COMPACTING TOOLS

The decision whether a given structural component can be manufactured by means of P/M-technique depends essentially upon the question whether a suitable compacting tool can be designed and built.
5. COMPACTING TOOLS

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5.1 Introductory Remarks

All compacting tools work by the same general principle:

Metal powder is filled, by gravity, into the cavity of a rigid die. There it is being compacted between two or more axially moving upper and lower punches to form a body of more or less complicated shape and of fairly homogeneous density. The so obtained compact is removed from the die by adequately shifting die and lower punches relative to one another.

The so described procedure appears fairly simple but, as usual, the devil is in the „nuts and bolts“, especially when dealing with structural components of complicated shape.

The following twelve points may give a first clue to the problems involved in designing a powder compacting tool:

1. All portions of the die cavity must, in a reliable way, be filled with exact amounts of powder.
2. The density distribution in the compact should be as homogeneous as possible.
3. In all portions of the die cavity, the densification of the powder should take place simultaneously, in order to warrant a sufficiently good binding between adjacent portions. It has to be taken into account that powder flows only very little in lateral directions during densification.
4. The compact must be removable from the compacting tool without getting damaged.
5. All required movements of tool members must be adequately controlled and must be repeatable with sufficient accuracy.
6. The tool should have as few punches as possible.
7. During the entire compacting cycle, punches must never jam, neither with the die, nor with core rods, nor with one another.
8. All tool members must withstand the load exerted upon them during the compacting cycle. They must be as wear-resistant as possible and have the highest possible life expectancy.
9. All functions of the tool must be optimally adapted to the functions available on the compacting press.
10. In order to keep set-up times to a minimum, the design of the tool should be such as to facilitate assembling and installation on the press.
11. In order to keep production stops as short as possible, worn-out tool members should be as easily replaceable as possible.
12. The manufacturing costs for the tool must be reasonable in relation to its expected life-time and to the total number of compacts to be produced in it.
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The experienced tool designer knows how difficult it is, in some cases, to do justice to all these points. The more complicated a structural component is, the larger is usually the required number of movements of tool members and of control functions on the press. In the following paragraphs, we will deal with several of the above listed points in more detail.

5.2 The Compacting Cycle

The compacting cycle can be divided into three stages:
1. Filling the die,
2. Densifying the powder, and
3. Removing the compact from the die.
Each of these stages is characterized by specific positions or movements of the individual tool members. And in each of these stages, specific technical problems occur, which we will now deal with in detail.

Figure 5.1. Three stages in a compacting cycle: 1) filling the die, 2) densifying the powder, 3) ejecting the compact.
5.2.1 Filling the die

The powder falls or flows by its own gravity from the filling device into the die cavity. It is almost trivial to mention that cavities having a wide cross-section are more easily filled with powder than such having a narrow cross-section. What is to be considered a narrow cross-section, in this respect, depends on the size of the biggest powder particles. Most commercial powders include particle sizes up to approx. 0.15 to 0.20 mm. In order to warrant an unimpeded powder flow and a satisfactory die fill, the smallest lateral dimension of a die cavity has to be considerably larger than the largest powder particle. Otherwise, bridging phenomena occur in the powder, of the kind as shown schematically at Fig. 5.2, entailing an uneven fill of the die cavity.

The powder may also segregate when flowing through narrow cross-sections. By experience, die cavities can be just about satisfactorily filled, if their smallest lateral dimension is approx. five times larger than the size of the largest powder particles. Thus, we can conclude that structural parts having lateral dimensions smaller than approx. 1 mm are not suitable to be compacted from powder.

In cases where the die cavity consists of several portions having different profiles and depths, the filling density of the powder in these portions may vary due to varying flow and filling behavior of the powder. It may also happen that the filling density in narrow portions is lower at the bottom than at the top. Such variations in filling density may result in correspondingly varying compact densities. In order to compensate for
variations in filling density between different portions of the die cavity, the filling depths of these portions have to be correspondingly pre-adjusted. Larger density variations in the powder compact have negative effects upon its green strength as well as upon its dimensional accuracy and mechanical properties after subsequent sintering and heat-treatment. In order to warrant a satisfactorily homogeneous density in powder compacts, the lateral dimensions of its different portions should measure at least 1/6 of their respective heights.

