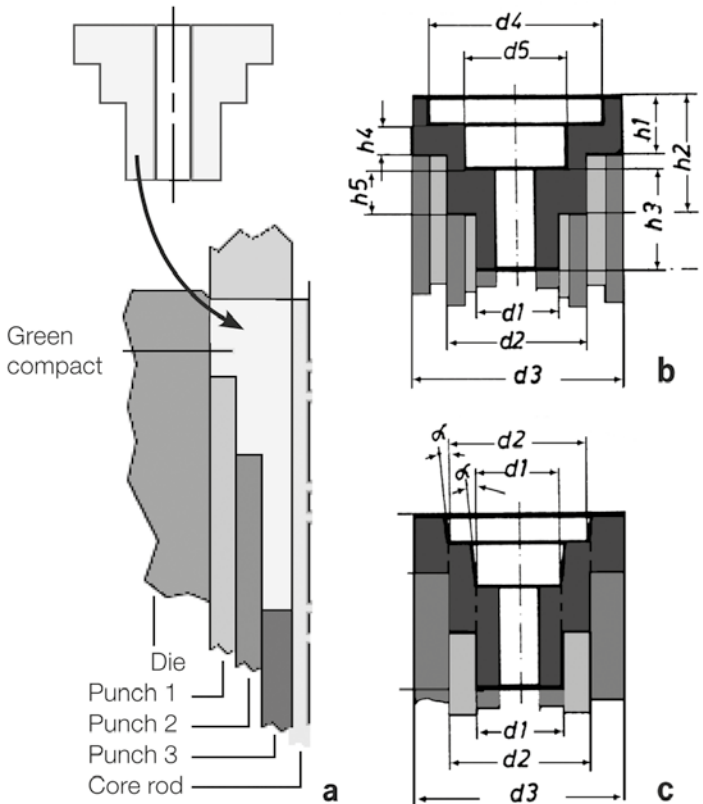
This will help the punch to withdraw without breaking the part. Moreover, it is highly recommended to consider using a radius instead of a chamfer.

If the part has to be produced by two upper punches, as shown in sketch (c), a vertical flat H_1 should be considered in order to prevent the formation of burr between the two punches. The recommended height H_1 is 0.2 - 0.3 mm.

8.3.2 Multiple Level Parts

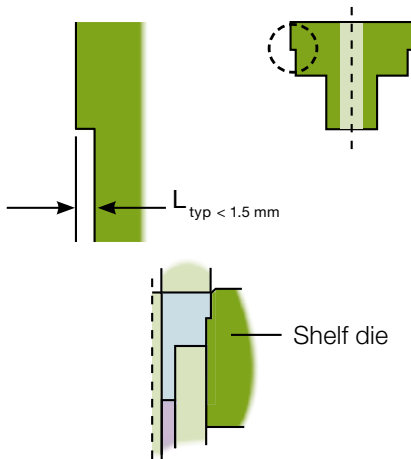
Multiple level parts can be produced with the appropriate tooling, using multiple punches, shelf dies, step punches and/or step core rods.

Fig. 8.11 Multiple Punches.



Where the widths of the steps allow it, several punches should be used as shown in sketch (a). A typical minimum width is 1.5 mm. However, during the design stage, one must take into account the tooling strength in order to avoid buckling of punches during compression.

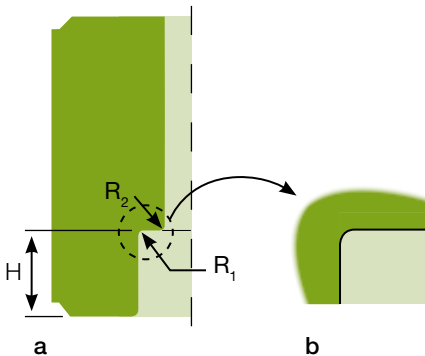
One should strive for a design with as few punches as possible. For example, the design in sketch (c) is to be preferred to the design in sketch (b). If the press is not designed to carry more than one lower punch, one must examine the possibility of using a shelf die.

Fig. 8.12 Shelf Die.

Shelf dies are used frequently, particularly when the surface of compression is too narrow to be produced by a punch. See sketch.

A shelf die sometimes leads to density distribution problems because the shelf (or step) is not a moving object.

Punch synchronization is then essential in order to optimize density at the shelf location. The die support system must be able to withstand the huge compressive force generated by the shelf. Some presses will not support this force at the die level.

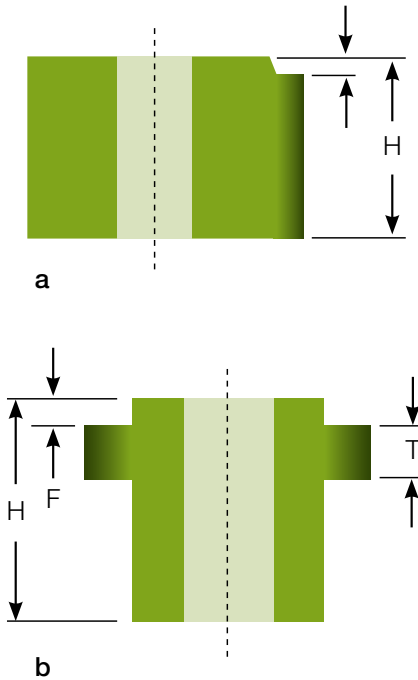
Fig. 8.13 Step Core Rod.

A step core rod can be used to produce levels providing that the press is capable of withstanding the compressive force.

A step core rod should have rounded off corners, as shown in sketch (a). The greater the radius, the less chance of breakage. However, the greater the radius R_1 , the more difficult it will be to obtain a good density ratio in this area. See sketch (b). A typical value of R is 0.5 mm.

The height of step H is not adjustable and can only be changed by re-machining the core rod.

Fig. 8.14 Step in the Punch Face.



A step can be obtained directly by a single punch providing that the height does not exceed 20% of the part's total height H . See sketch (a).

If the step's height is greater than 20% of H , the use of a second punch should be considered, otherwise the density will be extremely high under this step. A flange, as shown in sketch (b), is easily produced by powder transfer with the help of outer (upper and lower) punches.

This action is carried out in order to maintain a more uniform density distribution. None the less, if one wants to compress this flange without powder transfer with one single upper punch, one must avoid having a flange height F higher than its thickness T .

The cavity in the upper punch should be tapered in order to help the punch withdraw without breaking the part.

Compressing a flange of this kind without powder transfer will make its density higher than in the related hub.

Fig. 8.15 Profiled Faces.

Profiled faces, as shown in the sketch, can be produced without subdivided punches if $b_2 \leq 0.2 b_1$ and $b_3 \leq 0.1 b_1$. The angle α should be at least 5° .

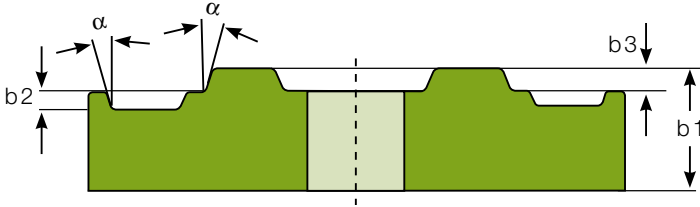
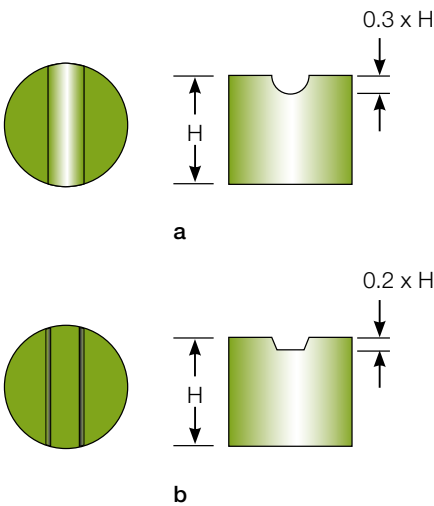


Fig. 8.16 Slot made by a Punch.



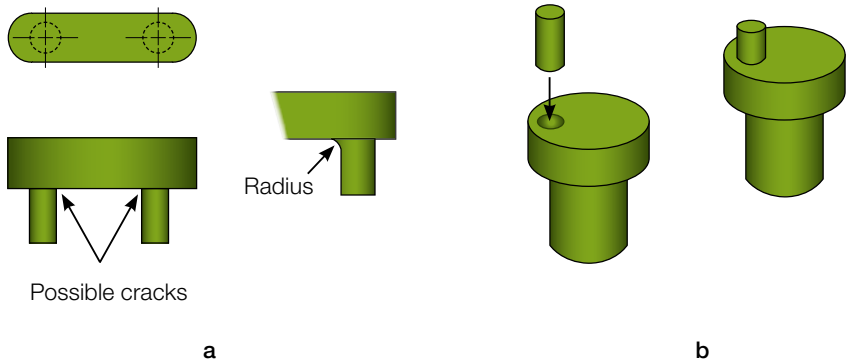
When a slot is produced by a punch, one must evaluate its acceptable depth. As the amount of powder under the slot is the same as in the region beside it, the local density under the slot will eventually be higher than anywhere else. This is due to the higher compression ratio.

Usually, in the case of a semi-circular slot, one avoids going over 30% of the part's overall height H . See sketch (a).

In the case of an angle slot, the above figure becomes 20%. See sketch (b).

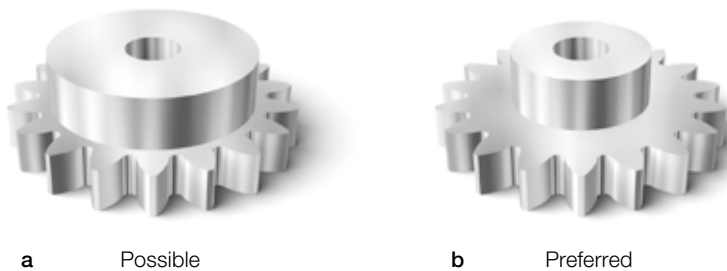
Here, one should not neglect to include an angle in order to avoid having the part stick to the punch during ejection.

Fig. 8.17 Flanges and Studs.



During ejection of a part with a long flange, an important constraint is produced at the junction between the flange and the stud giving rise to a possible cracking area. In order to counter the effect of these constraints, the use of a radius at the intersection is recommended. See sketch (a). Sometimes, it is less expensive and safer to produce a two-piece part. If the tenon has a small diameter relative to the part, it is then better to generate a hole (through or blind) during pressing, or to drill a hole in the green compact and then use it to insert a stud that will be held in place by the sintering process. See sketch (b).

Fig. 8.18 Gear Hub.



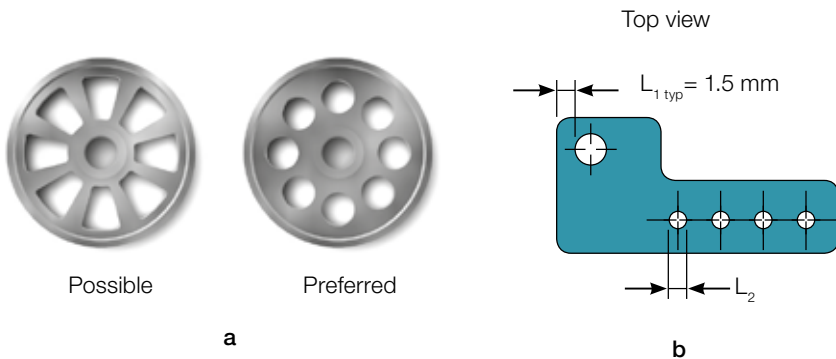
During the design of a gear, it is important to remember to leave enough room between the teeth and the hub. This extra space or land helps to insure stronger tooling and produce more resistant parts. If the space between the teeth and the

hub is very narrow, the punch used to compact these teeth will be very fragile. By leaving an extra space, designers will produce stronger tooling with stronger teeth. The part shown in the above sketch is to be compacted with the hub oriented downward.

8.3.3 Holes and Wall Thickness

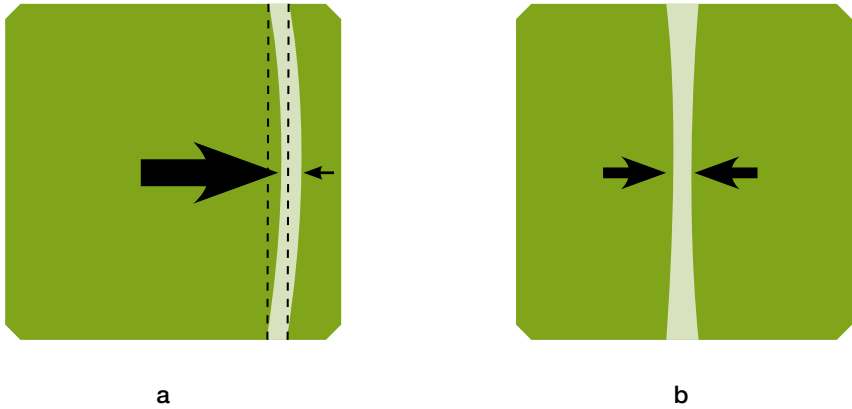
Holes are easily produced in powder metallurgy using a core rod during the compacting operation. However, some important aspects, as described below, will have to be observed.

Fig. 8.19 Holes.



Sketch (a) shows that it is possible to produce holes that will help lighten the part and save powder while reducing the pressing surface. It is much more economical to design round hole rather than polygonal holes, the reason being that the tooling is much simpler to produce.

Sketch (b) shows a part containing several holes. The distance L_1 between the hole and the side of the part should be sufficient to allow a good powder flow during die filling. The deeper the required filling space for the part, the larger a distance is needed. Typically, one should avoid a distance of less than 1.5 mm.

Fig. 8.20 Narrow Holes.

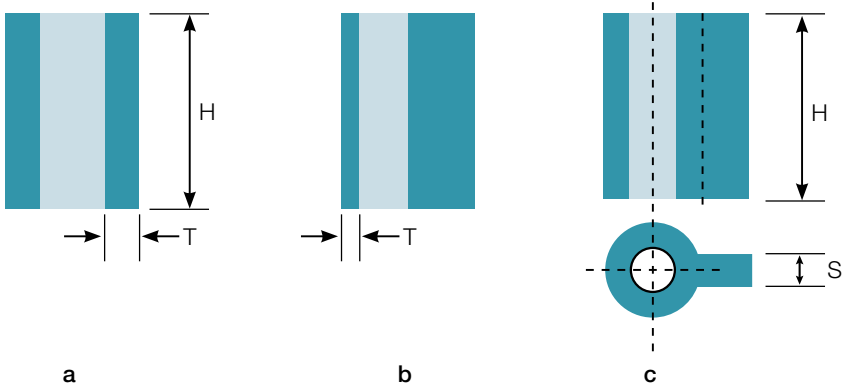
The minimum hole size is obviously the one obtained by the smallest machinable core rod. Again, the minimum size of the core rod depends on the part's height. If a very narrow hole diameter is produced in a part of great compacting height, the long thin core rod used to generate this hole will, during ejection of the part, be subjected to such high frictional forces that it breaks.

Sketch (a) shows what happens when a hole with a small diameter sits close to one side of the part. During compacting, the core rod, being guided both in the upper and in the lower punch, will bend because, under the high compaction pressure, the part expands radially more than the punches. This action is almost bound to produce cracks in the part and will eventually break the core rod.

Sketch (b) shows what happens when a narrow hole is subjected to almost symmetrical forces. Here, the core rod will not bend, but its elastic constriction at the middle will make ejection very difficult and might break the core quite rapidly.

Fig. 8.21 Wall Thickness.

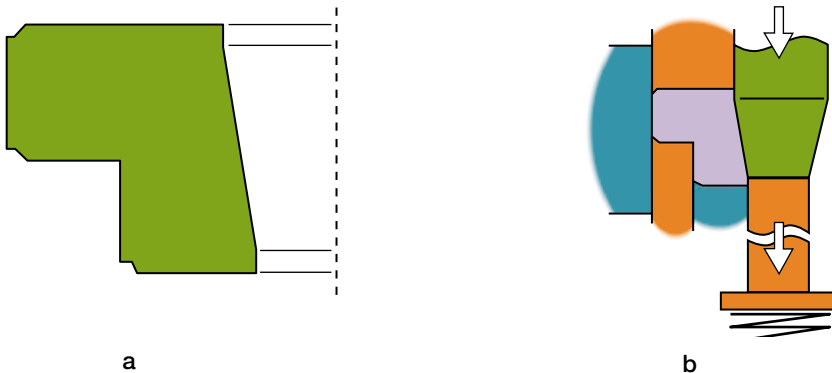
Narrow walls are to be avoided. They are not impossible to produce, but may cause a variety of problems in tool adjustments and the related life expectancy of the tooling. Moreover, after sintering, deviations (in flatness, diameter, etc.) will be more severe and make tolerances hard to maintain.



Factors indicative of narrow walls:

- When the ratio H/T , in sketch (a), is higher than 6
- When thickness T , in sketch (b), is less than 0.8 mm
- When the ratio H/S , in sketch (c), is higher than 6 (even though it was possible in some instances to obtain rates up to 18)

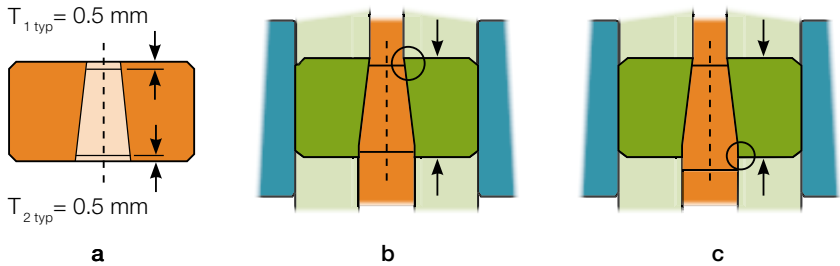
Fig. 8.22 Taper Holes (wider end up)



On occasion, a taper hole must be compressed in the direction shown in sketch (a). Normally, in such a case, it is not possible to produce a hole using conventional tooling. A possible solution to this problem is shown in sketch (b). A conventional core rod is set on a floating device (a spring or a hydraulic system). The sprung core rod, also known as "dummy core rod", whose function is to stop the powder from filling the space where the hole is to be located, is

then pushed away by an upper punch, giving form to the desired hole. Of course, one must take into consideration the presence of top and bottom flats.

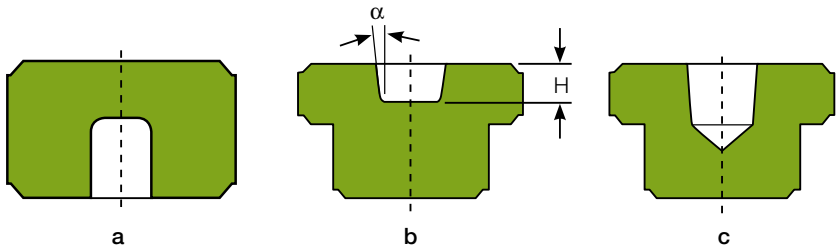
Fig. 8.23 Taper Holes (wider end down)



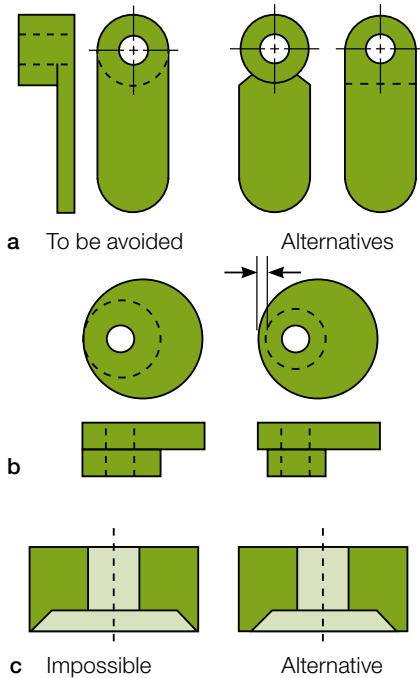
Flats are essential while pressing a part designed with a taper hole as shown in sketch (a). The typical values of T_1 and T_2 are 0.5 mm.

When the powder is compressed, one must check the upper punch so it does not touch the core rod. See sketch (b). Moreover, the lower punch should move farther away than the top side or the beginning of the taper form; otherwise, this might create sharp burrs at the hole's perimeter. See sketch (c).

Fig. 8.24 Blind Holes.



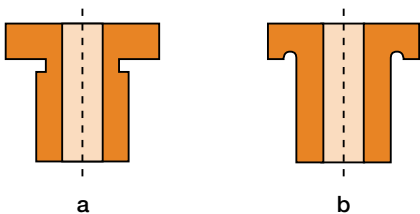
Parts with blind holes are easily produced. Ideally, the hole should be oriented downward as shown in sketch (a). Sometimes, however, they are pressed from the top as shown in sketch (b). When needed, an angle α is used to allow for punch withdrawal. One must also make sure that the depth H of the hole does not exceed 15% of the height of the powder column under the hole. If a deeper hole is required, then the use of a core rod with a pointed end should be considered. See sketch (c).

Fig. 8.25 Feather Edges.

It is not advisable to produce jointed parts by designing feather edges (bevelled). The tooling required will be extremely fragile. Ideally, one should alter its design in order to remove this feature. See opposite sketches.

Angles forming sharp edges are also difficult to produce. As shown in the sketches below, it is advisable to leave a flat zone on the contour.

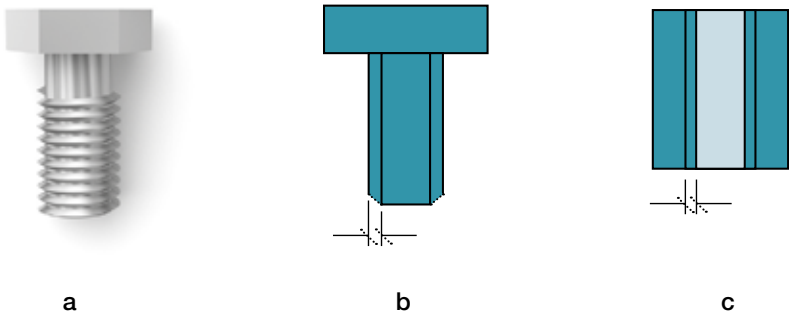
Fig. 8.25 a-c show some examples of poor design (left side) and good design (right side).

Fig. 8.26 Grooves and Undercuts.

A groove as shown in sketch (a) allows for the close assembly of two parts. This cannot be produced directly in the pressing operation because the parts ejection would be impossible to perform. Alternatives:

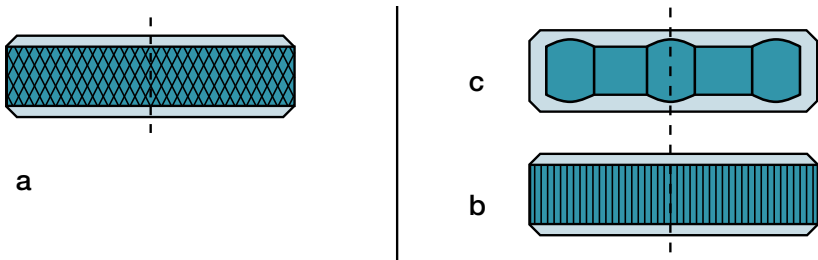
- A groove can be machined after sintering if it must be produced in this direction
- Produce an undercut in the opposite axis by a bulge on the face of the lower punch as shown in sketch (b)

Fig. 8.27 Threads.



Threads, as shown in sketch (a), cannot be directly obtained by pressing. Whether they be exterior or interior, threads must be machined after sintering. For this to be possible, a sufficient margin has to be added to the pertaining dimensions of the part. The minimum margin to be added depends on the type of thread required. Generally, the equivalent of the thread's own width will be sufficient. See sketches (b) and (c).

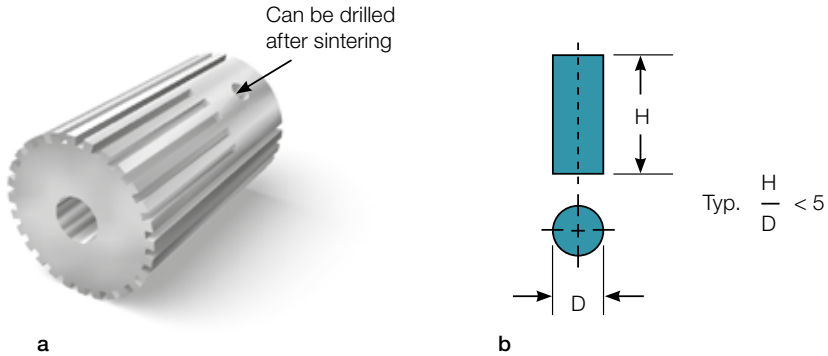
Fig. 8.28 Knurls.



Diamond knurls, as shown in sketch (a), cannot be obtained by pressing. Alternatives:

- Machine the knurls after sintering
- Generate straight knurls as shown in sketch (b). Straight knurls can be obtained at a minimum depth of 0.3 mm and its pattern should be rounded off by a radius of at least 0.1 mm. Remember that, if the knurls are not deep enough, a tumbling operation after sintering might spoil them
- Instead of knurls, produce a profiled periphery as shown in sketch (c)

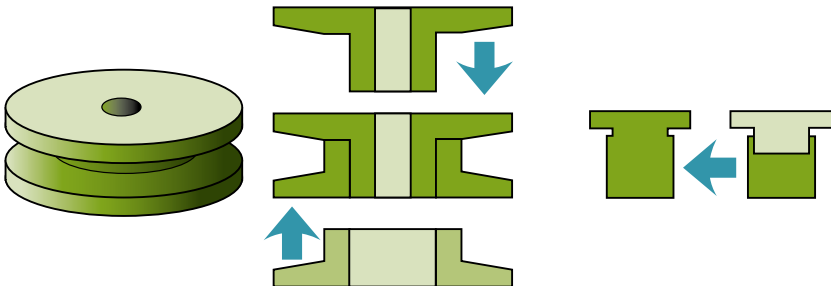
Fig. 8.29 Special Shapes.



It is possible in powder metallurgy to generate working features that would be difficult to obtain otherwise. For instance, parts with blind corners are often produced. One must pay attention in order for the part to be easily ejected after pressing. See Fig. 8.29a.

Very long parts should maintain ratio height/width lower than 5. If this ratio is higher than 5, the risk of rupture in the part increases rapidly. See Fig. 8.29b.

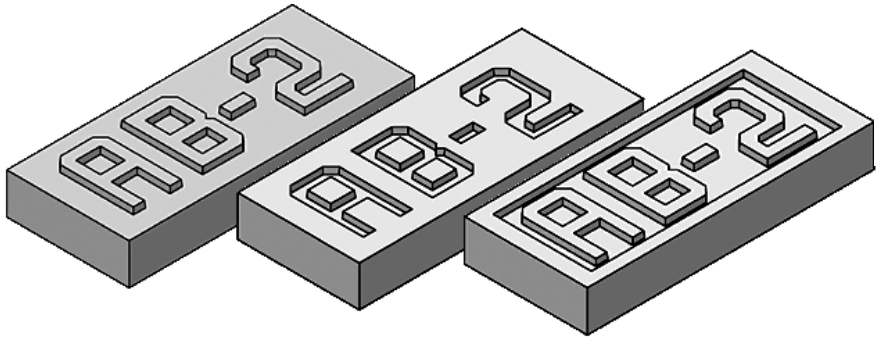
Fig. 8.30 Assemblies.



Assemblies may help solve some manufacturing difficulties or sometimes overcome the use of secondary operations. For instance, if one wants to compact a part including a slot or groove, it is possible to design the part in two pieces, which will then be assembled before sintering. While sintering, welding between the powder particles will hold the two pieces firmly together.

This technique is useful when the part to be manufactured uses a type of raw material recognized as being difficult to machine. See above sketches in Fig. 8.30.

Fig. 8.31 Alphanumeric Characters.



Alphanumeric characters can be produced on the pressing end face of the punch. These may take the form of raised, depressed or embossed markings as shown in the example above. The following rules should be observed:

- A minimum angle of 2° in the character outline
- A streak width larger than the character's thickness
- The symbols forming a hole in the punch face being a source of powder accumulation. This problem can be solved by coating its working face with graphite

8.4 Further Design Considerations

The design of metal powder structural parts is influenced not only by aspects of pressing technique and tooling, as illustrated in the preceding paragraph, but also by aspects of tooling economy, sintering behaviour and functionality of the parts.

8.4.1 Aspects of Tooling Economy

Considerable time is spent on setting up, adjusting and running in a tool on the press and when production series are short, the related costs comprise a relatively high proportion of the entire manufacturing costs. The more complicated a tool, the more time it takes to set it up and run it in and the higher are the related costs. Here, it is not only a question of labor costs but also of costs for lost production time on the press.

When short production series are involved, it may be more economic to compact a half finished part in a simpler tool, requiring shorter set-up and run-in times and finish the part by conventional machining. A typical example of this production philosophy is the gear hub shown in Fig. 8.32. In order to produce the hub of this gear directly in the compaction process, a multiple split upper punch is required, as shown in sketch (a).

Without hub, as in sketch (b), the part can be pressed with one single upper punch while the hub has to be machined after sintering. In the case of short production series, the cost for the subsequent machining operation will be lower than the sum of additional tooling costs for a more complicated upper punch and additional costs for longer set-up and run-in times on the press. In the case of long production series, however, this cost relation is reversed.

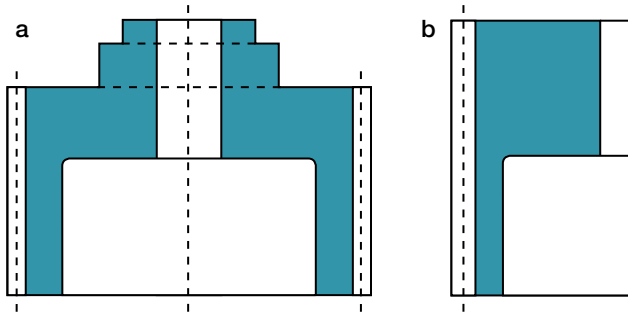


Fig. 8.32 Changing the design of a structural part for simpler P/M-tooling (in case of short production series).

8.4.2 Aspects of Sintering Behaviour

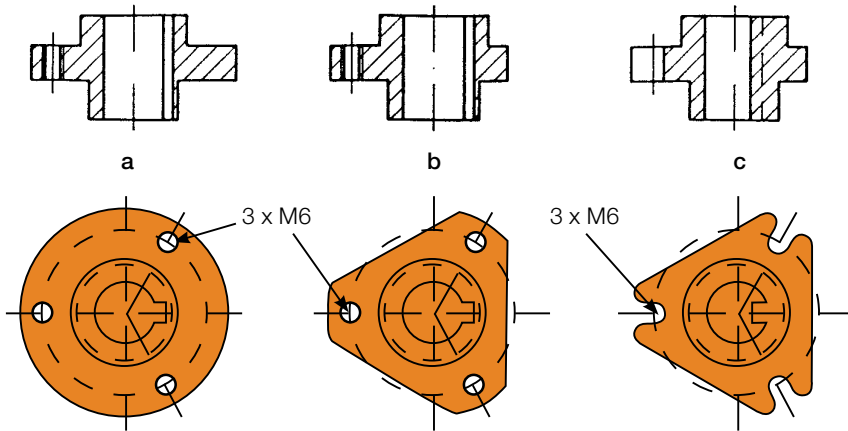
In the sintering process, structural parts may suffer dimensional changes and deformations which may have to be corrected by means of subsequent operations like coining and sizing or, in some cases, machining.

- Depending on powder composition, structural parts may shrink or grow during sintering. It is therefore worthwhile to examine if specifications on the physical properties of the part allow the choice of a powder composition which minimizes dimensional changes during sintering. Otherwise, dimensional changes may be difficult or impossible to correct by subsequent sizing.
- During heating up in the sintering furnace, thinner portions of a structural part get hot faster than thicker portions and the part may warp. It is therefore advisable to design structural parts so that extreme differences in the thickness of their different portions are avoided.
- Long bushings with decreased density at the center tend to form a waist due to uneven shrinkage. Such waist may be difficult or impossible to correct by sizing; and in this case, it should be examined if the application would not allow the use of two short bushings instead of one long.
- Thin disc-shaped parts and thin rings tend to warp during sintering if not properly supported.
- Massive parts can give problems during sintering because their surface is heated much faster than their core and the burning-off of lubricants is obstructed. This may cause the parts to crack if the heating rate in the sintering furnace is too high.

8.4.3 Aspects of Shape and Function

The shape of a structural part is primarily determined by its intended function, but it is also influenced by the peculiarities of the process chosen to manufacture it. The following example may illustrate how a structural part, originally designed to be manufactured by conventional machining (turning, drilling and milling), can be redesigned in order to take advantage of the unique shaping capabilities of P/M-processing. The part in question is a flanged coupling with a hub on either side of the flange. See Fig. 8.33.

Fig. 8.33 Optimizing the design of a flange coupling for P/M-processing.



In the original version (a), the part has a circular flange with three threaded holes and in its center bore it has a slot. Apart from the threaded holes, this version could easily be produced by powder metallurgy. A first step towards utilizing the shaping possibilities of powder metallurgy is version (b), where the circular flange has been replaced by a triangular flange while saving a substantial amount of weight.

In the optimally adapted version (c), the slot in the center bore has been replaced by a key (eliminating a weak spot in the original part) and the threaded holes have been replaced by rounded off slots for the connecting bolts. (The corresponding holes in the counterpart have to be threaded). By powder metallurgy, version (c) of this flanged coupling can be produced as easily as version (a). By conventional machining, version (c) would be much more difficult and expensive to produce than version (a).

There are plenty of other examples how powder metallurgy can produce functionally superior joints for torque transmission. By powder metallurgy, holes with splines, with triangular, polygonal, or more complicated cross-sections, can be produced as easily as round holes. In this way, superior axle-shaft joints can be produced which are impossible, or only at higher costs and greater difficulties, to achieve by conventional machining. Also in the case of gears, it may be worthwhile to utilize the unique shaping capabilities of powder metallurgy. The classical method of producing gears is hobbing. For reasons of maximum impact strength, the fillet radius at the gear base should be as great as possible. On the other hand, due to the geometrical preconditions of the milling process, there is an upper limit to this fillet radius.

The general rule of gear designing is the smaller the maximal achievable fillet radius, the higher has to be the strength of the steel from which the gear is to be manufactured. P/M-processing is not restricted by the geometrical preconditions of the milling process, i.e. it can generate a larger fillet radius.

When comparing classical methods with P/M-processing, the designer of gears should take into account the design freedom unique to PM, as well as differences in properties such as Young's modulus.

A further unique capability of P/M-processing is the deliberate generation of zones of different densities in a structural part. For instance, the hub of a pinion gear can easily be pressed with a lower density than the actual gear. In this way, the hub can be given self-lubricating properties by oil-impregnation, while the denser gear part possesses the necessary higher strength.

In the case of the flanged joint shown in Fig. 8.33, the neighbourhood of the bolt holes could be pressed with increased density in order to prevent plastic deformation of the flange when the bolts are tightened. Lower densities in zones of a structural part where higher strength is not needed helps to increase the life of the corresponding compacting punches and, in some cases, may allow the use of a smaller press.

8.4.4 Examples of P/M - Parts of different Complexity

The range of structural parts actually produced by powder metallurgy methods stretches from relatively simple to extremely complex types. The frequency of the various types decreases with their degree of complexity. A typical frequency spectrum related to different classes of complexity is shown in the diagram in Fig. 8.34.

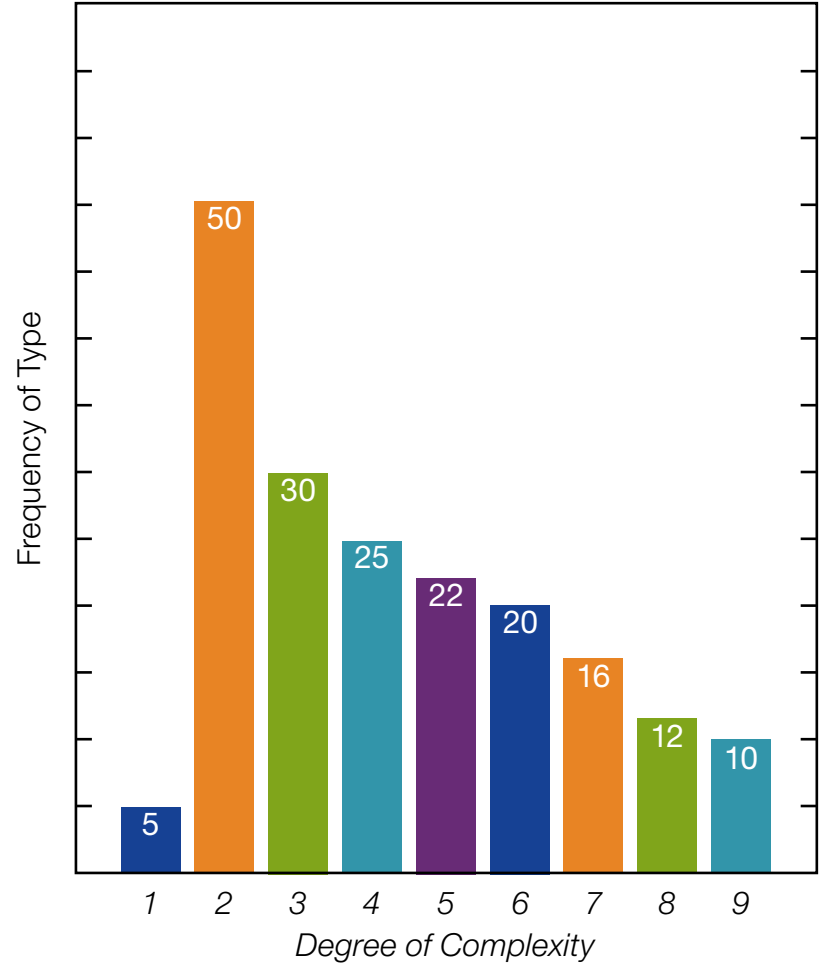


Figure 8.34 Frequency of P/M-parts related to their degree of complexity.

Extremely simple parts are typically rare because, here, P/M-processing cannot easily compete with conventional mass production methods. But as soon as the parts have some ever so small design features impossible or difficult to produce by conventional methods, their frequency in the spectrum of metal powder structural parts is very high.

As their degree of complexity increases further, they become less frequent again because of increasing costs for tooling and processing. Some structural parts representative of different classes of complexity are shown in the photographs and drawings in Figs. 8.35 - 8.38.



Figure 8.35.a. Selections of components with degree of complexity 2 according to diagram in figure 8.34.



Figure 8.36.a. Selections of components with degree of complexity 3 according to diagram in Figure 8.34.

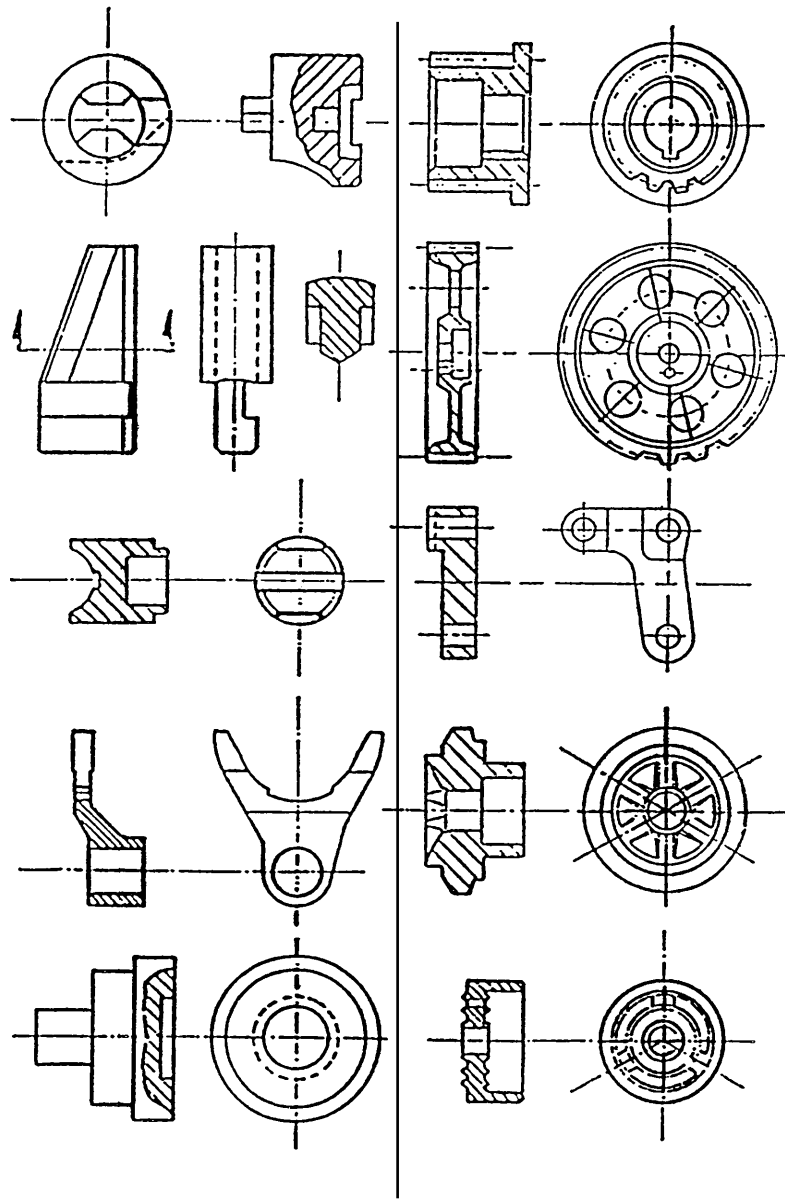


Figure 8.36.b. Selections of components with degrees of complexity 3, according to diagram in Figure 8.34.



Figure 8.37.a. Selections of components with degree of complexity 4 according to diagram in Figure 8.34.

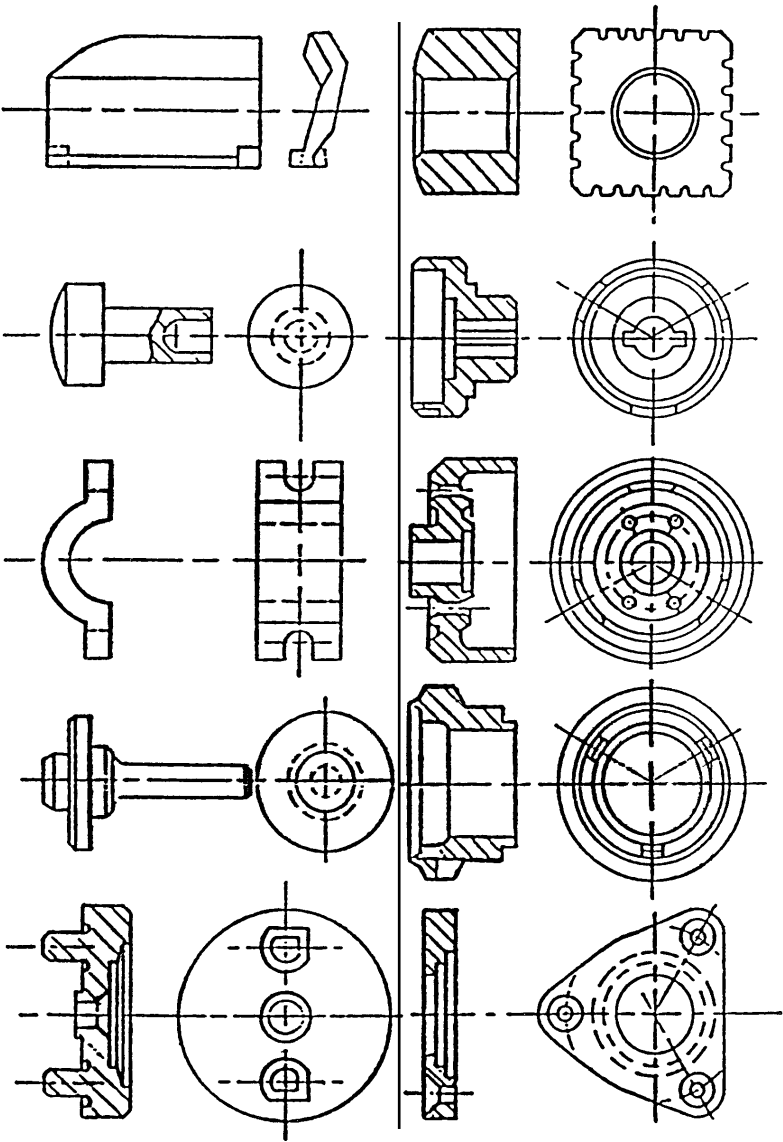


Figure 8.37.b. Selections of components with degree of complexity 4, according to diagram in Figure 8.34.



Figure 8.38.a. Selections of components with degree of complexity 5 according to diagram in Figure 8.34.