5.2.2 Densifying the Powder

In Chapter 4, it has been explained that, due to friction between powder and die wall (core rod), compacts are denser at their two ends near the moving compacting punches, than at their center. The location of lowest density in a compact is usually apparent to the naked eye as a dull zone on the shining lateral surface of the compact. In most cases, it is best for the properties of the compact if the zone of lowest density, the neutral zone, is located approx. half-way between top and bottom of the compact. This is the case when densification takes place between upper and lower punches that move symmetrically relative to the compacting die. Such symmetrical punch movement can, in principle, be achieved in three different ways, as illustrated at Fig. 5.3.
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Figure 5.3 Three different concepts to achieve symmetrical double-sided densification:

a) Stationary die, and two punches moving symmetrically towards one another,

b) Stationary lower punch and a "floating" die,

c) Stationary lower punch, and the die being withdrawn at half the speed of the upper punch.
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a) The die is stationary, and the symmetrical movements of the upper and of the lower punch are generated directly by the press.
b) The lower punch is stationary, and the die is supported by springs or hydraulic cushions to compensate for its gravity. As the upper punch compresses the powder, frictional forces, occurring at the die wall, move the die downwards relative to the stationary lower punch. (Floating-die principle).
c) The lower punch is stationary. The movements of the die and of the upper punch are actively controlled in such a way that, during densification, the die moves downwards relative to the stationary punch at half the speed of the upper punch.

In case a), the compact is ejected from the die by a corresponding upwards movement of the lower punch. (Ejection principle). In cases b) and c), the compact, resting on the stationary lower punch, gets clear of the die as the latter is being stripped downwards. (Withdrawal principle). Each of the three mentioned procedures, requires the availability of specific functions on the compacting press.

The procedure of the floating die (b) demands only two simple functions from a press: one mechanically or hydraulically generated downward stroke of an upper ram capable of exerting large forces, and one mechanically or hydraulically generated downward stroke of a lower ram capable of exerting somewhat smaller forces.

This procedure is not applicable to compacts having portions of different compacting heights. It also has the disadvantage that the movement of the die, during densification, is generated entirely by frictional forces which are uncontrollable since they are heavily influenced by variations of the lubricant content in the powder, by variations of the die temperature during production and by progressing wear on the die wall. Today, for complicated structural parts, procedures according to a) or c), or combinations of both, are being utilized. They require multiple-function presses, having at least two separately controllable movements capable of exerting large forces, and at least one separately controllable additional movement capable of exerting somewhat smaller forces.

As an example of procedure a), four stages of the compacting cycle for a bushing are shown schematically at Fig. 5.4. As can be seen, die and core rod do not shift position during densification of the powder. During ejection, the core rod remains in the bushing until the bushing has left the die and has expanded elastically. Than the core rod is withdrawn frictionless. This has a double advantage:
1. the required ejecting force is considerably smaller and,
2. the pores in the surface of the bore stay open – which they do not if the surface is plastically deformed under high frictional shearing stresses caused by a core rod withdrawn under pressure.
(A bushing without open pores in the surface of its bore has no self-lubricating properties).
In the case of thin-walled bushings, the narrow space between die and core rod can be filled more easily if, at the beginning of the filling process, the core rod is withdrawn to a lower position. After the wider die cavity has been filled with powder, the core rod is raised to its normal position, pushing excessive powder back into the filling-shoe. See schematic illustration at Fig. 5.5.
As an example of procedure c), three stages of the compacting cycle for a simple two-level part are shown schematically at Fig. 5.6. Die and lower punches are mounted on a tool rig, a so-called adapter, which, as a whole, is inserted into the press. Typical for this particular tooling principle is a sidewise retractable slide which, during the compacting phase, supports one of the lower punches.

The right lower punch is, via a connecting rod, lifted to its filling position by means of a spring. During the compacting phase, the lower ram of the press pulls the die platen down at half the speed of the upper punch, while the left lower punch rests on the stationary base platen of the adapter. Under the pressure built-up in the densified powder, the right lower punch moves downwards, against the force of the supporting spring, until it sets upon the slide.

After compacting, the lower ram of the press pulls the die platen further down, and a wedge attached to the die platen forces the slide sidewise. The now unsupported right lower punch follows the die platen down until the compact has come completely clear of the compacting tool.

Compacting tools with sliding supports for split lower punches were first utilized in Germany during World War 2, when complicated armory components had to be compacted on plain presses. Today, this tooling principle is on the way out, because it is
not suitable for complicated multilevel parts with high requirements for precision and homogeneous density. But it is still being utilized for less complicated two-level parts when modern multifunctional presses are not available.

5.2.3 Removing the Compact from the Die

During the compacting cycle on a mechanical press without any auxiliary devices, the upper punch exerts its maximum pressure at the lower dead-point. Then, it moves upwards again, suddenly taking the axial pressure off the compact and the lower punches which now expand elastically in axial direction.