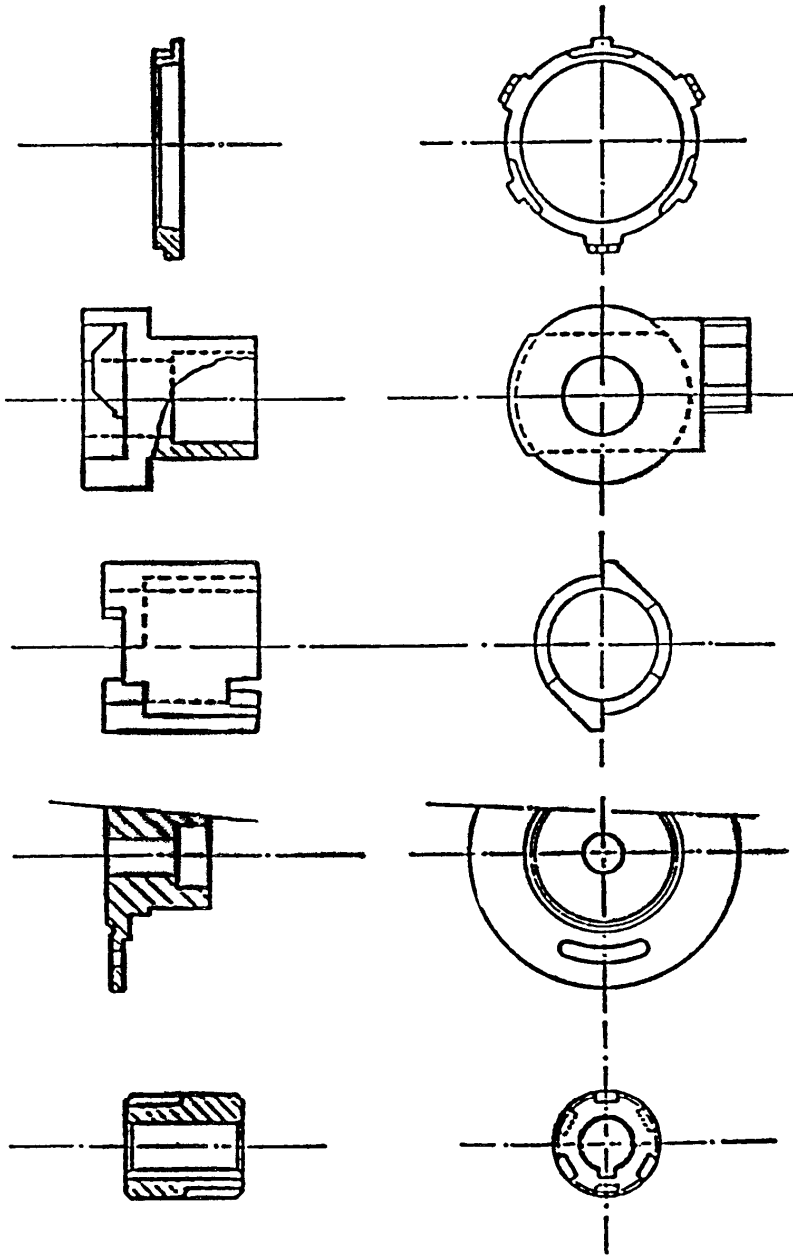


Figure 8.38.b. Selections of components with degree of complexity 5, according to diagram in figure 8.34.



Figure 8.39 Component with degree of complexity 8 according to diagram in Figure 8.34

8.5 Concluding Remarks

Experience tells that the unique design possibilities of P/M-processing are not automatically evident to all consumers of structural parts.

When a designer of machine components is unfamiliar with the possibilities and preconditions of P/M-processing, he designs, in the first instance, for conventional manufacturing methods. First in a relatively late phase of development, when an intended new component turns out to be too complicated or too expensive to be produced by conventional methods, the designer turns to P/M-processing as a last resort. But then, it may already be too late.

Although, P/M-processing, in principle, could offer a suitable or even better solution to the problem, adapting the component's design to P/M-processing may be unacceptable, in this late phase of development, because it entails a change of the entire assembly in which the component is integrated.

Earliest and closest possible cooperation on the designer level between consumer and producer is to the benefit of both.

This chapter deals with the characteristics of sintered iron-based materials for the industrial production of structural parts with closely controlled dimensional and physical properties.

Sintered Iron-Based Materials



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9.2	Alloying Systems, Microstructures and Properties.	51
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9.1 General Aspects

There are several ways to achieve desired strength properties with iron-based sintered materials. The most important parameters of influence are:

- Density
- Sintering conditions
- Alloying elements
- Heat-treating conditions

These parameters should be controlled within the closest possible limits, because even small variations may cause unacceptably wide scatter of dimensional changes during sintering and thus spoil the dimensional stability of the sintered parts.

Density is of prime importance with respect to the mechanical properties of sintered structural parts, because tensile strength and fatigue strength increase in approximate linear proportion, elongation and impact strength exponentially, with sintered density. See schematic diagram in *Fig. 9.1*.

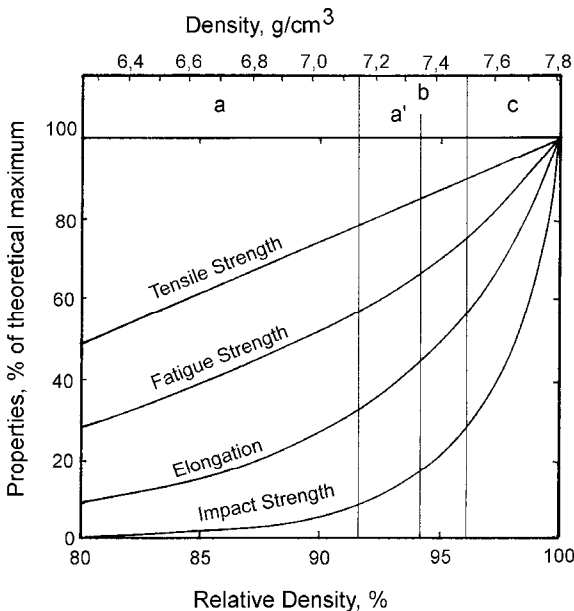


Figure 9.1. Increase of sintered properties with sintered density. Schematically,
 a = compacting + sintering.
 a' = warm die compacting
 b = compacting + sintering + re-pressing + re-sintering
 c = powder forging

Sintered density mainly depends on compact density which, in turn, depends on compaction pressure and lubricant system. Compaction pressures higher than about 650 N/mm^2 are not normally practiced because of the risk of over-stressing the compacting tool.

With maximum pressing loads tolerable under mass production conditions ($600 - 650 \text{ N/mm}^2$), densities up to $7.1 - 7.2 \text{ g/cm}^3$ are achievable. This density range can be extended up to $7.3 - 7.4 \text{ g/cm}^3$ when utilizing a warm-pressing technique developed by Höganäs.

Densities up to $7.5 - 7.6 \text{ g/cm}^3$ can only be achieved by pre-sintering and re-pressing the compacts before final sintering (chapter 7. § 7.2). Still higher densities, up to $7.7 - 7.8 \text{ g/cm}^3$, can be achieved by means of hot-forging pre-pressed (and pre-sintered) compacts.

Sintering conditions decide (1) how fast and efficient powder particles in the compact weld together and pores get rounded, (2) how fast homogenization of alloying elements takes place (chapter 6. § 6.2) and (3) whether sensitive alloying elements oxidize or not (chapter 6. § 6.4).

In iron powder metallurgy, sintering is most commonly carried out in continuous mesh-belt furnaces operating at 1120 to max. 1150°C . Sintering temperatures of $1250 - 1350^\circ\text{C}$ accelerate the homogenization of alloying elements and are beneficial when using oxygen-sensitive alloying elements like chromium and manganese. With modern materials and furnaces, chromium alloys can now be sintered at 1120°C . Mesh-belt furnaces cannot withstand temperatures above 1150°C .

Time at peak temperature is usually no longer than 20 to 30 minutes, since longer sintering times yield only marginally improved properties which do not justify the increased sintering costs.

Alloying elements dissolved in the base metal, give rise to the formation of various microstructures and increase the materials resistance to deformation. *See Fig. 9.2a*. Alloying elements also influence the dimensional change of structural parts during sintering. Alloying elements are indispensable with respect to the hardenability of conventional as well as sintered steels. *See Fig. 9.2b*.

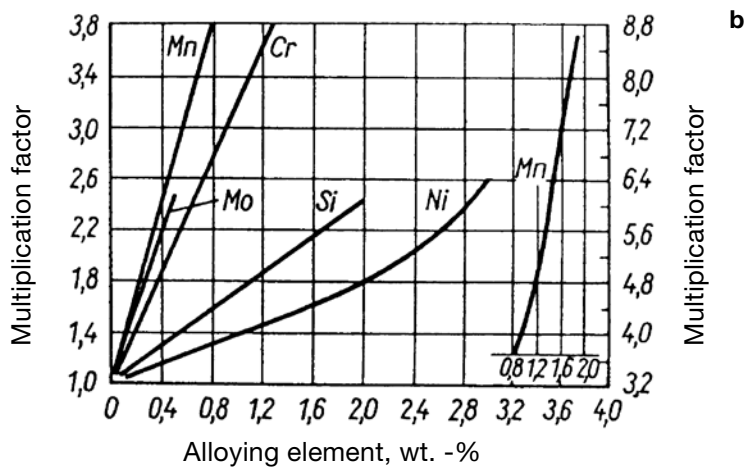
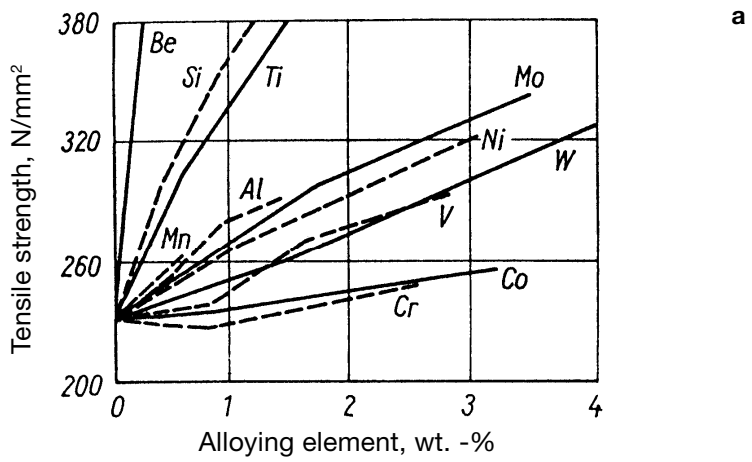


Figure 9.2. Influence of alloying elements upon tensile strength (a) and hardenability (b)

In principle, alloying elements have the same effect on sintered steels as on conventional steels. However, not all alloying elements common in conventional steels can be utilized in sintered steels because some of them, as e.g. Mn and V, are too easily oxidized in commercial sintering atmospheres (chapter 6. § 6.4). On the other hand, elements undesirable in conventional steels, like e.g. phosphorous ("blue brittleness"), can have beneficial effects on sintered steels (chapter 6. § 6.2.4).

Alloy compositions of sintered steels for structural parts have to be carefully selected not only with respect to desired strength but also with respect to dimensional stability during sintering. With alloy compositions yielding hardness levels above 150 - 180 HV, it is important that dimensional changes of the structural parts during sintering are as small as possible and even more important, that the scatter of these dimensional changes is kept within the closest possible limits.

While parts with hardnesses up to 150 HV can be sized or coined fairly easily, sizing or coining becomes increasingly difficult and eventually impossible the more their hardness exceeds this level. In the mass production of high-strength high-precision parts, it is therefore important that dimensional changes during sintering (and subsequent heat-treatment) are insensitive to the small unavoidable variations in process parameters and material composition.

Heat-treating conditions, when applied to sintered steel components, must be especially well controlled to ensure the highest possible degree of dimensional stability of the component in the hardening and tempering procedure. Asymmetric cooling during quenching of a sintered component, especially when of complex shape, may lead to distortions so severe that the part must either be rejected or subjected to expensive re-machining which would wipe out the cost advantage of P/M technology over conventional production methods.

Dimensional stability of the sintered parts depends on the accuracy with which the above mentioned parameters can be controlled. Two examples shown in Fig. 9.3 illustrate the influence of small variations in compact density, sintering conditions and powder composition on the dimensional changes of powder compacts during sintering. It can be seen from these examples that intelligently chosen types and amounts of alloying elements can make dimensional changes of sintered compacts less sensitive to varying processing parameters.

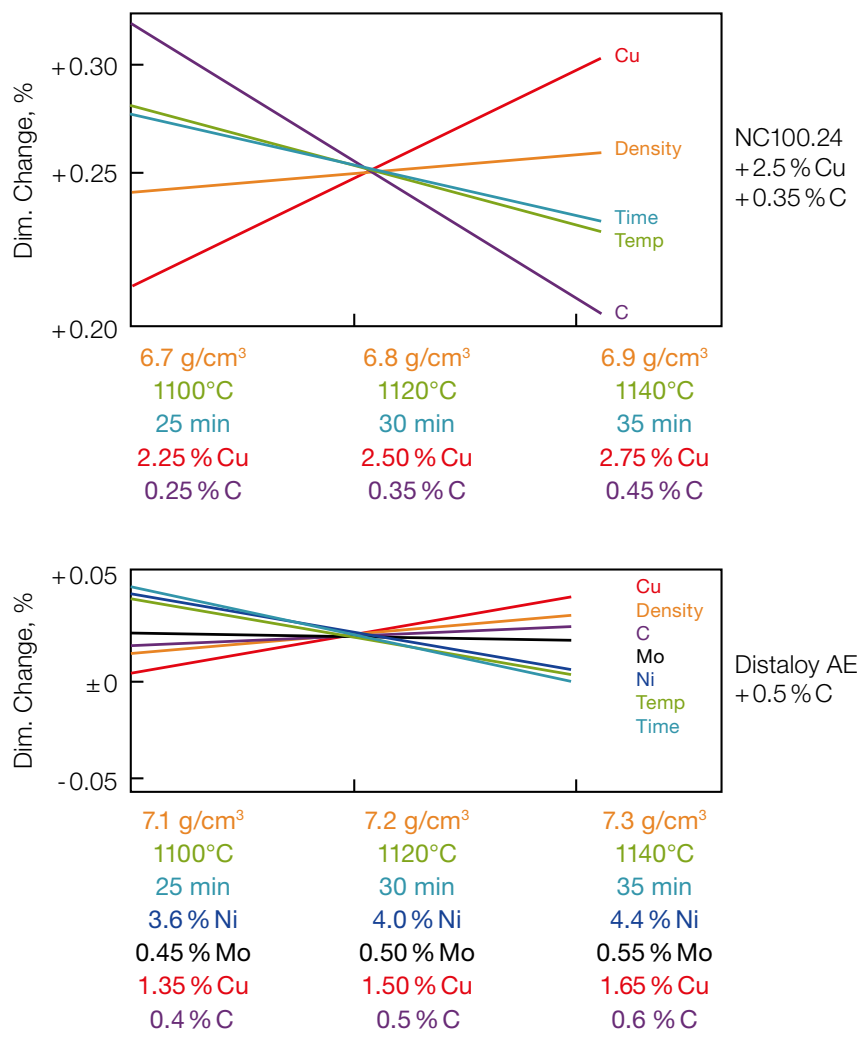


Figure 9.3. Influence of variations in compact density, sintering conditions and powder composition on dimensional changes during sintering.

9.2 Alloying Systems, Microstructures and Properties

In the majority of cases, sintered iron and steel components are today made of materials based on one or the other of the following alloying systems:

- Plain Iron
- Iron - Carbon
- Iron - Copper
- Iron - Copper - Carbon
- Iron - Phosphorus - Carbon
- Iron - Copper - Nickel - Carbon
- Iron - Copper - Nickel - Molybdenum - Carbon
- Iron - Nickel - Molybdenum - Carbon
- Iron - Chromium - Molybdenum - Carbon
- Iron - Chromium - Carbon

These materials are often mechanical mixtures of plain iron powder with the respective elements and some lubricant in powder form. Such mixtures can be compacted more easily than fully pre-alloyed powders. However, mechanical powder mixtures tend to segregate when transported and handled. Therefore are many of these materials today available in the form of partially pre-alloyed non-segregable press-ready powder mixes known under the trade-names Distaloy® and Starmix® (chapter 3).

Microstructures of sintered alloyed steels, produced from powder mixes, are typically much more heterogeneous than those of conventionally alloyed steels. While carbon diffuses very rapidly in the basic iron powder and soon reaches equilibrium during sintering, other alloying elements like copper, nickel and molybdenum diffuse much slower and would reach equilibrium only after extremely long sintering times (*chapter 6, Fig. 6.9*). Hence, produced under commercially acceptable sintering conditions, these materials will always exhibit a certain degree of heterogeneity. For subsequent heat treatment fully pre-alloyed materials are sometimes preferred.

9.2.1 Plain Iron

Ever since the late 1930's, when powder metallurgy methods were first being utilized on a larger industrial scale in Europe and in the USA, self-lubricating bearings and sintered structural parts for low-strength and soft-magnetic applications have been produced from plain iron powders. *Fig. 9.4* shows the microstructure of a plain sponge iron powder (NC100.24) compacted to a density of 7.10 g/cm^3 .

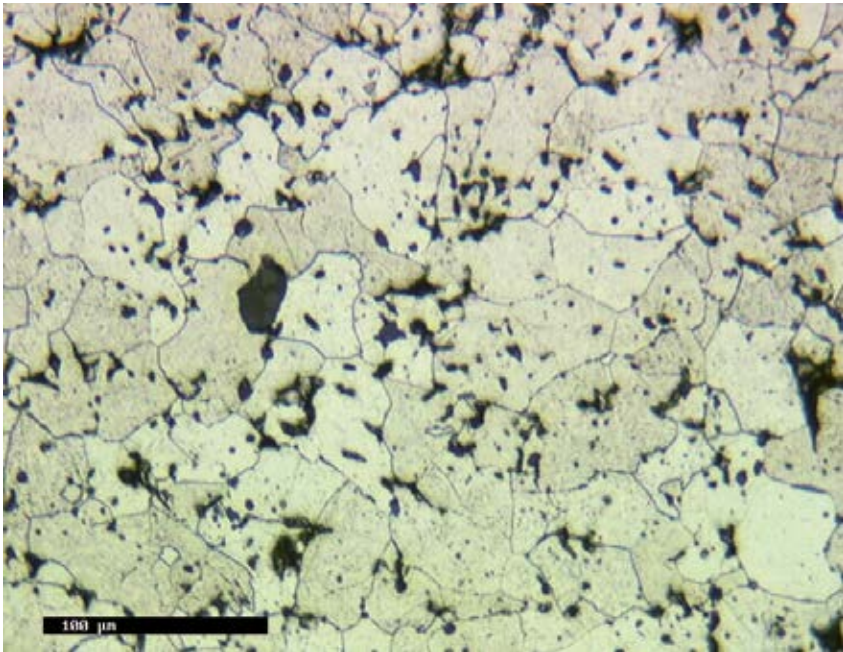


Figure 9.4. Microstructure of NC100.24, sintered 30 min at 1120°C . Sintered density: 7.10 g/cm^3 .

Fig. 9.5 shows the microstructure of a plain atomized iron powder (ASC100.29) compacted to a density of 7.10 g/cm^3 . Both materials have been sintered for 30 min at 1120°C in $90\% \text{ N}_2 + 10\% \text{ H}_2$.

Despite comparable densities and identical sintering conditions, the two materials differ significantly with respect to both grain size and pore structure, the NC100.24-material having a smaller grain size and a more finely dispersed pore structure than the ASC100.29-material. Note that a considerably lower compacting pressure was sufficient to compact ASC100.29 to almost the same density as NC100.24.

Grain size is a parameter which has an important influence upon the physical properties of plain iron. With decreasing grain size, strength generally increases, but with increasing grain size, ductility and soft-magnetic properties are improving. Thus, for high-density soft-magnetic applications, ASC100.29 is a good choice. On the other hand, NC100.24, because of its superior green strength after compacting, is the better choice for self-lubricating bearings with high porosity and for complex low- to medium-strength structural parts. In order to achieve strength levels above 200 N/mm^2 with plain sintered iron, densities above 7.2 g/cm^3 are necessary.

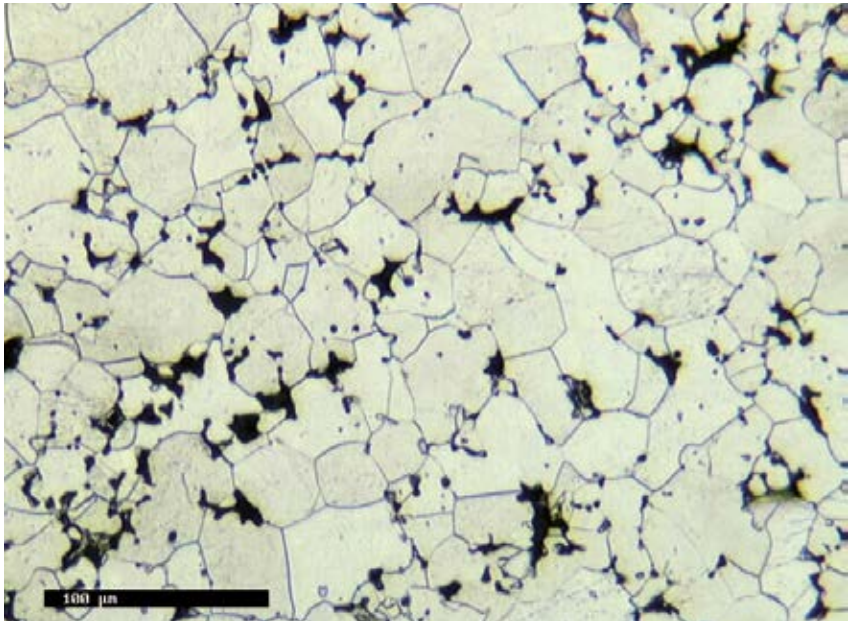


Figure 9.5. Microstructure of ASC100.29, sintered 30 min at 1120°C . Sintered density: 7.10 g/cm^3 .

9.2.2 Iron - Carbon

A very efficient way to boost tensile strength and hardness of sintered iron is to alloy it with carbon. Most conveniently, this is achieved by adding graphite powder to the iron powder before compacting and sintering. Being an interstitial alloying element, carbon dissolves very rapidly in the iron powder structure during sintering. However, successful sintering of carbon containing materials requires a very carefully controlled non-decarburizing sintering atmosphere (chapter 6, § 6.4).

Fig. 9.6 shows the microstructures of two sintered iron-carbon steels containing 0.2 and 0.5 wt.-% dissolved carbon respectively. Areas of pearlite and ferrite are clearly visible. Both materials were made from atomized iron powder (ASC100.29), sintered for 30 min at 1120°C in 90% N₂ + 10% H₂ and having a sintered density of 7.10 g/cm³.

Apart from the presence of pores, these microstructures are practically identical with those of corresponding conventional plain carbon steels. The effect of dissolved carbon on tensile strength, elongation and dimensional change of sintered iron is shown in the diagram in *Fig. 9.7*. In sintered as well as in conventional carbon steels, carbon contents above 0.8 wt.-% produce a brittle cementite network in the former austenite grain boundaries and should be avoided.

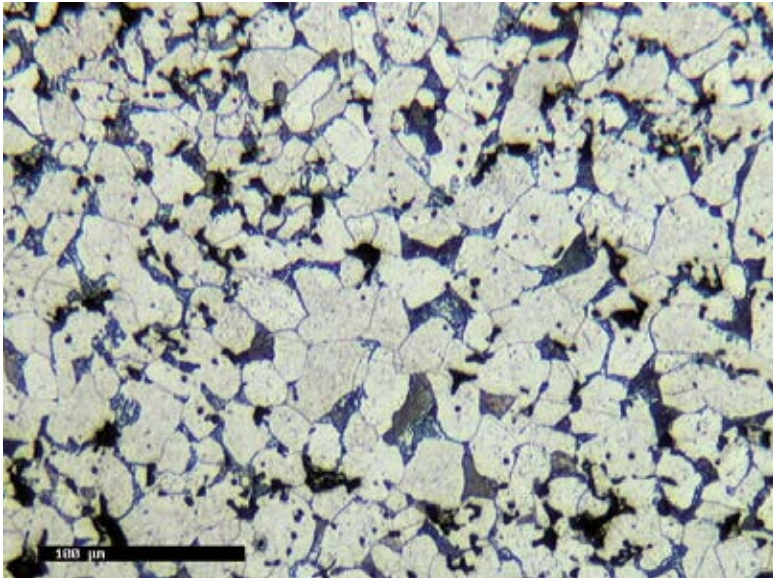
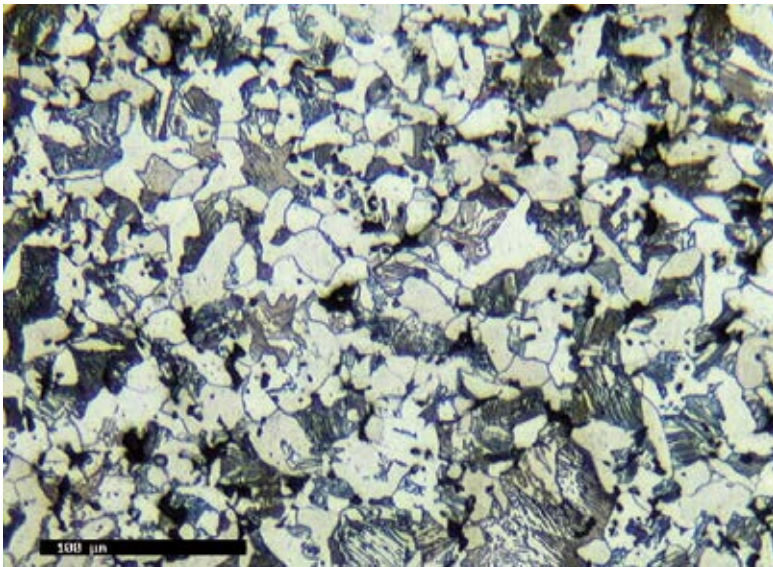
**a****b**

Figure 9.6. Microstructures of (a) ASC100.29 + 0.2% C and (b) ASC100.29 + 0.5% C, both materials sintered 30 min at 1120°C. Sintered density: 7.10 g/cm³ for both.

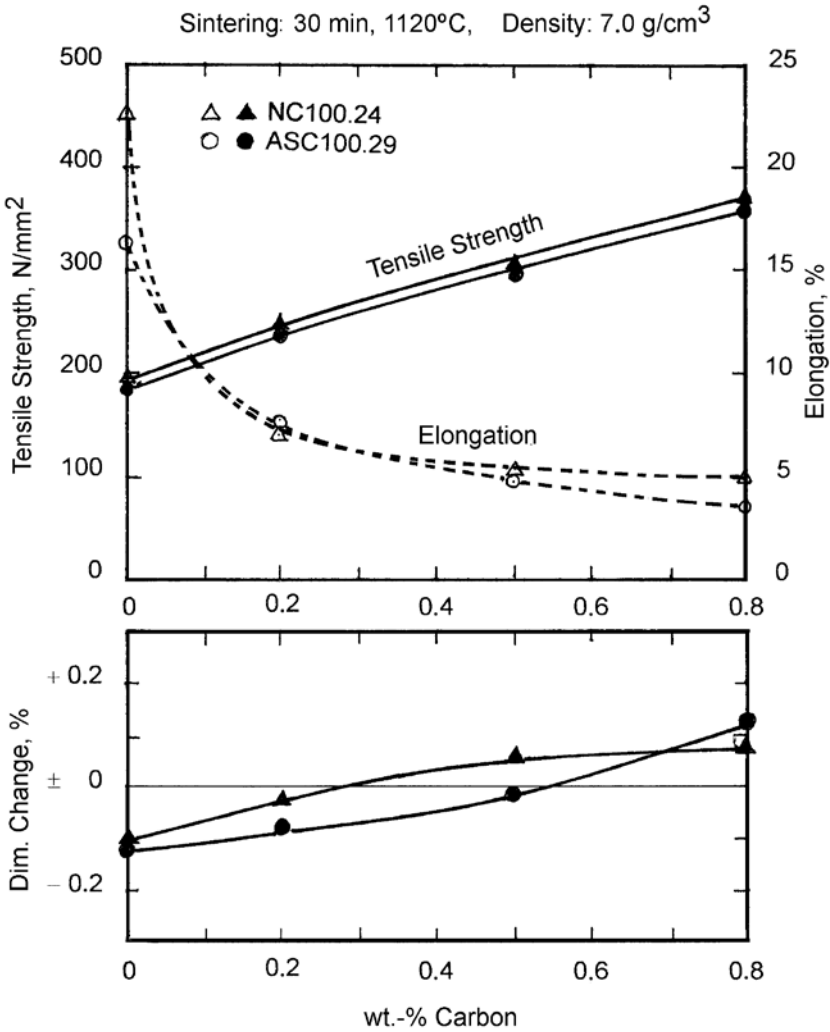


Figure 9.7. Influence of carbon content upon the properties of sintered iron.

9.2.3 Iron - Copper, Iron - Copper - Carbon

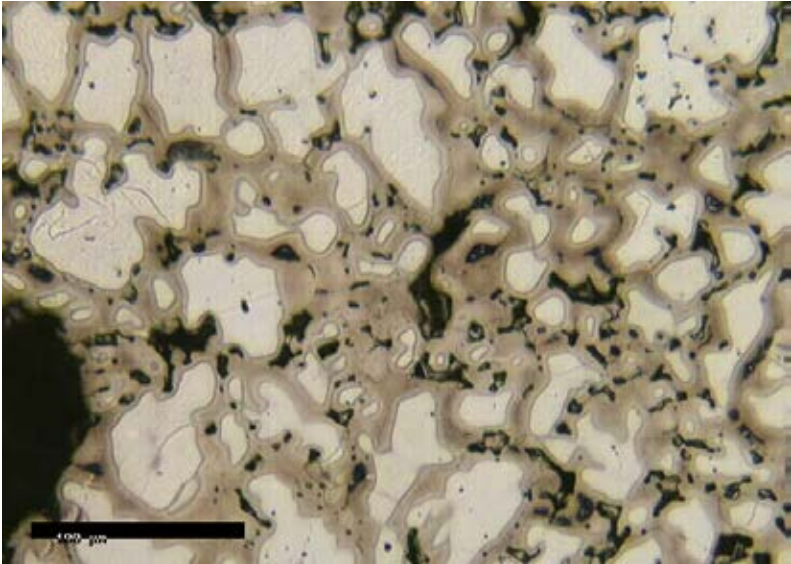
Mixtures of iron and copper powder have a twofold benefit:

1. Copper melts at 1083°C, i.e. below sintering temperature and rapidly infiltrates the pore system of the compact from where it diffuses relatively easily into the iron powder particles.
2. Copper is dissolvable in γ -iron (austenite) up to approx. 9 wt.-%, but only up to 0.4 wt.-% in α -iron (ferrite) at room temperature; consequently, iron-copper alloys can be precipitation-hardened by low-temperature annealing after sintering – and actually do so to a certain extent already on passing the cooling zone of the sintering furnace.

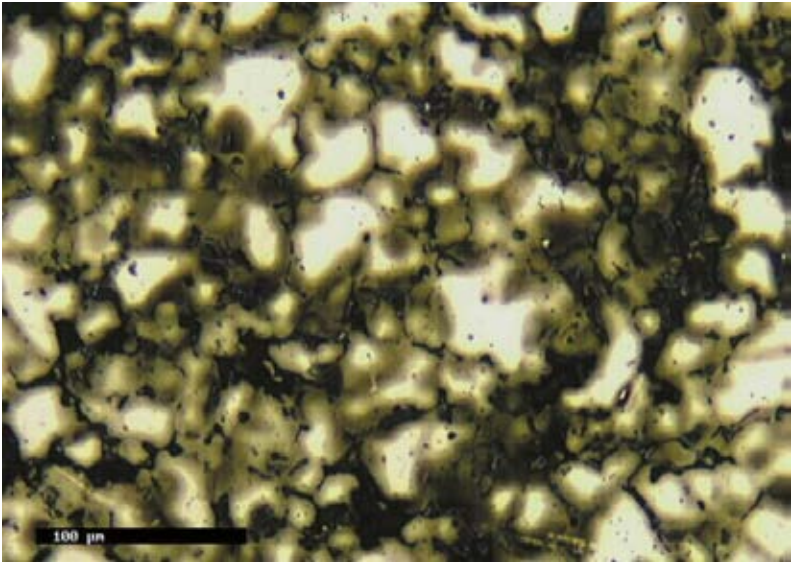
Copper is added to the basic iron powder usually in amounts from 1.5 to 4 wt.-%.

Fig. 9.8 shows the microstructures of two iron-copper materials containing 2 and 4 wt.-% admixed copper respectively, compacted to densities of approx. 7.10 g/cm³ and sintered for 30 minutes at 1120°C. As can be seen, the copper is not completely homogeneously distributed in the iron matrix after sintering.

Regions of higher copper concentration appear on the micrographs as brownish seams along grain boundaries and former iron particle surfaces.



a



b

Figure 9.8. Microstructures of (a) ASC100.29 + 2% Cu and (b) ASC100.29 + 4% Cu, both materials sintered 30 min at 1120°C. Sintered density: 7.10 g/cm³ for both.

With copper contents higher than about 2.5 wt.-%, compacts tend to grow to such extent during sintering that their dimensional tolerances are difficult to control. To maintain, during sintering, the dimensional stability of copper-containing structural parts, suitable amounts of graphite are added to the iron-copper powder mix. The carburizing effect of graphite during sintering counteracts the growth-producing effect of copper (*chapter 6, Fig. 6.18*).

A further beneficial effect of these graphite additions is an additional increase in strength. The diagram in *Fig. 9.9* illustrates the effect of carbon additions on tensile strength, elongation and dimensional changes of sintered iron-copper materials.

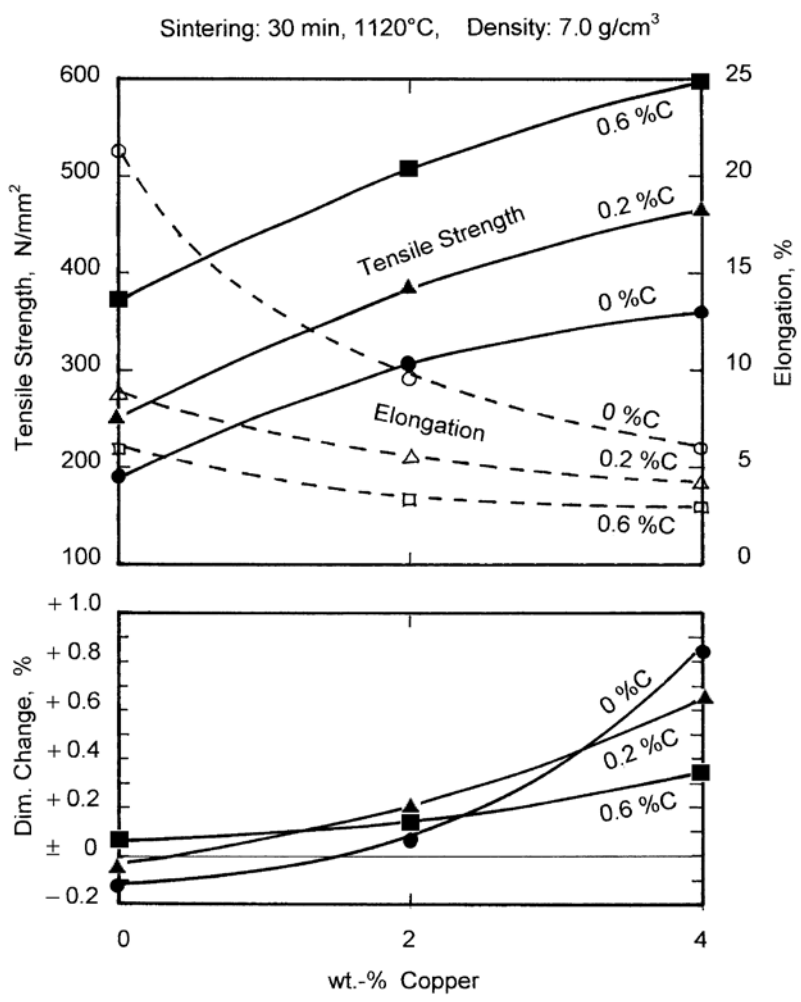
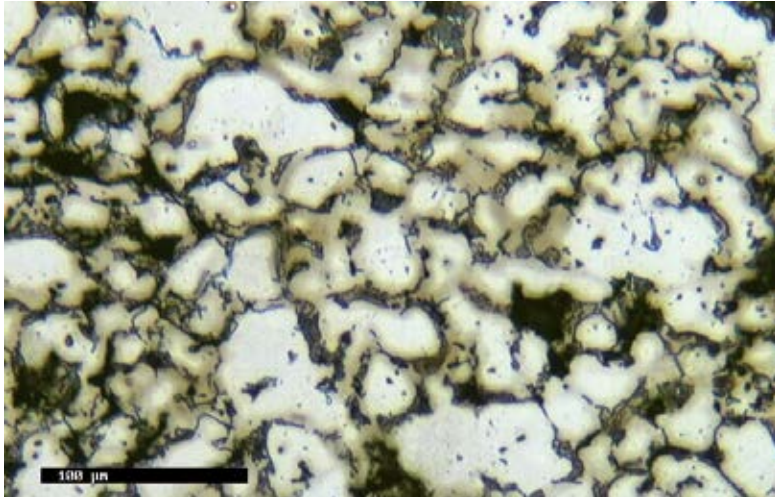


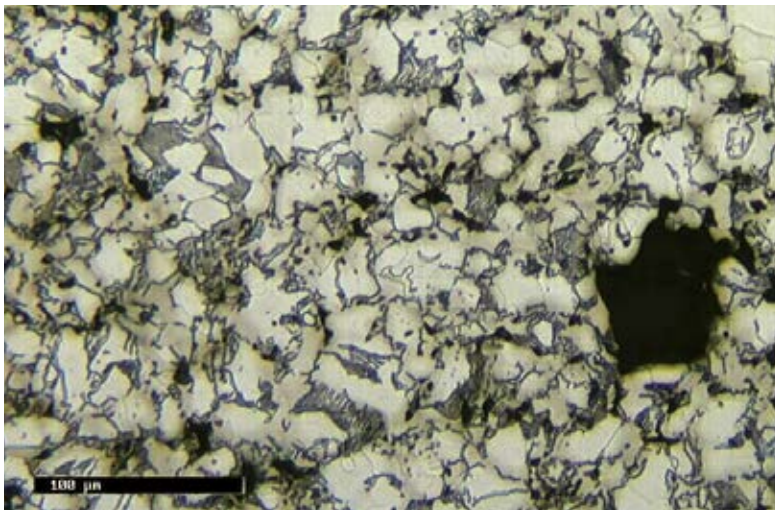
Figure 9.9 Influence of carbon content upon the properties of sintered iron-copper materials. Base powder NC100.24.

Fig. 9.10 shows the microstructures of two iron-copper materials containing 2 wt.-% copper and 0.2 resp. 0.6 wt.-% carbon, compacted to densities of approx. 7.10 g/cm³ and sintered for 30 minutes at 1120°C in endogas. On the micrograph taken of the material with 0.2 wt.-% carbon, it appears that dissolved copper concentrates in carbon-rich areas of the iron structure where it has partly disintegrated the pearlite. It is likely that copper, during heating-up to sintering

temperature, has preferably penetrated the boundaries between ferrite and cementite lamellae, while austenitization of pearlitic areas was delayed (chapter 6, § 6.2.3). In the material with 0.6 wt.-% carbon, copper appears to be more homogeneously distributed.



a



b

Figure 9.10. Microstructures of (a) SC100.26 + 2% Cu + 0.2% C and (b) SC100.26 + 2% Cu + 0.6% C, both materials sintered 30 min at 1120°C. Sintered density: 7.10 g/cm³ for both.

9.2.4 Iron - Phosphorus - Carbon

In conventional steel-making, phosphorus is a most undesirable element since it provokes irreparable segregation during solidification which make the steel brittle. In iron powder metallurgy, however, phosphorus has proven to be a very potential strength-increasing alloying element. Here, phosphorus is normally added to iron powder as a very finely ground Fe_3P -powder which, compared with other phosphorus compounds, is relatively soft and less harmful to compacting tools.

During sintering, phosphorus and iron form an eutectic melt (10% P, 1050°C) which rapidly infiltrates the pore system of the compact and enhances the sintering process (*see chapter 6, Fig.6.15*).

The diagram in *Fig. 9.11* shows the influence of phosphorus and carbon upon tensile strength, elongation and dimensional change. A comparison of this diagram with the one in *Fig. 9.9* is most interesting. In both cases, the basic iron powder is NC100.24. As can be seen, additions of 0.3 to 0.6% phosphorus have a very similar effect on tensile strength and elongation as additions of 2 to 4% copper. However, phosphorus additions affect the dimensional change during sintering to a much lesser degree than copper additions and produce shrinkage rather than growth of the sintered parts.

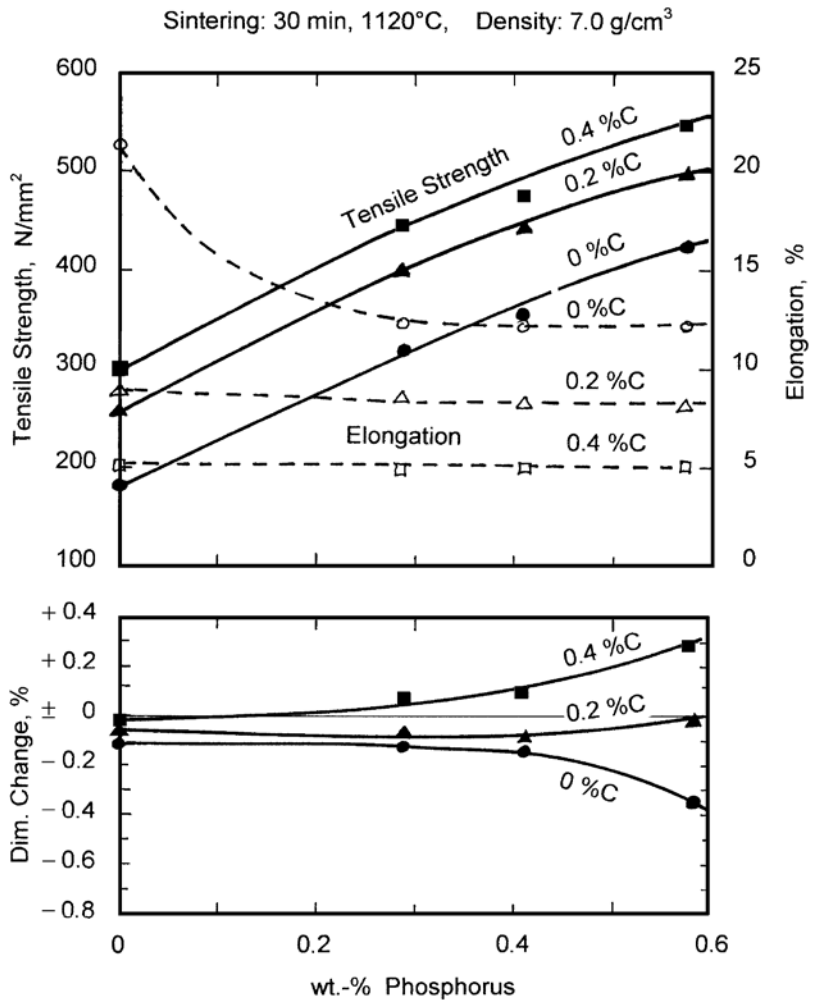


Figure 9.11 Influence of phosphorus and carbon additions upon the properties of sintered iron materials. Base powder NC100.24.

Fig. 9.12 shows the micrographs of two sintered materials containing 0.45% phosphorus, one without and one with 0.5% carbon. Note the rounded-off pores of medium size and the absence of small pores.

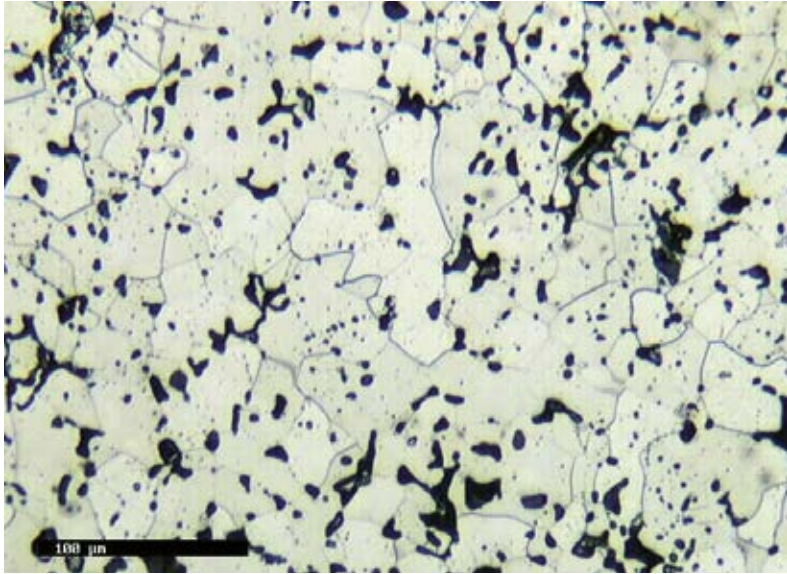
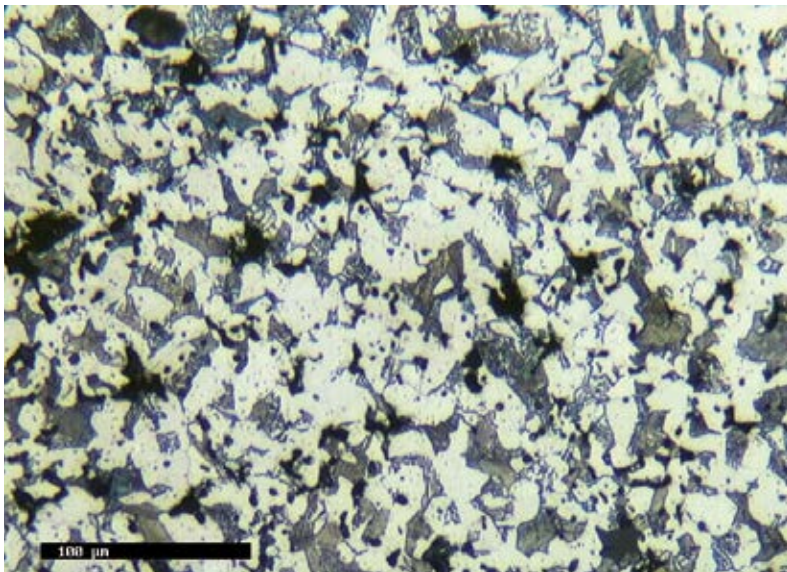
**a****b**

Figure 9.12. Microstructures of (a) NC100.24 + 0.45% P and (b) NC100.24 + 0.45% P + 0.5% C, both materials sintered 30 min at 1120°C. Sintered density: 7.10 g/cm³ for both.

This particular pore structure has a very beneficial influence on impact strength – a phenomenon which can be explained in terms of a substantially reduced notch effect. See Fig. 9.13.