If there are lower punches of different length (as e.g. when compacting flanged bushings), their different axial expansions can create cracks in the compact yet before it leaves the die. Different elastic expansion of differently high portions of the compact add to this effect. See schematic illustration at Fig. 5.7.

Cracks caused by this effect are malicious, especially in flanged bushings, because they are difficult to detect and do not heal during subsequent sintering. In order to avoid this kind of cracks, all portions of the compact must be kept under a well balanced moderate axial pressure during the whole ejecting procedure.
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At the end of the compacting phase, die and lower punches are shifted relative to one another in such a way that the compact is being pushed towards the exit of the die. To achieve this effect, it is irrelevant whether the die is stationary and the punches are moving or vice versa. The important point is that, during this procedure, the lower punches are not moving relative to one another in such a way that cracks are created in the compact.

As the compact exits the die, the protruding part, freed from the compressive lateral stress of the die, expands laterally, while the rest of the compact is still constrained in the die. In this transient phase, high shearing stresses occur which may create horizontal cracks in the compact as illustrated schematically at Fig. 5.8a.

Figure 5.7 Crack formation due to different elastic expansion of two lower punches when the upper punch is being released.
In order to reduce these shearing stresses, the die is slightly tapered at the exit, and its rim is rounded off. See schematic illustration at Fig. 5.8b.

Particularly susceptible to cracking during ejection are compacts of the type as schematically illustrated at Fig. 5.9. The compact shown consists of a sturdy upper portion and a thin skirt-like lower portion. Shock absorber pistons for automobiles fall into this category.
The lateral contours of certain portions of a complicated compact are partly or entirely defined by lateral faces of core rods and punches. In order to clear all portions of the compact from the tool without creating cracks, the movements of all tool members involved in the ejecting process must be separately controllable. This requires not only a complicated tool design but also a press equipped with adequate auxiliary functions.

After ejection, the compact has to be removed from the press, without getting damaged. In the simplest case, the next stroke of the filling shoe pushes the compact to a chute on which it slides, in single file with its equals, into a suitable container for intermediate storing before sintering.

Fragile compacts, and compacts of delicate shape, have to be picked up carefully by means of a small automatic gripping device which transfers them individually to a special tray on which they subsequently can pass through the sintering furnace. Compacts must, of course, have sufficient green-strength to withstand handling without abrasion or breakage. And they should, if ever possible, have one sufficiently plane face to stand on stable on their way through the sintering furnace.

In certain cases, it may be advantageous to turn the compacts automatically as they come out of the die before letting them slide down a chute or before placing them on a tray.
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5.2.4 Compacting Cycle on Presses equipped with Multiple Platen Systems

Complicated sequences of punch movements are required in cases where the shape of the compact cannot be duplicated proportionally by the filling space. A typical example is a component with a blind hole and a flange at the same end, as shown at Fig. 5.10. The only way to produce this part, if the type of press allows it, is by powder transfer:

First, the die cavity is filled up with powder as if the blind hole was at the opposite end of the die. Then dropping this column of powder, without densifying it, downwards to the lower end of the part. The different powder columns must then be densified at different rates proportional to their initial heights in order to achieve the same pressure gradient in all powder columns, such as to avoid radial powder transfer and to achieve favorable positions of the neutral zones. In order to avoid cracks during ejection of the compact, a certain axial pressure must be maintained, on all portions of the compact.

Last, when the compact has cleared the die, the inner upper punch is extracted from the compact against the supporting outer upper punch. Many structural parts, such as employed in the automobile industry, are of multi-level type with shapes even more complex than the example shown at Fig. 5.10.

The complicated sequences of punch movements involved in the compacting procedure for these parts can be performed successfully only on special types of presses. During all stages of the compacting cycle, the time- pressure- and stroke-depending movements of die, core rods and various upper and lower punches have to be coordinated in the correct relation to one another.
On modern hydraulic CNC-presses with integrated multi-platen adapter, working according to a combined withdrawal/ejection procedure, up to ten separately controllable movements of die, core rods and punches are available. By means of a precision-measurement system in combination with a highly sensitive servo-hydraulic
system, exactly timed sequences of all required movements can be programmed both with respect to pressure and stroke length. At Fig. 5.11, a multi-platen adapter, type D O R S T M PA/H 140, for seven separately controllable movements is shown.