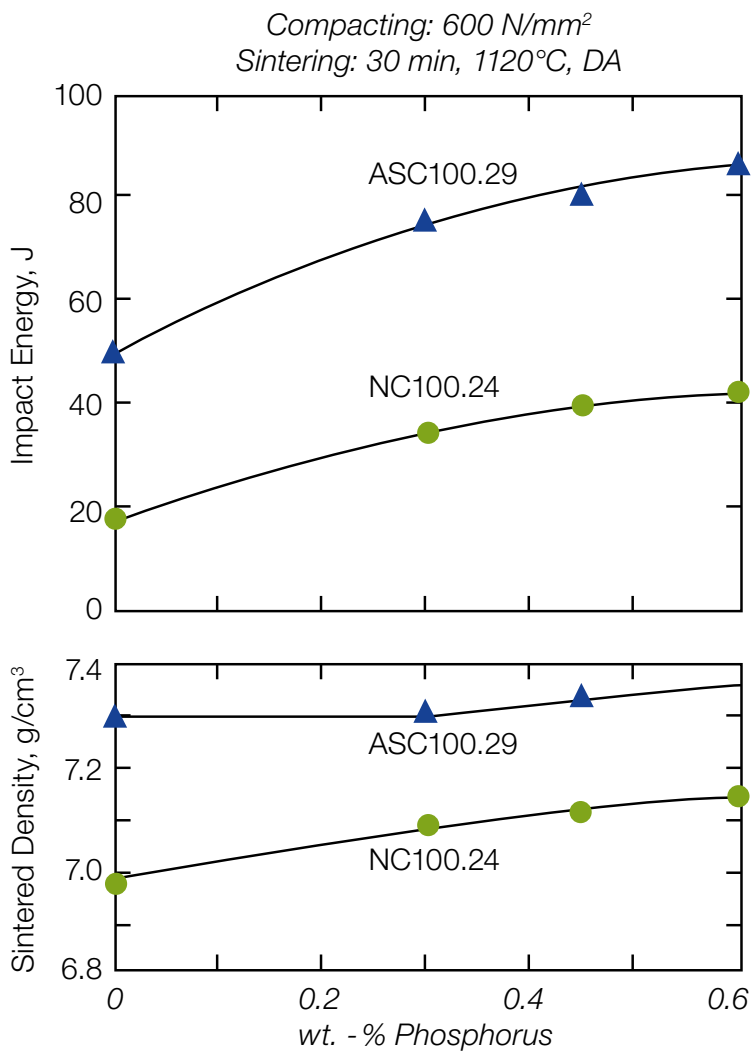


Figure 9.13 Influence of phosphorus additions upon impact strength of sintered iron materials.

9.2.5 Iron - Copper - Nickel - Carbon

Adding nickel to iron-copper and iron-copper-carbon mixes has approximately the same effect on tensile strength and elongation as increasing the copper content. However, the essential advantage in substituting some of the copper with nickel is a considerable reduction of the dimensional change during sintering.

See Fig. 9.14 where tensile strength, elongation and dimensional change of sintered parts, made of mixes containing varying amounts of copper and nickel, are shown in comparison.

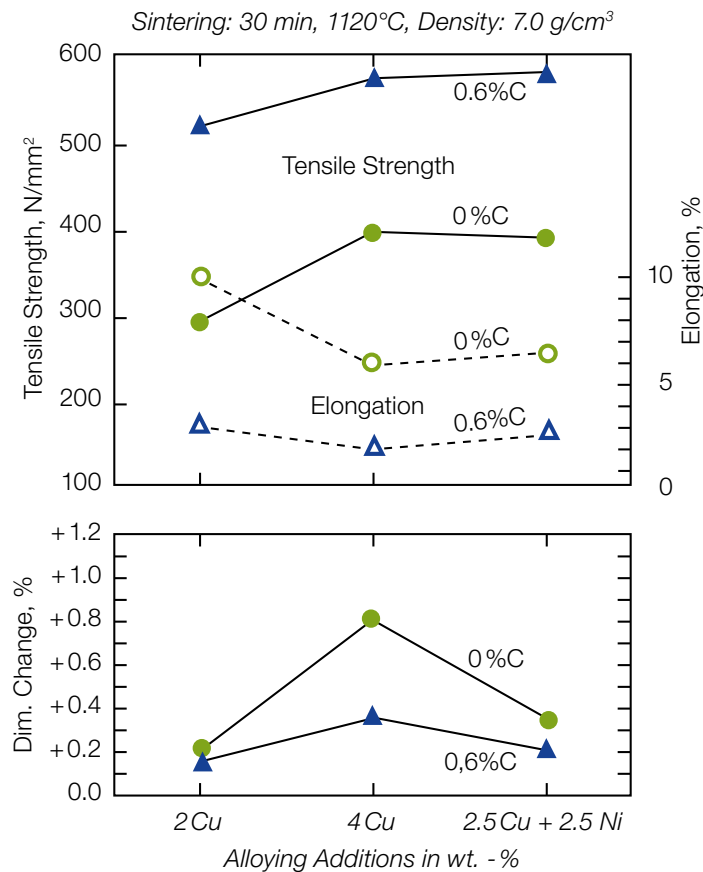


Figure 9.14 Influence of varying proportions of nickel and copper additions upon the properties of sintered iron materials.

Fig. 9.15 shows the microstructure of a sintered iron-based material, containing 2.0% Cu+2.5% Ni+0.6% C.

On the microstructure of the carbon containing material, apart from ferrite and pearlite, small areas of nickel-rich austenite appear in the neighbourhood of pores and former particle surfaces. Locally, the nickel concentration is so high, that the normal cooling rate after sintering was sufficient to produce small spots of martensite.

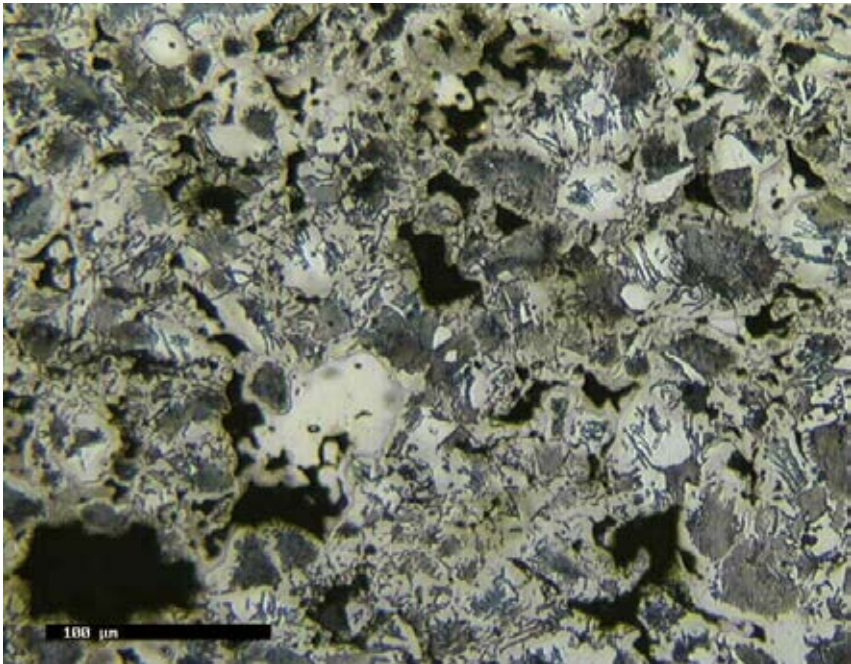


Figure 9.15. Microstructure of SC100.26 +2.0% Cu + 2.5% Ni + 0.6% C, sintered 30 min at 1120°C. Sintered density: 7.10 g/cm³.

9.2.6 Iron - Copper - Nickel - Molybdenum - Carbon

Höganäs has developed a variety of materials containing Mo in combination with Ni or Cu, or both Ni and Cu, which have proven very successful in the production of structural parts for high-strength and high-accuracy applications. Some of these materials are homogenous alloys with the trade-name Astaloy™, but most of them are partially pre-alloyed non-segregable powder mixes with the trade-name Distaloy®.

Mixed with appropriate amounts of graphite, Astaloy™ and Distaloy® materials, yield high strength properties, show good dimensional stability during sintering and respond very well to subsequent heat-treatment. The most common of these materials are listed and briefly characterized below.

Astaloy Mo is an atomized iron powder homogeneously alloyed with 1.5% Mo. It has high compressibility (only slightly lower than unalloyed atomized iron powder) and fair green-strength. With carbon additions of 0.2 to 0.6%, it has excellent hardenability.

Astaloy 85 Mo is an atomized iron powder homogeneously alloyed with 0.85% Mo. It has high compressibility (only slightly lower than unalloyed atomized iron powder) and fair green-strength. With carbon additions of 0.2 to 0.6%, it has very good hardenability.

Distaloy SA is based on the sponge iron grade SC100.26 to which 1.75% Ni, 1.5% Cu and 0.5% Mo have been diffusion-bonded. Being based on sponge iron powder, this material has high green-strength. Mixed with appropriate amounts of graphite it yields high strength after sintering and responds well to subsequent heat-treatment.

Distaloy AB has the same chemical composition as Distaloy SA but is based on the atomized iron powder grade ASC100.29. Being based on atomized iron powder, it has high compressibility. Mixed with appropriate amounts of graphite it yields high strength after sintering and responds well to subsequent heat-treatment.

Distaloy AE is based on the atomized iron powder grade ASC100.29 to which 4% Ni, 1.5% Cu and 0.5% Mo have been diffusion bonded. Being based on atomized iron powder, it has high compressibility. Mixed with appropriate amounts of graphite it yields high strength after sintering and responds very well to subsequent heat-treatment.

Distaloy DC contains 2% Ni and 1.47% Mo and is produced by diffusion-bonding of the Ni-powder to Astaloy Mo, an atomized iron powder homogeneously alloyed with 1.5% Mo. This material is especially designed to achieve very closely restricted dimensional scatter of the sintered components, irrespective of compact density. This makes the material ideal for components of intricate shape with internal density variations. With admixed graphite, this material ensures high strength after sintering as it forms a relatively large amount of bainite and some martensite at the low cooling rates (0.5 - 0.8°C/s) in the cooling zone of a common belt furnace.

(The letters **DC** stand for "Dimensional Control").

Distaloy DH contains 2% Cu and 1.47% Mo and is produced by diffusion-bonding 2% Cu-powder to Astaloy Mo. Admixed with graphite, this material can be transformed into a very hard martensitic-bainitic microstructure directly from sintering heat, when the belt furnace is equipped with a convective cooling system allowing cooling rates of 4 - 8°C/s. With these cooling rates, tensile strength values up to 1100 N/mm² (sintered density 7.0 g/cm³) are achievable. (The letters **DH** stand for "Direct Hardening").

Distaloy HP contains 4% Ni, 2% Cu and 1.41% Mo and is produced by diffusion-bonding 4% Ni-powder and 2% Cu-powder to Astaloy Mo. Because of its high nickel content, this material, admixed with graphite yields approx. 2 - 3% retained austenite. The combination of nickel and copper results in a dimensional change close to zero. Due to its high alloy content, the material has very high strength after sintering. Common sintering conditions and cooling rates in belt furnaces produce a microstructure of martensite and bainite. Tensile strength values between 950 and 1000 N/mm² (sintered density 7.0 g/cm³) can be achieved. (The letters **HP** stand for "High Performance").

The diagram in *Fig. 9.16* shows the influence of varying additions of copper and carbon on the sintered properties of Astaloy Mo.

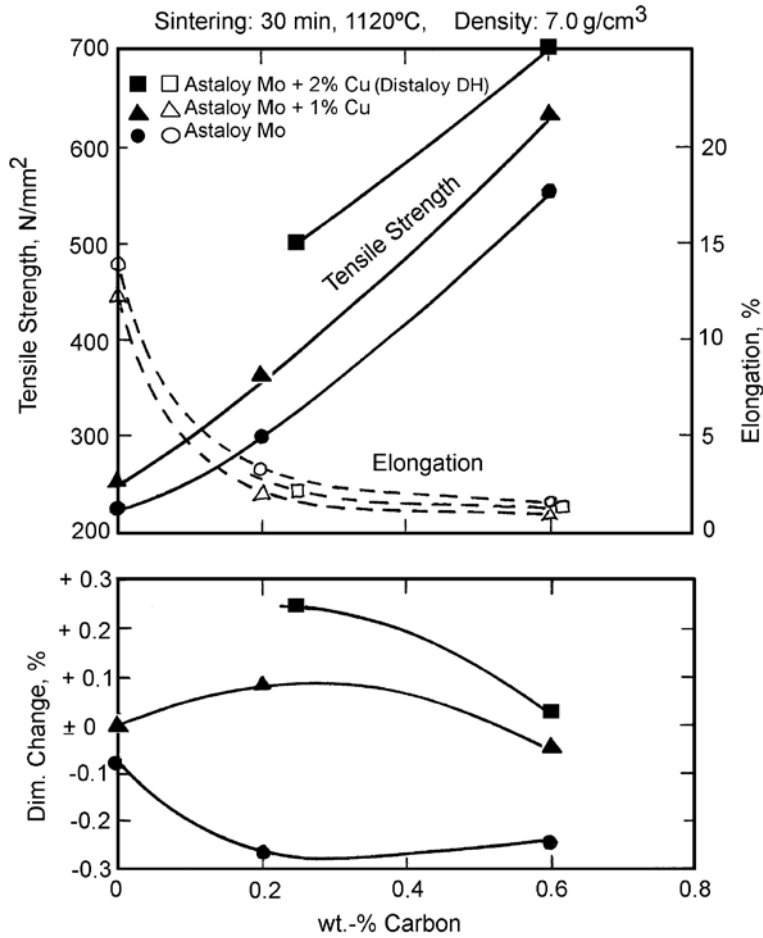


Figure 9.16 Influence of copper and carbon additions upon the properties of sintered iron materials pre-alloyed with molybdenum (Astaloy Mo).

9.2.7 Iron – Nickel – Molybdenum – Carbon

This alloying system offers a good combination of added strength and hardenability along with easy handling in terms of compaction and sintering. Depending on required properties of the final component, Höganäs has developed two different grades within this system.

Astaloy LH is fully pre-alloyed with 0.9% nickel and 0.9% molybdenum. This combination offers good hardenability and good compressibility. Furthermore, having a very robust dimensional change during sintering makes it suitable for high performance components requiring subsequent heat treatment. Addition of up to 2% copper makes this grade very well-suited for sinter-hardening. *Fig. 9.17* shows the microstructure of Astaloy LH + 2% Cu + 0.7% C, cooling rate 0.8°C/s. The structure is a mix of martensite and bainite and with increased cooling rate, it will be fully martensitic.



Figure 9.17 Microstructure of Astaloy LH + 2% Cu + 0.7% C, sintered at 1120 °C, 30 min.

Distaloy AQ is a pure iron powder to which 0.5% nickel and 0.5% molybdenum have been diffusion bonded. This grade was specifically developed for applications requiring a subsequent heat treatment such as case hardening or through hardening. After such heat treatments hardness and strength levels are comparable to those of much higher alloying contents. Another key characteristic is the excellent compressibility offered and a particular suitability for sizing after sintering, due to excellent ductility. *Fig. 9.18a* shows the as-sintered structure and *Fig. 9.18b* the structure after quench & temper.

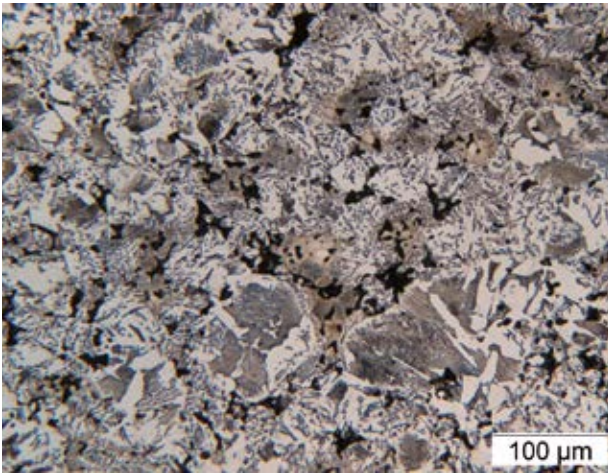
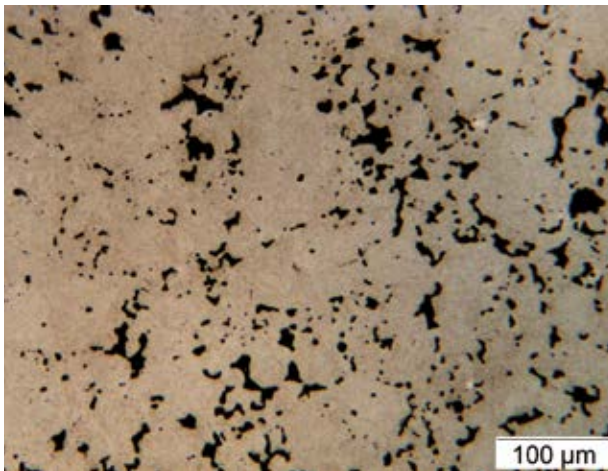
**a****b**

Figure 9.18 Microstructure of a) Distaloy AQ + 0.5% C, sintered at 1120 °C, 30 min. and b) Distaloy AQ with 0.6% C quenched and tempered.

9.2.8 Iron – Chromium – Molybdenum – Carbon

By introducing chromium as an alloying element in PM steels a very high hardenability may be combined with a low alloying cost. This has opened the door for very high performance as-sintered properties at a reasonable cost. The oxygen affinity of chromium does put some restrictions on sintering atmosphere. For example, endogas cannot be used due to its high oxygen partial pressure.

Astaloy CrM is fully pre-alloyed with 3% chromium and 0.5% molybdenum. Due to the high hardenability of these alloying elements a very high strength and hardness is achievable already after sintering and at moderate densities. It also offers a very good response to sinter-hardening. *Fig. 9.19* shows the martensitic structure in Astaloy CrM + 0.5% C with a cooling rate of 1 °C/s.

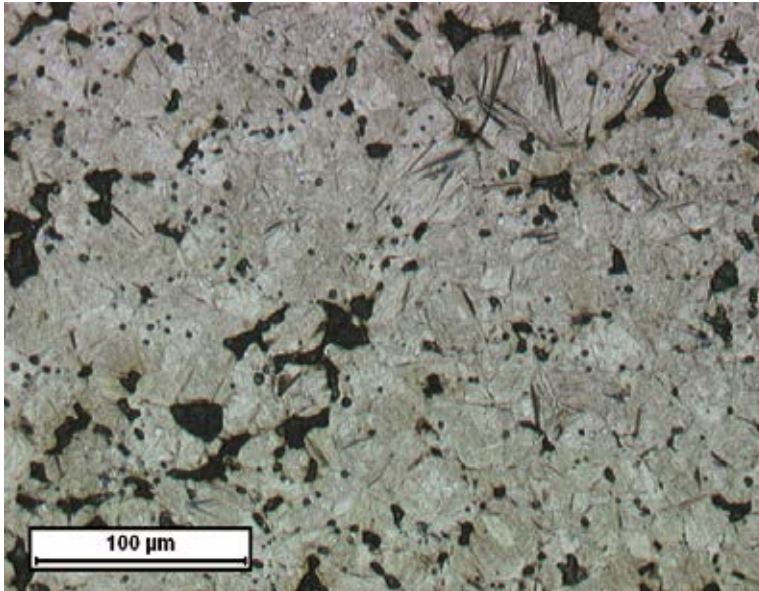


Figure 9.19 Microstructure of Astaloy CrM + 0.5% C, sintered at 1120 °C, 30 min with cooling rate 1 °C/s.

9.2.9 Iron – Chromium – Carbon

Astaloy CrA is fully pre-alloyed with 1.8% chromium, offering a combination of low cost, robust processing behaviour and high strength. Good compressibility and the ferrite/pearlite structure in as-sintered condition provide a very versatile grade. Addition of copper or nickel enables sinter-hardening for added strength. *Fig. 9.20* shows the fully pearlitic structure in Astaloy CrA + 0.8% C.

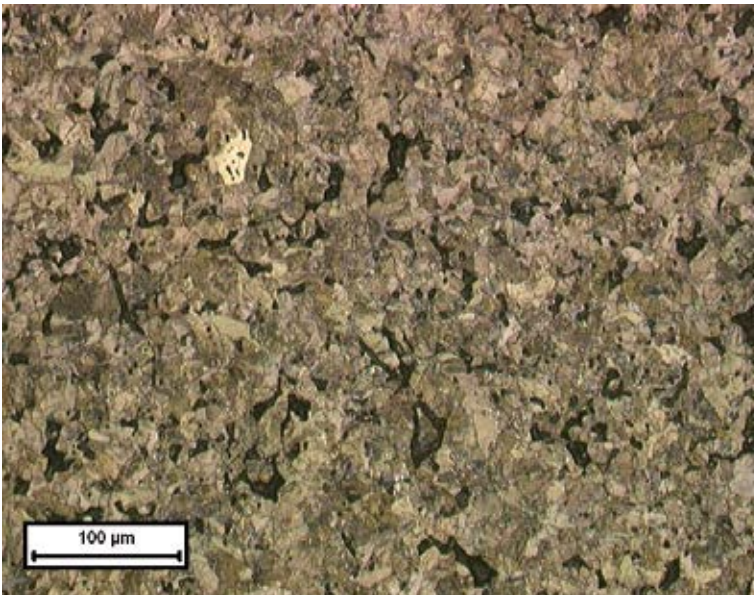


Figure 9.20 Microstructure of Astaloy CrA + 0.8% C, sintered at 1120 °C, 30 min.

9.2.10 Hardenability of Astaloy™ and Distaloy® materials

The strength properties of Astaloy™ and Distaloy® materials can be substantially increased by means of subsequent heat-treatment after sintering. The excellent hardenability of Astaloy™ and Distaloy® materials is illustrated by CCT-diagrams and related microstructures presented in *Figs. 9.21 to 9.25*. To establish such CCT-diagrams is a rather laborious affair. However, a rough guideline to the hardenability of a sintered iron-based material can be obtained conveniently by determining the microhardness as a function of distance from surface on a polished cross-section of a hardened sample of adequate size, e.g. a tensile-test bar.

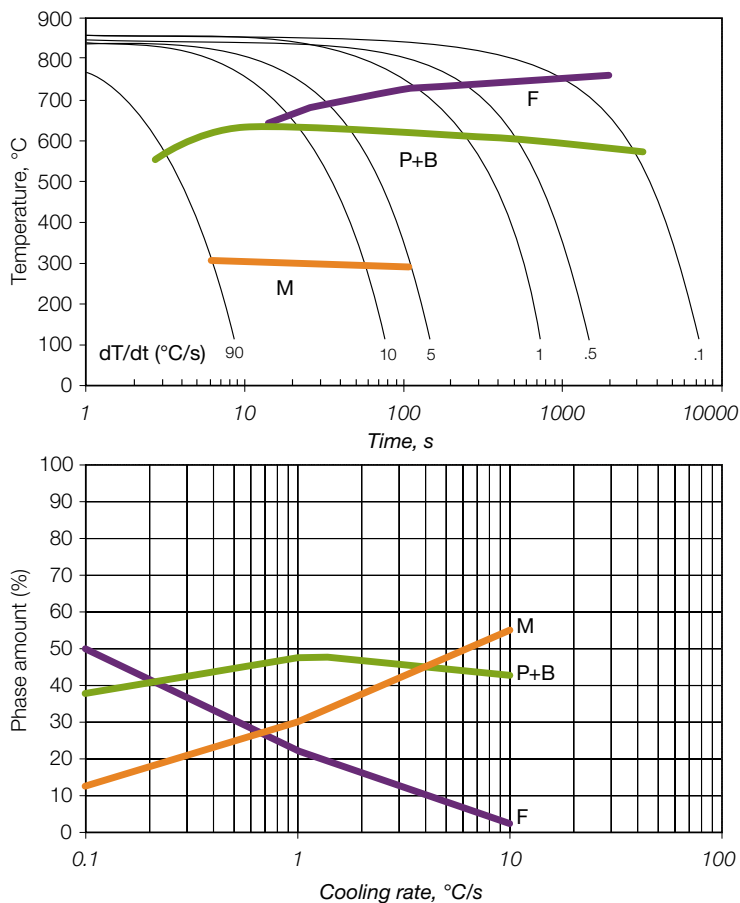


Figure 9.21.a. CCT-diagram for Distaloy SA + 0.45% C, sintered 30 min at 1120°C in endogas; cooling from 850°C. F=Ferrite, P=Pearlite, B=Bainite, M=Martensite

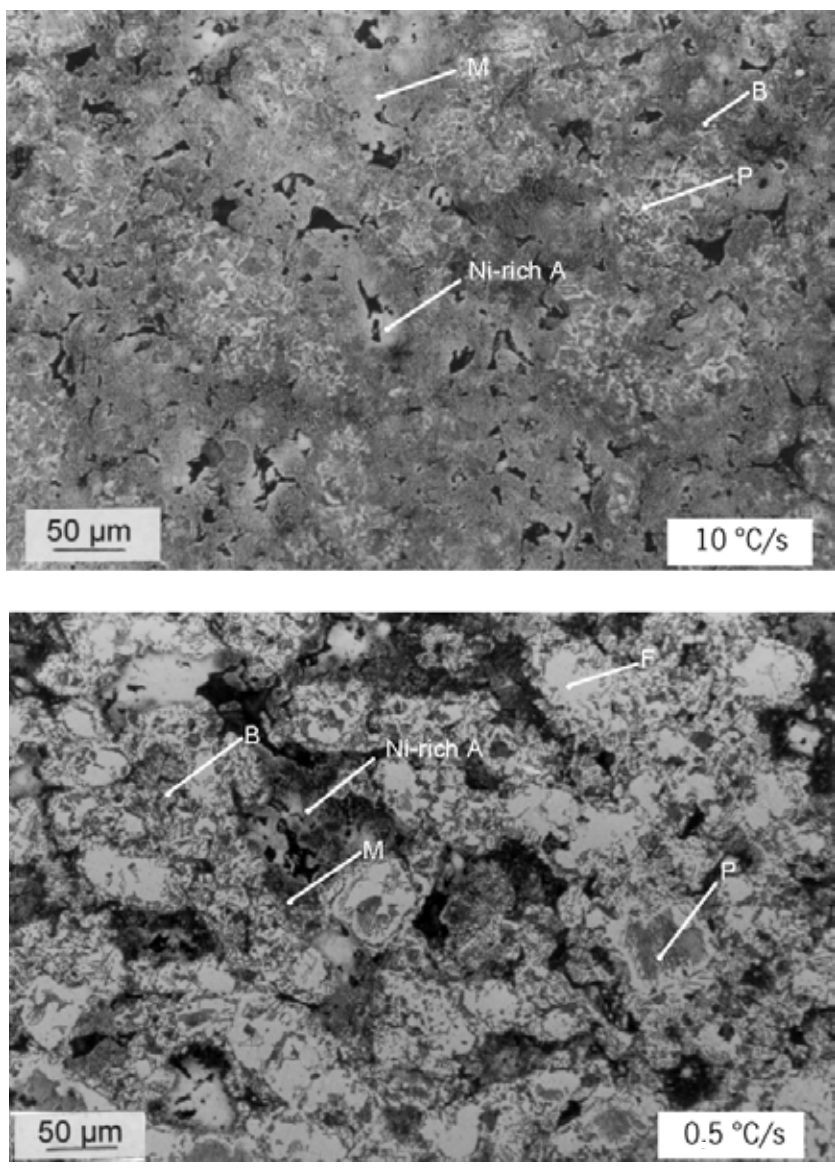


Figure 9.21.b. Microstructures of sintered Distaloy SA + 0.45% C, cooled from 850°C.

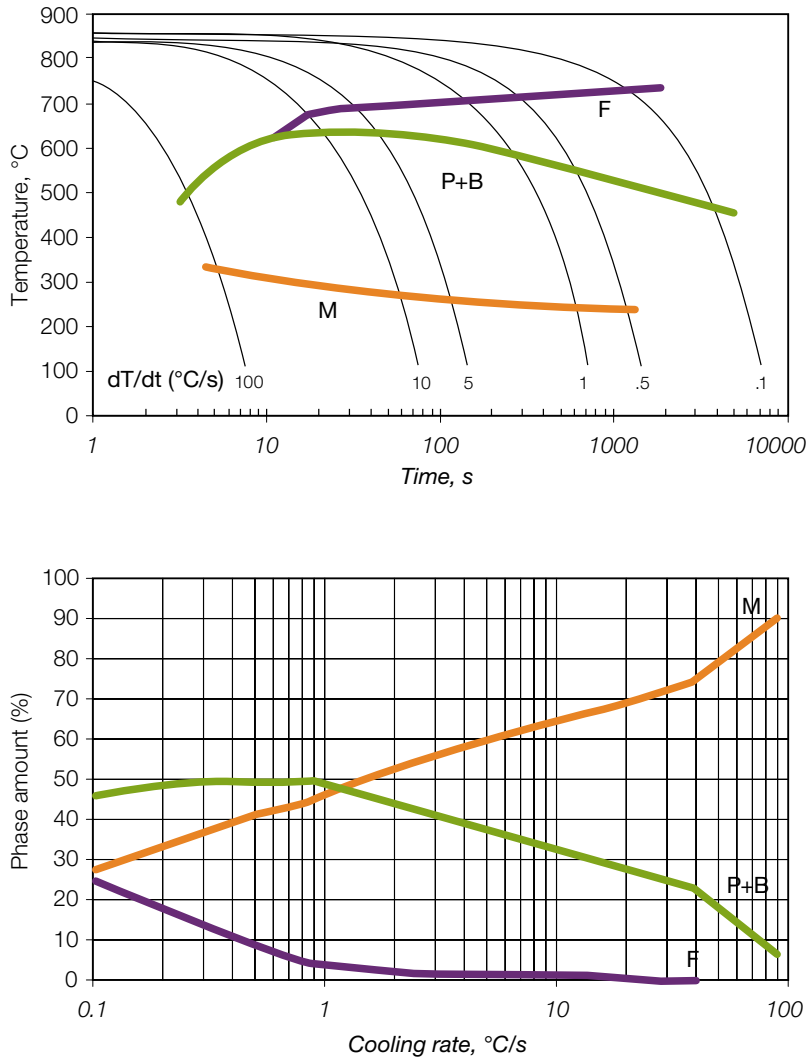


Figure 9.22a CCT-diagram (top) and amount of phases (bottom) for Distaloy AE + 0.50% C, sintered 30 min at 1120°C in endogas; cooling from 850°C. F=Ferrite, P=Pearlite, B=Bainite, M=Martensite

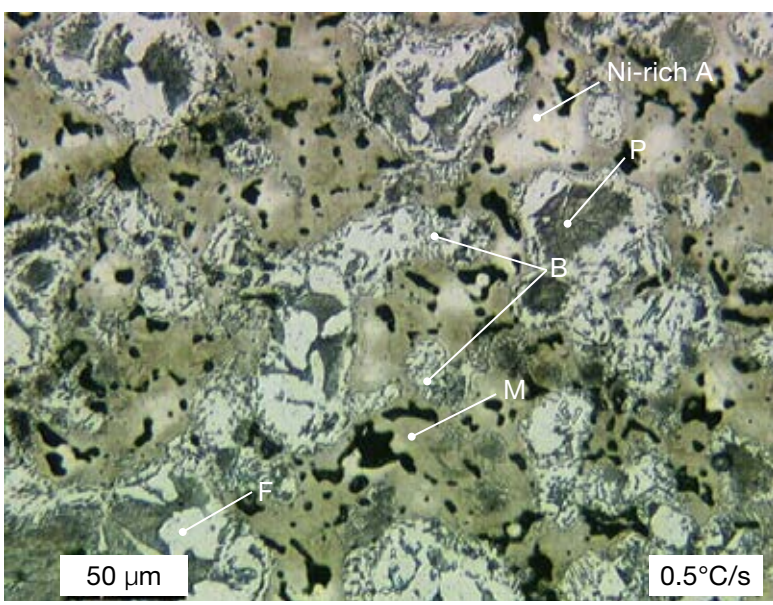
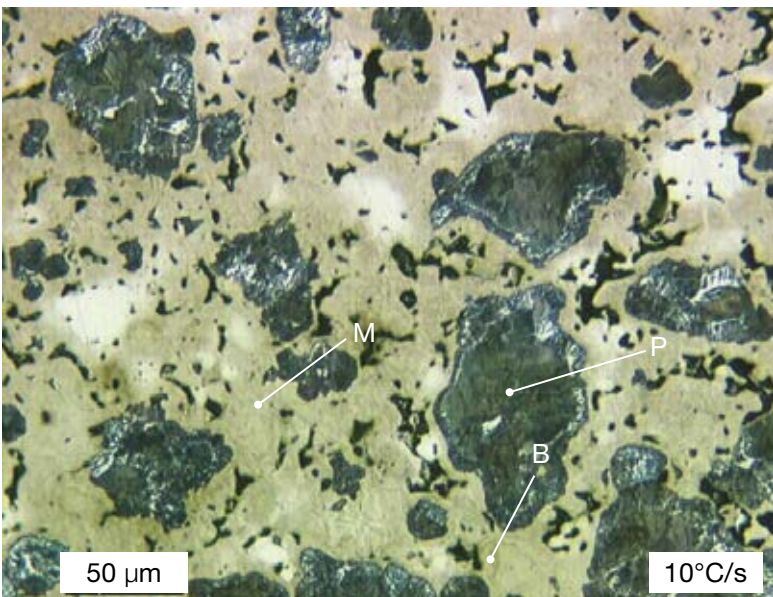


Figure 9.22.b. Microstructures of sintered Distaloy AE+ 0.50% C, cooled from 850°C.

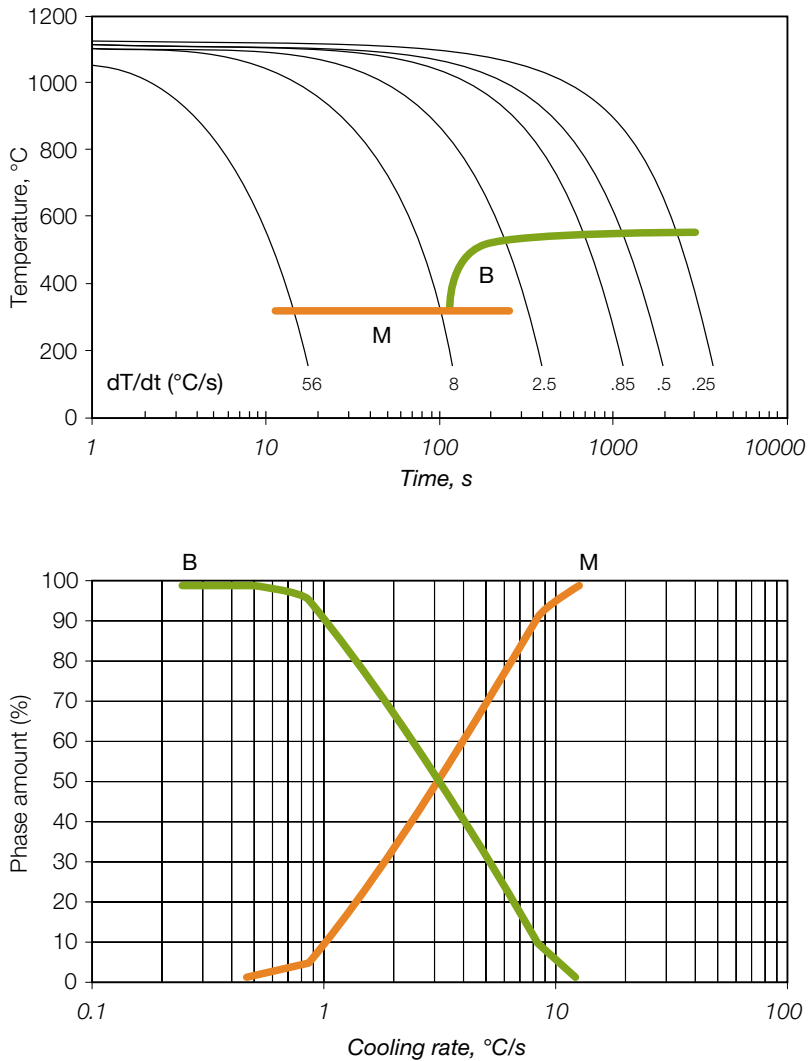


Figure 9.23 a. CCT-diagram (top) and amount of phases (bottom) for Distaloy DH + 0.40% C, sintered 30 min at 1120°C in endogas; cooling from 1120°C.

F=Ferrite, P=Pearlite, B=Bainite, M=Martensite

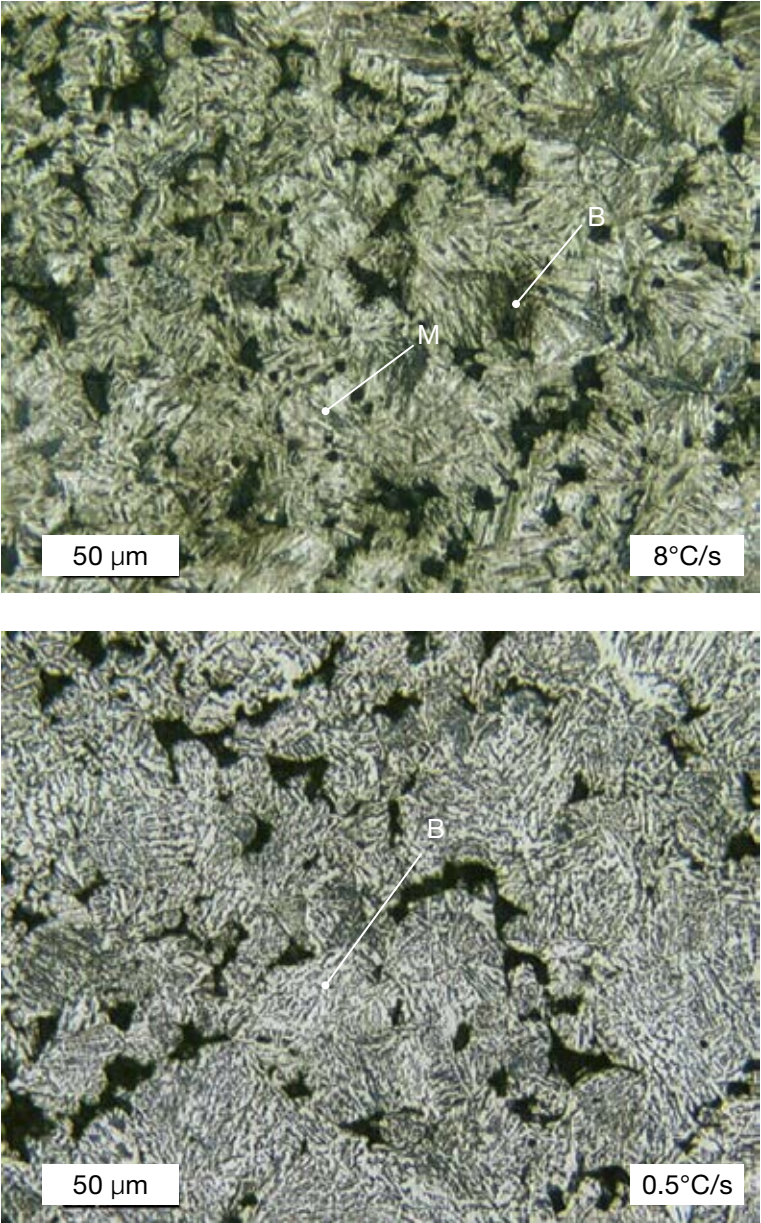


Figure 9.23 b. Microstructures of sintered Distaloy DH + 0.40% C, cooled from 1120°C.

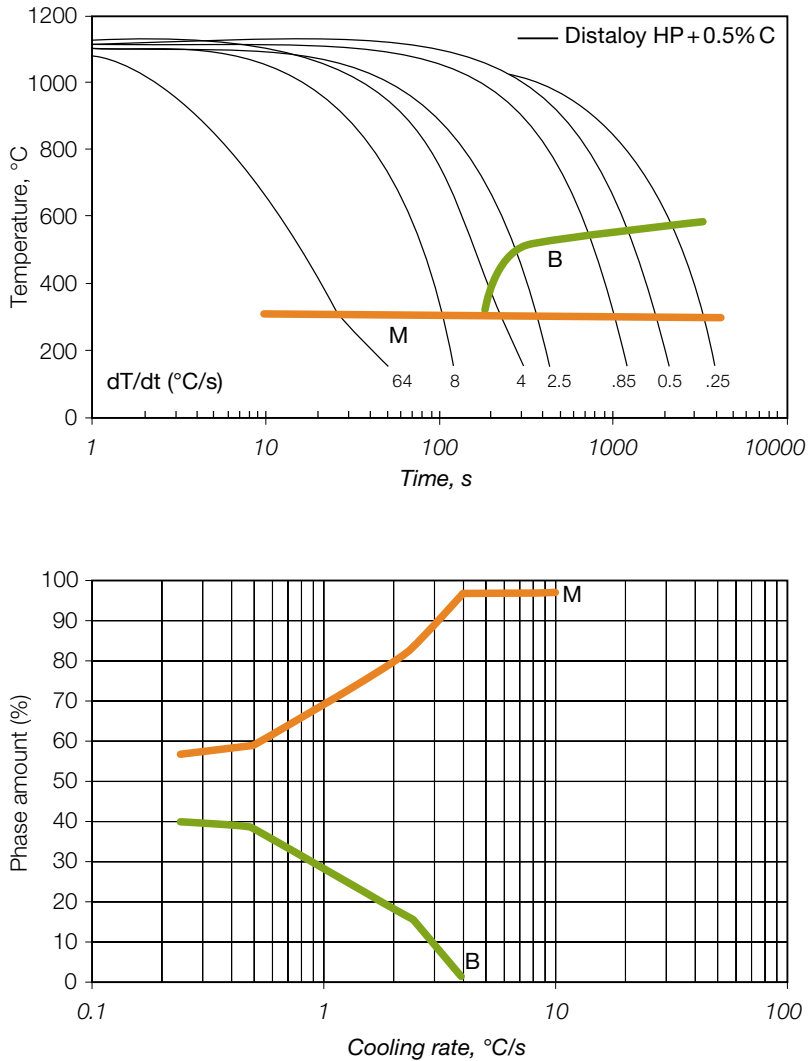


Figure 9.24.a. CCT-diagram (top) and amount of phases (bottom) for Distaloy HP + 0.50% C, sintered 30 min at 1120°C in endogas; cooling from 1120°C.

F=Ferrite, P=Pearlite, B=Bainite, M=Martensite

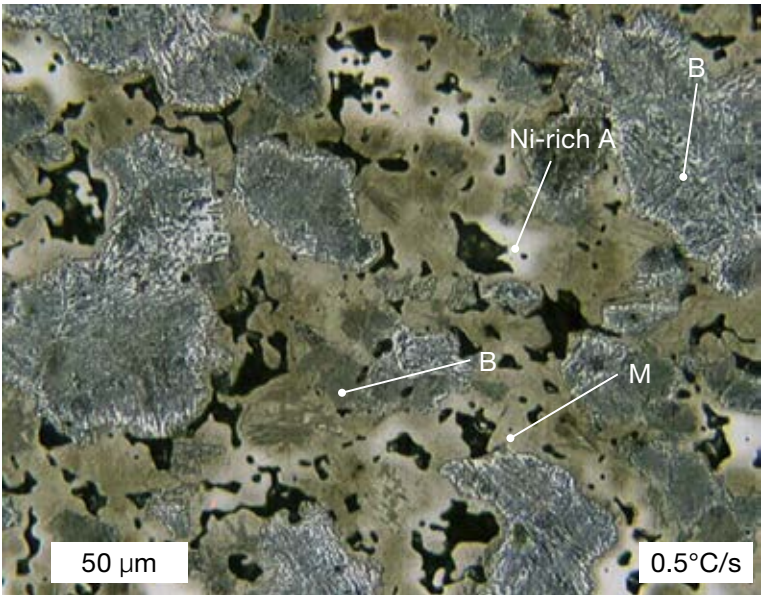
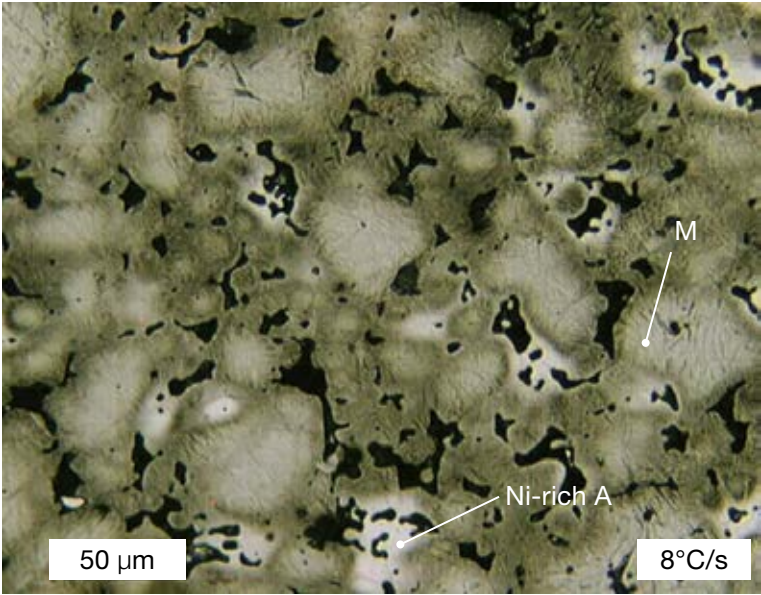


Figure 9.24 b. Microstructures of sintered Distaloy HP +0.50% C, cooled from 1120°C.