Figure 5.11 Multi-platen adapter, Type D O R S T M PA/H 140 with seven separately controllable tool movements, used for compacting a double-gear as shown at Fig. 5.12. [5.1]
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This type of adapter is utilized e.g. for compacting a double-gear with internal splines as shown in the schematic diagram at Fig. 5.12. The double-gear has upper and lower faces on three different levels each. Apart from die and core rod, which move simultaneously, the tool has three separately controllable upper punches, one stationary and two separately controllable lower punches.

![Diagram of compacting a double-gear](image)

**Table 5.12** Four stages in compacting a double-gear with internal splines on a multi-platen adapter, type D O R S T M A P/H 140. [5.2]

<table>
<thead>
<tr>
<th>Compact weight</th>
<th>139 g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average density</td>
<td>6.84 g/cm³</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>50.5 mm</td>
</tr>
<tr>
<td>Total height</td>
<td>22 mm</td>
</tr>
<tr>
<td>Strokes</td>
<td>8.8 per min</td>
</tr>
<tr>
<td>Fill position</td>
<td>Powder transfer</td>
</tr>
<tr>
<td>Press position</td>
<td>Withdrawal position</td>
</tr>
</tbody>
</table>

The achieved homogenous density distribution in this part is indicated on the drawing shown at Fig. 5.13.

![Density distribution diagram](image)

**Figure 5.13** Density distribution in the double-gear produced on a multi-platen adapter as shown at Fig. 5.12. [5.3]
5.3 Designing a Compacting Tool

In the following, we outline the principle procedure of designing a compacting tool. As a representative example, we choose a part having two parallel holes and two portions of different height as shown at Fig. 5.14. Based on the technical drawing of this structural part, a proportionally correct sketch of the tool is being developed from which the required functions of the various tool members can be understood.

Subsequently, exact dimensions and tolerances for all tool members are being established. Eventually, adequate tool materials as well as machining- and heat-treating procedures are being considered.

### Table 5.1 Technical data

<table>
<thead>
<tr>
<th>Press</th>
<th>TPA 140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adapter</td>
<td>MPA/H140</td>
</tr>
<tr>
<td>Compacting Force</td>
<td>95 ton</td>
</tr>
<tr>
<td>Compacting Speed</td>
<td>8.8 pieces/min</td>
</tr>
<tr>
<td>Powder</td>
<td>Höganäs Distaloy AE</td>
</tr>
<tr>
<td>Compacting Area</td>
<td>12.6 cm²</td>
</tr>
<tr>
<td>Weight</td>
<td>139 g</td>
</tr>
<tr>
<td>Average Density</td>
<td>6.83 g/cm³</td>
</tr>
</tbody>
</table>
5.3.1 Functional Sketch of the Tool

The development of the functional sketch proceeds, essentially, in four steps:

**Step 1.**
First, it has to be decided which way around the part is best to be compacted. Since the part has one relatively flat and one stepped face, the most practicable way to compact it is with its flat face up. Then, one undivided upper punch suffices, but two lower punches are required.

**Step 2.**
After it has been decided with which side up the part is to be compacted, a vertical section through the part is outlined on drawing paper and all vertical boundaries of the section are extended upwards and downwards. These extended lines indicate already the vertical contours of die, punches and core rods. The horizontal boundaries of the section indicate the positions of the punch faces at the end of the compacting stage. See sketch (a) at Fig. 5.15.

Figure 5.14 Drawing of a crank having two portions of different height and two axial bores, intended to be manufactured by PM-technique.
Step 3.
The required filling depths for the two portions of the part can be calculated by means of the ratio $Q$ between compact density and filling density (apparent density) of the powder according to the following relationship:

$$Q = \frac{\text{Compact Density}}{\text{Filling Density}} = \frac{\text{Depth of Fill}}{\text{Height of Compact}}$$

Commercial iron powders have filling densities between 2.4 and 3.0 g/cm$^3$. If we base our example on an assumed filling density of 2.60 g/cm$^3$, and an assumed compact density of 6.45 g/cm$^3$, then: $Q = 6.45/2.60 = 2.47$.

In order to obtain the required depths of fill, the heights $H_1$ and $H_2$ of the two portions of our part have to be multiplied with this factor. The height of the left portion of the part is $H_1 = 17$ mm, and the height of its right portion is $H_2 = 13$ mm. Thus, the respective depths of fill are $F_1 = 17\text{mm} \times 2.47 = 42$ mm and $F_2 = 13\text{mm} \times 2.47 = 32$ mm.