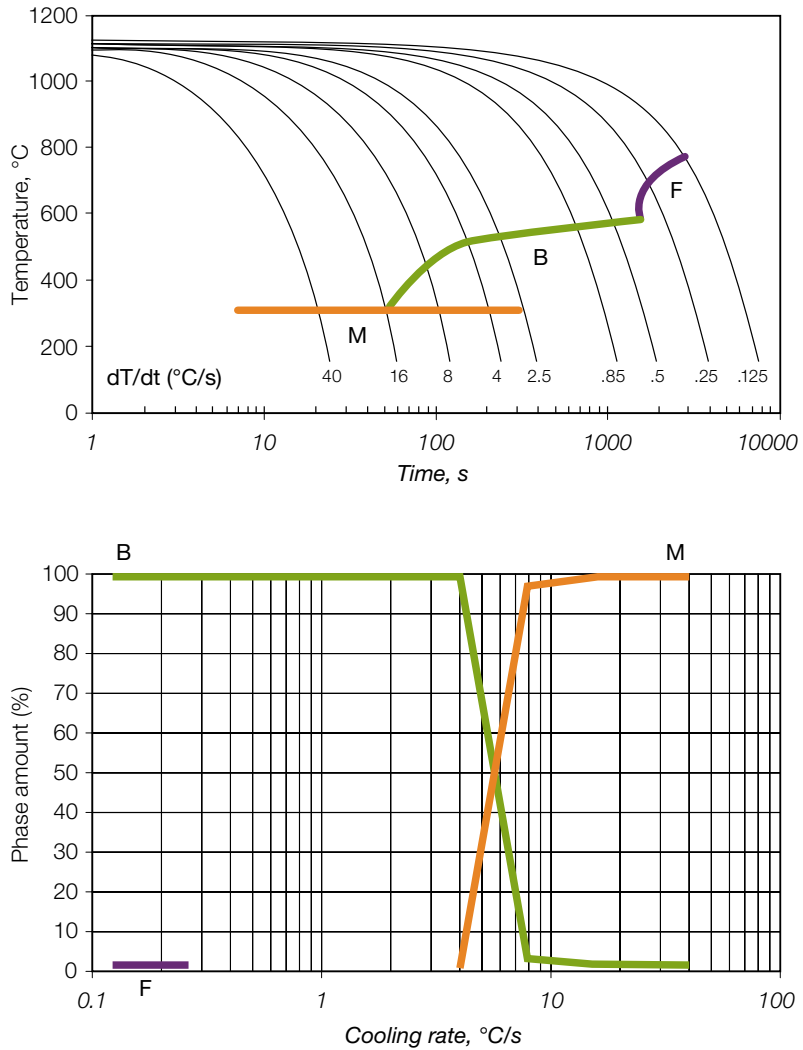


Figure 9.25.a. CCT-diagram (top) and amount of phases (bottom) for Astaloy Mo + 0.60% C, sintered 30 min at 1120°C in endogas; cooling from 1120°C.

F=Ferrite, P=Pearlite, B=Bainite, M=Martensite

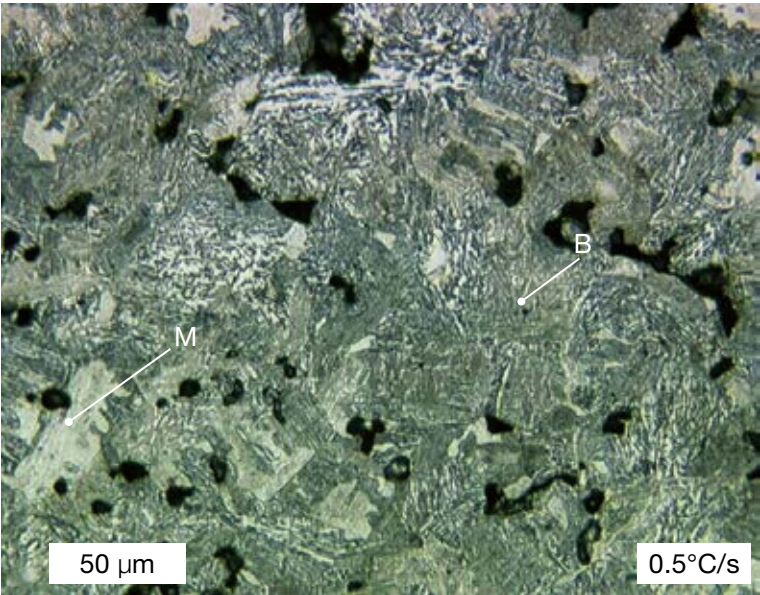
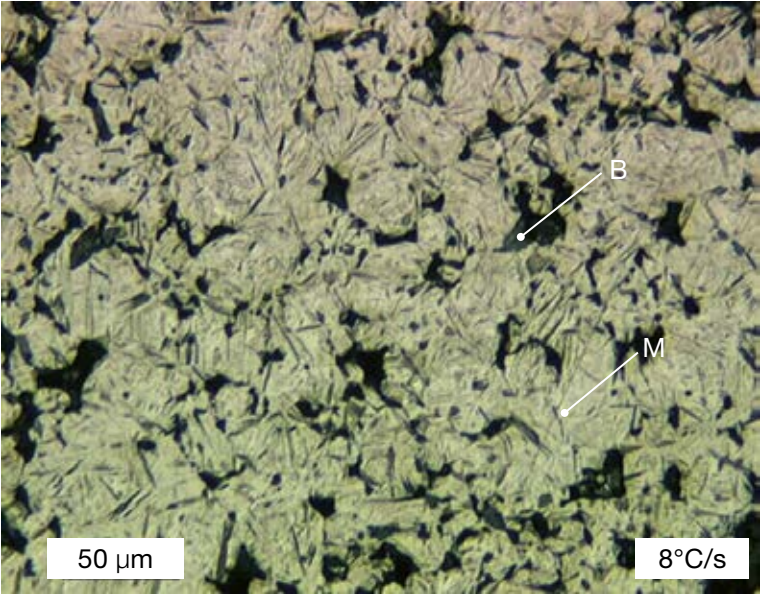


Figure 9.25b. Microstructures of sintered Astaloy Mo + 0.60% C, cooled from 1120°C.

See example in *Fig. 9.26* and related microstructures in *Fig. 9.27*

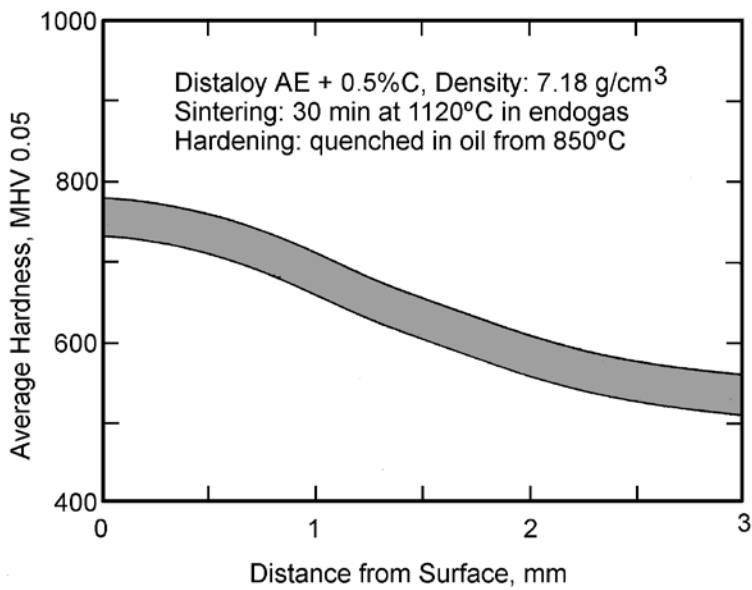
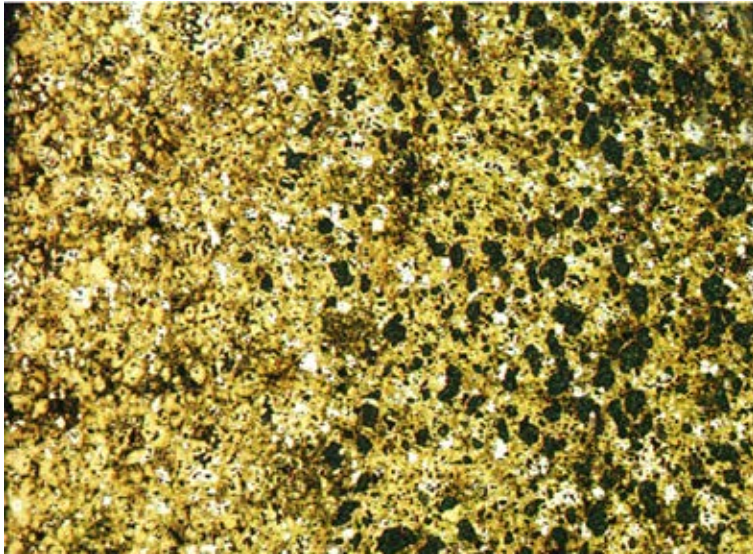


Figure 9.26. Variation of microstructure and microhardness with distance from surface.

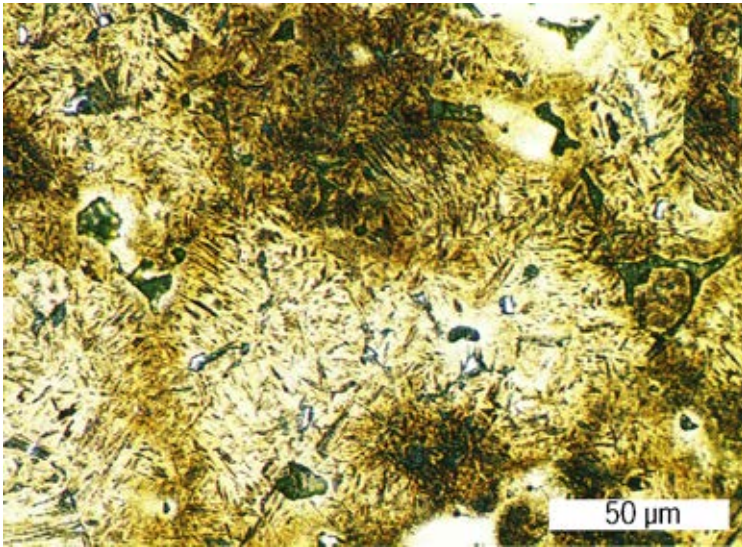
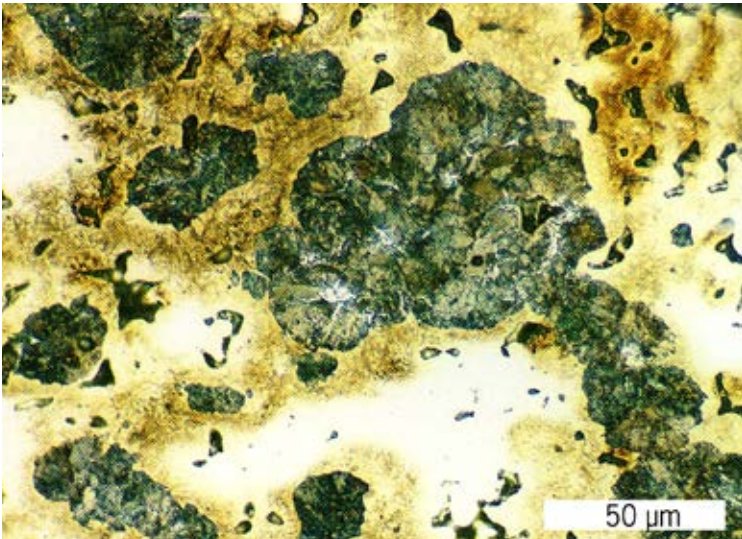
**a****b**

Figure 9.27. Microstructure of sintered and hardened Distaloy AE + 0.5% C; 6mm thick sample oil-quenched from 850°C. (a) surface, (b) center.

More extensive and detailed information about all materials treated in this chapter can be found on www.hoganas.com.

9.3 Typical Applications

As has been demonstrated in the preceding paragraph, a large number of different iron-based materials are available to achieve a great variety of sintered properties and combinations of such properties. Thus, the question is opportune: "Which of these materials is best for what application?" – There is no simple answer.

The final choice in each particular case is normally the result of a chain of laboratory tests, design adaptations, pilot production, functional tests and commercial considerations. Examples of parts actually produced from materials as described above are presented in Table 9.1 and may serve as a guide. Some of them are also shown on the photograph in *Fig. 9.28*.

Table 9.1. Applications for Various Sintered Iron-Based Materials

Code	Name of sintered structural part	Material	Density g/cm ³	Manufacturing procedure (P ₁ S ₁ P ₂ S ₂ etc)
A	Belt pulley	Iron-Copper-Carbon	6.6	P ₁ S ₁ P ₂
B	Exhaust pipe flange	Iron-Phosphorus	7.0	P ₁ S ₁
C	Synchronizing hub	Iron-Chromium-Molybdenum-Carbon	7.0	P ₁ S ₁ (M)*
D	Lock part	Iron-Nickel-Copper-Molybdenum-Carbon	6.8	P ₁ S ₁
E	Connecting rod	Iron-Copper-Carbon	7.75	P ₁ S ₁ PF M
F	Planetary carrier	Iron-Copper-Carbon	6.8	P ₁ S ₁ (B)
G	CAM lobes	Iron – Chromium – Carbon	7.3	P ₁ S ₁ P ₂ HT
P ₁ =Compacting, S ₁ =Sintering, S ₁ (B) = Sinterbrazing, P ₂ =Re-pressing, S ₂ =Re-sintering, M=machining, PF= Powder Forging, HT= Heat Treatment * for hub height				



a.



b.



c.



d.



e.



f.



Figure 9.28. Collection of structural parts made of various sintered iron-based materials,

- (a) Belt pulley,
- (b) Exhaust pipe flange,
- (c) Synchronizing hub,
- (d) Lock part,
- (e) Connecting rod,
- (f) Planetary carrier,
- (g) CAM lobes.

g.

9.3.1 Developing New Applications

Even today the PM industry is relying heavily on the automotive industry. This is partly due to significant volumes for each component, which justifies the tool cost per part. However, it is also related to the fact that PM components are reasonably well-known within the automotive industry, whereas the PM manufacturing route is virtually unknown to many other industries. Consequently, one of the main challenges for the entire PM industry is to raise the awareness of this net-shape manufacturing technology among other industries.

One way of doing this is to apply a more holistic view on application development, integrating component design with selection of material and process conditions. Only by combining all these, it is possible to offer the most cost-effective PM solution. Höganäs has entered this route, calling it the Power of Powder concept.

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.



Supplementary Operations

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10.2	Heat-Treatments	94
10.3	Infiltration and Impregnation	109
10.4	Machining and other Operations	112



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 10.1. Supplementary Operations

Operation		Purpose
Heat-treatment	Through hardening: austenitizing, quenching, tempering	• improve cross-sectional hardness and strength
	Precipitation hardening	• see above
	Case hardening: – carburizing – carbonitriding – nitriding – plasma nitriding – nitrocarbonizing – induction hardening	• improve surface hardness
	Annealing/Tempering	• eliminate internal stresses
Infiltration and impregnation	Infiltration – with metals	• increase density and properties • make parts pressure-tight
	Impregnation – with polymers	• make parts impermeable to gases and fluids
	Impregnation – with oil	• give parts self-lubricating properties
Machining and other operations	Machining	• provide parts with threads, undercuts and transverse holes
	Deburring and Cleaning: – barreling – vibratory deburring – abrasive blasting – ultrasonic bath – electrolytic alkaline	• remove burrs • clean parts from shop soil, grease and other contamination
	Joining: – brazing – welding – other methods	• join different sintered parts together to achieve component of more complex shape
	Peening and Plating: – shot peening – surface rolling – peen plating – electroplating	• hardens surface and improves fatigue strength • improve parts' appearance and corrosion resistance
	Corrosion Protection: – Steam treatment – Phosphatizing	• improve parts' corrosion- and wear- resistance

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
- tempering

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

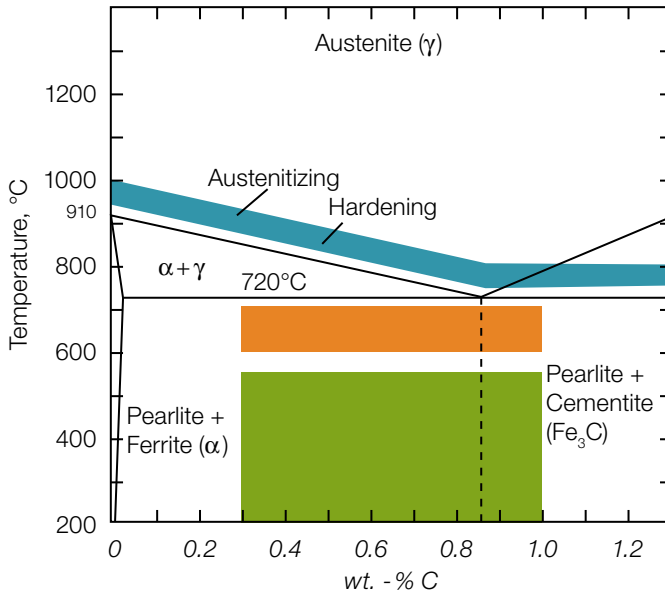


Figure 10.1. Heat treating diagram for carbon steels.

Austenitizing

In a non-decarburizing atmosphere, the parts are heated to and held at a temperature about 50°C 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.

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, chromium and molybdenum. See Fig. 9.2b in the preceding chapter.

CCT-diagrams and related microstructures of a variety of sintered steels have been presented in Figs. 9.21 - 9.25 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 - 5 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).

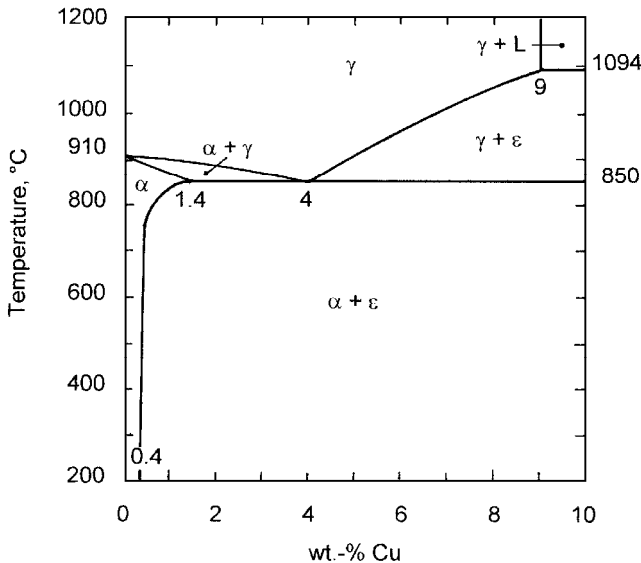


Figure 10.2 Iron-rich corner of Fe-Cu phase diagram.

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 carburizing and carbonitriding and these two methods will therefore, be especially emphasized in this paragraph.

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 carburizing 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. This is usually the case at sintered densities above 7.1 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 HV5 (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 in *Fig. 10.3*.

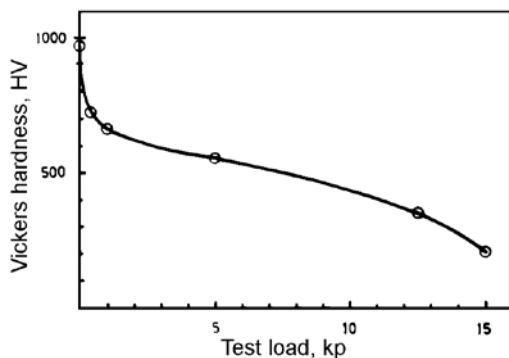


Figure 10.3 Influence of test load on the Vickers hardness number with surface-hardened sintered steel.

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. HV0.05 (test load 50 g). See diagram in *Fig. 10.4*. The hardness values obtained with HV5 reflect the density of the core rather than the hardness of the case.

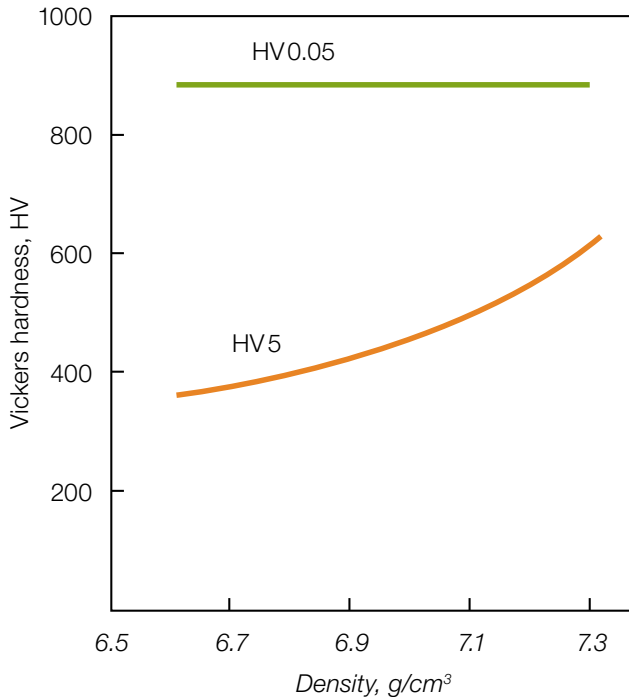


Figure 10.4 Influence of sintered density upon macro- and microhardness of low-alloyed sintered steel.

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 HV0.1 (or HV0.05). The emphasis here is on average microhardness. Sintered steel parts usually have a more heterogeneous microstructure than conventional steel parts.

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 in *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.

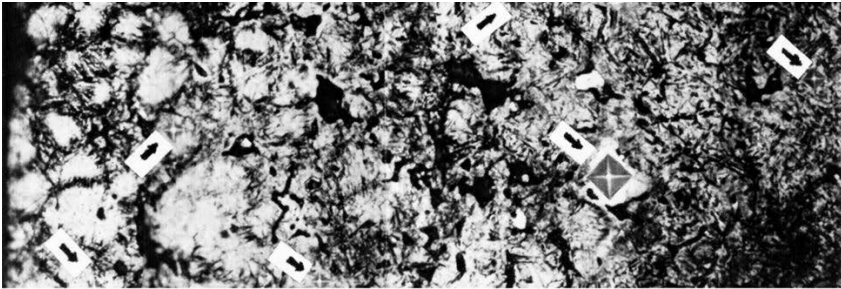
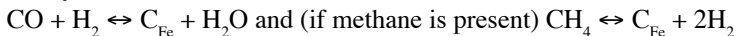


Figure 10.5 Scattering of microhardness indentations (HV0.05) in the microstructure near the surface of surface-hardened sintered low-alloyed steel (Distaloy AB).

Carburizing

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



Water vapor and excess hydrogen are flushed by a continuous stream of fresh carburizing 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 carburizing time. This means, to double the case depth, the carburizing time has to be increased fourfold.

* 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 CO_2/CO as a function of carburizing temperature for maintaining desired carbon potentials. The proper CO_2/CO -ratio can be checked conveniently by means of an infrared gas analyzer.

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 carburizing conditions are 1 to 4 hours at 850 to 860°C. At higher temperatures, carburizing times as short as 15 minutes may suffice.

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

The diagram in *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 carburized for 2 hours at 850°C and quenched in oil.

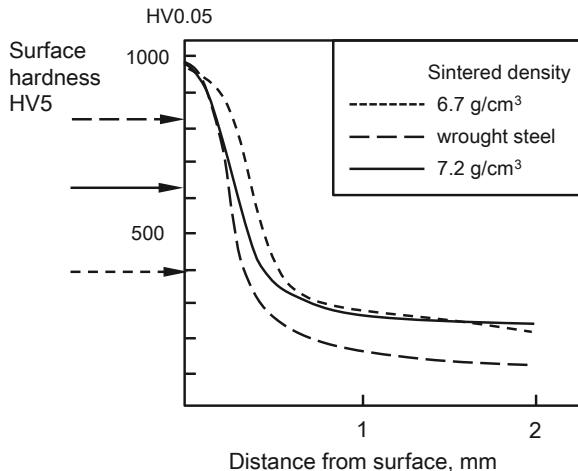


Figure 10.6 Microhardness profiles of sintered iron (ASC100.29, two different densities) and of wrought structural steel (SAE 1017) in comparison, all carburized for 2 hours at 850°C in endogas and quenched in oil of 50°C).

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

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

Carburizing can also be done in a vacuum furnace, where controlled amounts of a carbon-containing gas such as acetylene or propane, are pulsed into the furnace. This surface carburizing process is then followed by quenching in gas at high pressure, which is usually carried out in a separate chamber.

Vacuum Carburizing

Vacuum carburizing is a modern method of inducing a carburized surface layer. Combined with high-pressure gas quenching it offers an alternative process route for case hardening – a process gaining ground in industrial heat treatment.

The process incorporates pulsing of a carbon-containing gas, for instance propane or acetylene, into a low-pressure chamber filled with the components to be carburized. By adjusting temperature, number and length of pulses as well as time for carbon diffusion, the obtained case depth can be controlled.

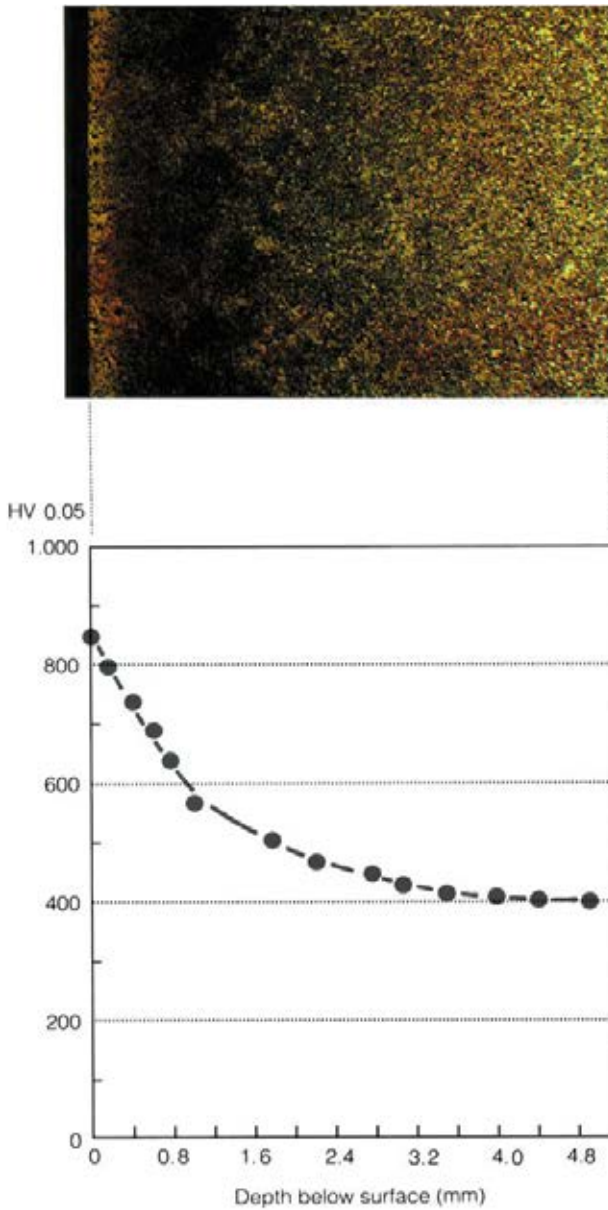
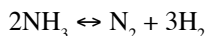


Figure 10.7 Microstructure and microhardness profile of a low-alloy sintered steel (Astaloy Mo + 0.2 wt.% C, sintered density 7.10 g/cm³), carburized for 30 min at 920°C in endogas.

Carbonitriding

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



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 carburizing, 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 carburizing process should be preferred. Normally, carbonitrided or carburized 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 carburizing and carbonitriding can be seen from the respective microhardness profiles shown in *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 carburized material. The hardness (HV5) on the surface is practically identical with both materials.

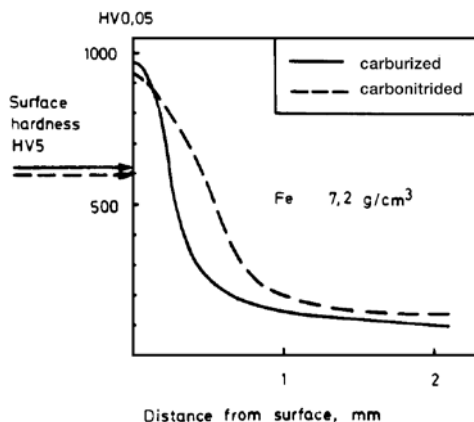


Figure 10.8 Microhardness profiles of sintered iron (ASC100.29) carburized/carbonitrided respectively for 2 hours at 850°C and quenched in oil of 50°C.

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

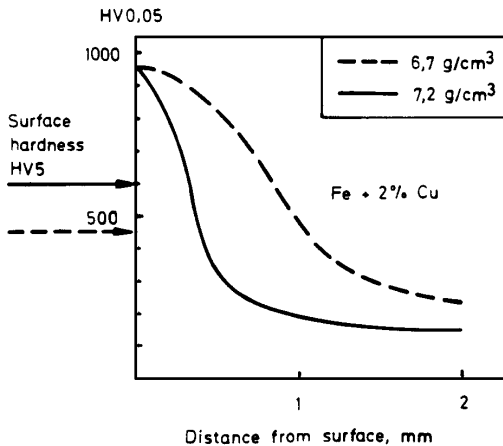


Figure 10.9 Microhardness profiles of sintered Fe + 2 wt.% Cu (treatment: 2 hours at 850°C, quenched in oil of 50°C).

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

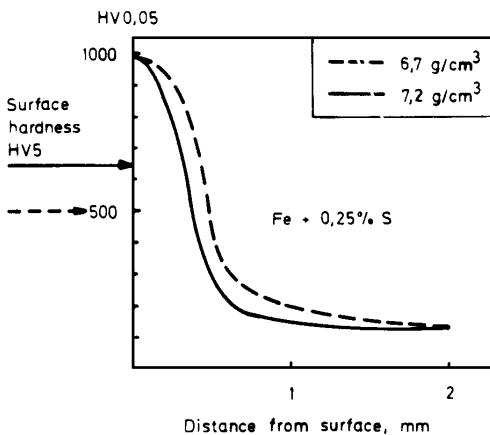
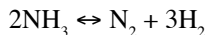


Figure 10.10 Microhardness profiles of sintered Fe + 0.25% S, carbonitrided for 2 hours at 850°C and quenched in oil of 50°C.

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.

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:



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 carburizing and carbonitriding, the parts need not to be quenched and may cool normally. Due to porosity in PM, nitriding times should be considerably shortened.

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. 10.11 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 in *Fig. 10.7*, it can be seen that, for the same material, plasma-nitriding has yielded a much smaller case than carburizing.

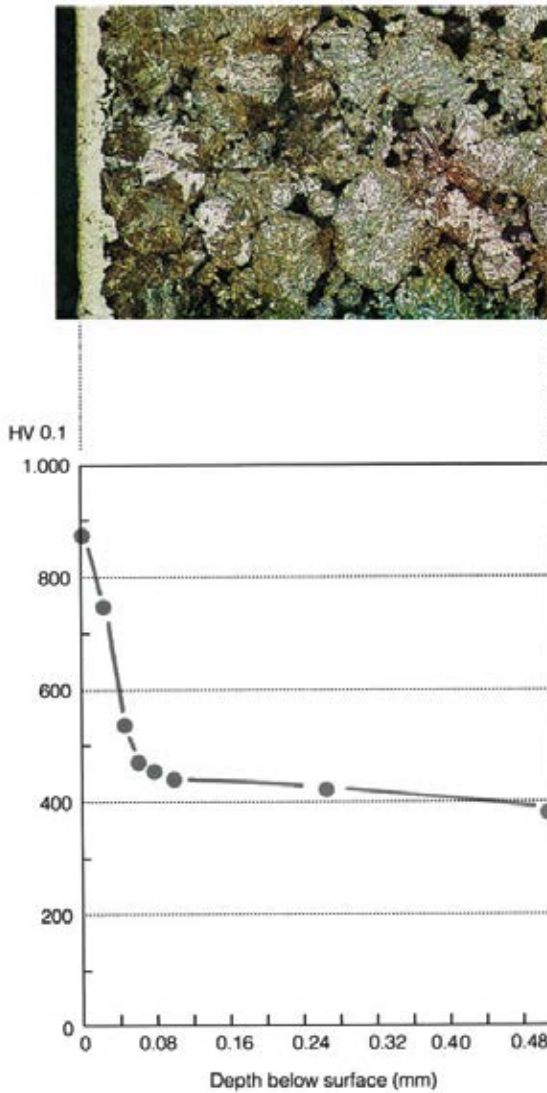


Figure 10.11 Microstructure and microhardness profile of a plasma-nitrided low-alloyed sintered steel (Astaloy Mo + 0.5 wt.% C, sintered density 7.10 g/cm³)

Nitrocarburizing

In this process, the emphasis is put on nitriding, but some carburizing 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 carburizing 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. 10.12* shows a section through an induction-hardened chain sprocket made of Distaloy AB + 0.7% C, having a sintered density of 7.10 g/cm³.

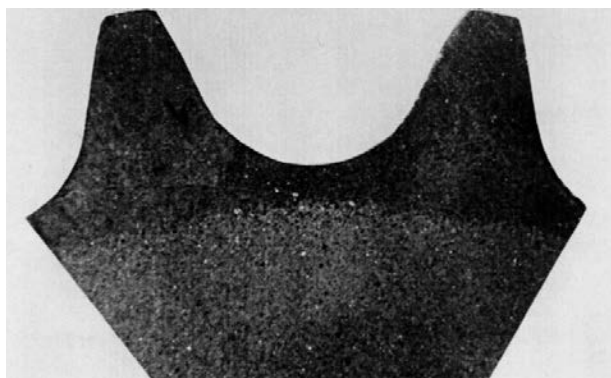


Fig. 10.12 Section of an induction-hardened chain sprocket. (Distaloy AB + 0.7% C, density 7.10 g/cm³). The hardened area appears dark on the photomicrograph.

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

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.

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 as well as for machining purposes. 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

Type of oil	Characteristics and fields of application	Range of operating temperatures
Mineral Oils	Very economic lubricants for medium loads and speed at moderate temperatures.	-20 °C – +90 °C
Synthetic Oils	Good long-time behaviour at medium loads. Suitable for higher speeds and higher temperatures.	-40 °C – +120 °C
Silicon Oils	Suitable at high temperatures and low loads. Insufficient long-time behaviour.	-60 °C – +200 °C

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 during machining is prohibited if components are to be subsequently impregnated with oil. 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 and mechanical 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.

Machinability of PM Steels

At the present state of art it is more or less impossible to formulate universally applicable relationships between specifications of a sintered PM material and its machinability. Moreover, the definition of “machinability” is an issue of its own. The selections of PM material (including its condition) in combination with a machinability enhancing additive and the setting of cutting parameters, defined by tool grade, tool geometry as well as speed and feed, generate a great number of factors and offer a large combination of choices. Due to the nature and mechanisms of the chip-removing process, the combinations of these factors and combinations of choices could optimize and improve machinability but in worst case do quite the opposite.

To test and determine machinability of PM steels, different methods and techniques are available. Often the main objective is to generate data which correlates the established tool wear to one or several input variables such as the PM material itself, cutting speed, enhancing additive or tool grade and tool geometry. A relatively inexpensive and fast method is the so-called drilling test. This test rates machinability by the number of holes it is possible to drill before a predestined value, i.e. to a certain edge wear or to a total drill break down. One variant of this method is standardized in “*MPIF Standard 35*” (“*Material Standards for PM Structural Parts*”). A more thorough, but also more time consuming, method for testing machinability is using a single point tool such as turning as the machining operation. By studying surfaces close to the edge of a turning insert, a deeper understanding could be achieved to determine the type of generated wear. This is crucial to improve and optimize machinability.

A detailed description of a turning test method is found in the standard “SS-ISO 3685” (“Tool-life testing with single-point tools”).

Over the years, several machinability enhancing additives have been investigated using drilling and turning tests like the ones described above. It has been found that some additives dramatically improve machinability. The additives MnS and MnX and the more recently developed additive MnM, have had the most beneficial effect on machinability.

Numerous empirical data on machining behaviour and machinability of various sintered PM materials has been generated and are available, but the frame of this paragraph is too limited to present them. *Figure 10.13* shows an example of additive influence on turning machinability.

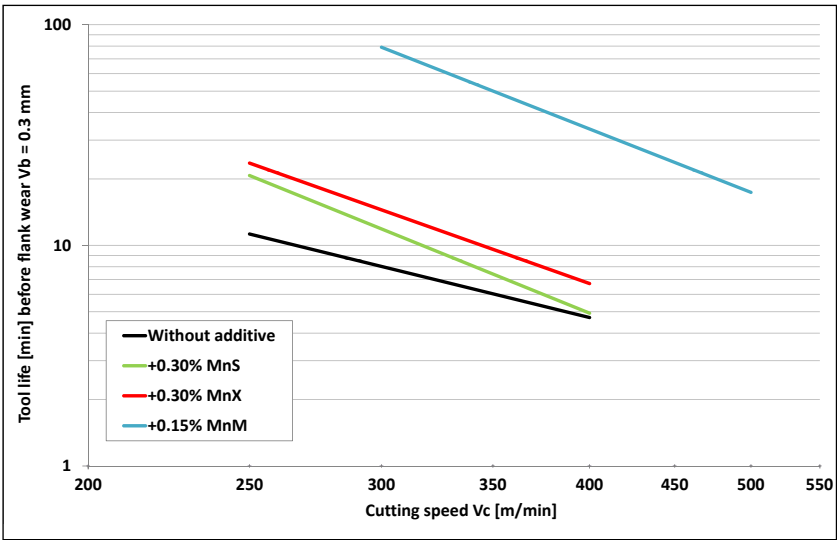


Fig. 10.13 As-sintered AHC100.29 + 2% Cu + 0.8% C. Turning parameters: Insert Sandvik Coromant CNMG120404-WF, grade GC4215, feed $f = 0.1$ mm/rev, cutting depth $a_p = 0.4$ mm, dry.

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 8, 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-Sonic Cleaning

In this operation, the parts are placed in a tank containing a medium that can carry ultra-sonic 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 non-metallic coatings. Due to the alkaline character of the solution, there is very little risk of corrosion.

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, groves 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 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 braze alloy. 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/cm^3 ; for brazing after sintering, the parts should have a sintered density higher than 6.5 g/cm^3 .
- Use a special brazing powder mix designed not to penetrate the pores. 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 in *Fig. 10.14*. To warrant good results, the entrance to the gap between the two parts to be joined should be sufficiently wide.

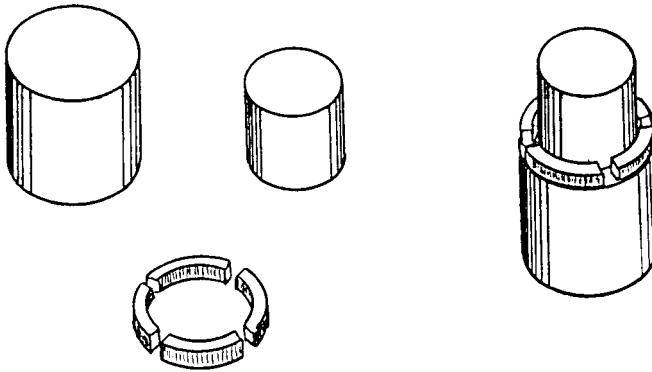


Figure 10.14 Application of brazing powder preform on assembly of two green iron powder compacts before sintering.

This can be achieved e.g. by putting a chamfer on the edge of one of the parts as shown schematically in *Fig. 10.15*.

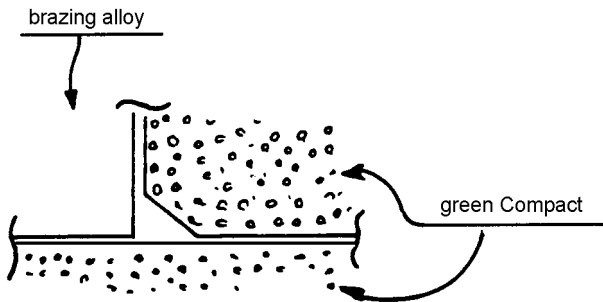


Figure 10.15 Optimal set-up for sinter brazing.

Approximately 0.2 - 0.5 grams of braze alloy per cm^2 joint area are needed; but the exact amount must be determined empirically from case to case. The tensile strength of a brazed gap is approx. 400 N/mm^2 .

Two interesting examples of brazed assemblies of sintered iron parts, mass-produced for the automobile industry, are shown in *Figs. 10.16* and *10.17*.



Figure 10.16 Planetary carrier for transfer case, assembly of two brazed sintered iron parts.



Figure 10.17 Side plate for power steering pump, assembly of two brazed sintered iron parts.

Welding

Welding is a joining technology also applicable to PM steels and all general considerations for welding apply to sintered steels as well. However, due to the presence of porosity and the lower impact strength of sintered steels compared to wrought steels, there are some additional aspects to consider.

Weldability of PM steels improves with increasing density and decreasing carbon content. As a general rule of thumb, carbon content should be kept below 0.3% and density above 7g/cm^3 . Special attention should be paid to ductility, as welding inevitably lowers impact strength in or close to the heat affected zone (HAZ). As previously described, PM steels usually have significantly lower impact strength and elongation compared to corresponding wrought steels. Hence

any given welding process needs to be optimized for the PM steel being used. However, it should be noted that welding of PM is currently in industrial practice and a number of mass manufactured PM components are today being welded.

A further general recommendation is to avoid welding of PM materials containing sulphur or phosphorous. The same goes for steam-treated and copper-infiltrated PM steels. Completely in line with wrought steels, welding of quenched and tempered components is not recommended.

Other Joining Methods

Shrink-fitting is a joining method ideally suited for sintered parts of annular shape. One of the two parts to be joined 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 **Outer Diameter** that fits exactly into the **Inner Diameter** of the shrinking part. The two green parts are stacked 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 joined 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.

10.4.4 Rolling, Peening and Plating

Surface rolling is a process where the surface layer of a component is densified and/or calibrated to meet demanding tolerances.

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 materials are closed by plastic deformation. Closed surface pores reduce the risk of electrolyte penetrating the pore system of the sintered part 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 and zinc.

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).

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_2O) at a temperature close to but below 550°C . Under these conditions, the following oxidizing reaction takes place at the surface of the parts:



The Fe_3O_4 (magnetite) forms a brownish-black, strongly adhering and highly wear-resisting, 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_2) emerging from above reaction is constantly diluting the steam (H_2O). If the H_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_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:



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.

The various conditions just described are illustrated in the diagram in *Fig. 10.18*

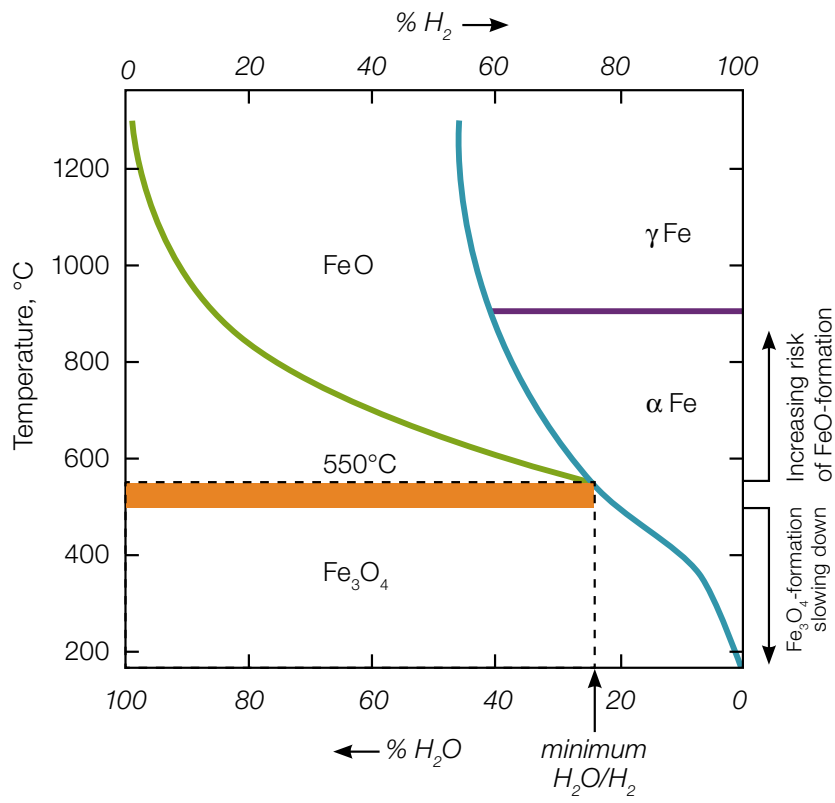


Figure 10.18 Suitable and unsuitable conditions for the steam treatment of iron parts.

The influence of steam treatment upon the mechanical properties of plain sintered iron parts is illustrated in the diagrams in *Fig. 10.19*. 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/cm^3 .

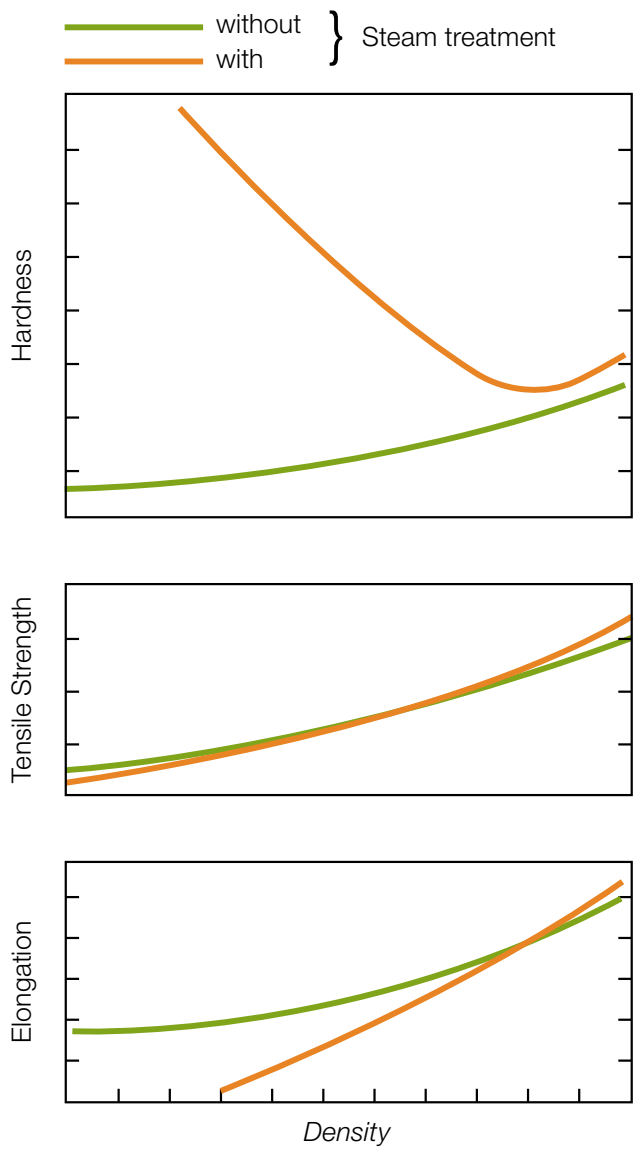
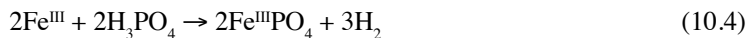


Figure 10.19 Influence of steam treatment upon the properties of plain sintered iron parts.

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:



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

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