We decide that the left powder column is to be compacted symmetrically from top and bottom. This means, during densification of the left powder column, the upper punch and the left lower punch are to travel equal distances inside the die. Consequently, at the end of the densification process, the center of the left portion is located half-way between the upper rim of the die and the filling position of the left lower punch.

Thus, we mark the position of the upper rim of the die at distance $F_1/2 = 21$ mm above and the filling position of the left lower punch at distance $F_1/2 = 21$ mm below the center of the left portion. Then, at distance $F_2 = 32$ mm below the so found upper rim of the die, we mark the position of the right lower punch. See sketch (b) at Fig. 5.15.

Step 4.
Assuming that a minimum guidance in the die of 25 mm is required for the lower punches, the die has to be at least 25 mm higher than the largest filling depth. Thus, we mark the lower rim of the die at distance $A = F_1 + 25$ mm = 67 mm below its upper rim.

Eventually, the lengths of the punches are to be considered. Both lower punches have, of course, to be long enough to fully eject the compact from the die, i.e. they have to be at least 67 mm long.

The upper punch has, of course, to be long enough to penetrate the die as deep as needed to attain the desired compact height, i.e. its length has to be at least $(F_1 - H_1)/2 = 12.5$ mm. To these lengths, a margin of 5 - 10 mm should be added to allow for the correction of worn punch profiles. After this, the rough design of our compacting tool is complete. See sketch (c) at Fig. 5.15.
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Figure 5.15 Step-by-step sketching of a compacting tool for the component shown at Fig. 5.14: a) drawing the contours of die walls, punches and core rods, b) finding the filling positions of the lower punches and finding the position of the upper rim of the die, c) finding the location of neutral zones and finding the position of the lower rim of the die.

Compact Height:

H₁ = 17.0 mm
H₀ = 13.3 mm

Depth of Fill:

F₁ = Q₁ = 42.0 mm
F₂ = Q₂ = 32.1 mm

Punch Strokes:

X₁ = Y₁ = 12.5 mm
X₂ = Y₂ = 8.6 mm

Location of Neutral Zone:

E₁ = 21.9 mm
E₂ = 18.6 mm

Compact Density = 6.42 g/cm³
Apparatus Density = 2.89 g/cm³
Q = 6.42/2.89 = 2.24
E = F X (X₁ + Y₁)

1 = upper rim of die, 2 = upper punch, 3 = lower punch, 4 = lower punch, 5 = core rod, 6 = core rod, 7 = lower rim of die.
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The final design of this tool, conceived for the withdrawal method, can be seen from the drawing shown at Fig. 5.16.

Of special interest, in this context, is the location of the neutral zone (zone of lowest density) in the two sections of our compact. In chapter 4 (Compacting of Metal Powders) it has been explained that, due to frictional forces at the die wall, the compact density decreases with increasing distance from the face of a moving punch.

If only the upper punch is moving relative to the die, the zone of lowest density is located at the face of the stationary lower punch. If upper and lower punch are moving symmetrically relative to the die, the zone of lowest density appears exactly half-way between the faces of the moving punches. If the two punches move unsymmetrically, the zone of lowest density lies nearer to the face of the lesser moving punch.

![Figure 5.16 Complete design of the tool sketched at Fig. 5.15, adapted to the withdrawal principle with sliding support.](image)

The relationship between punch movements and location of the neutral zone can be described by a simple formula. Let $F$ the depth of fill, $X$ and $Y$ the distances traveled by the upper and lower punch respectively, and $E$ the distance of the neutral zone from...
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the upper rim of the die, then the following general relationship applies:

\[ E = F \frac{X}{X + Y} \]  \hspace{1cm} (5.1)

If upper and lower punch move symmetrically relative to the die, i.e. if \( X = Y \), it follows:

\[ E = \frac{F}{2} \]  \hspace{1cm} (5.2)

During densification of the left portion of the compact, upper and lower punch travel the same distance \( X_1 = Y_1 = 12.5 \text{ mm} \). Thus, according to (5.2), the neutral zone of this portion is located at distance \( E_1 = \frac{F_1}{2} = 42 \text{ mm}/2 = 21 \text{ mm} \) below the upper rim of the die.

The location of the neutral zone in the right portion of the compact can be calculated as follows. Since the upper punch has a 1.5 mm deep groove (to form the little bulge on top of the right portion), it can dip into the die approx. 1.5 mm deep without noticeably densifying the right powder column; (the powder escapes into the groove).

Until reaching its lowest position, the upper punch travels a remaining distance of \( X_2 = X_1 - 1.5 \text{ mm} = 11 \text{ mm} \). Simultaneously, the right lower punch travels a distance of \( Y_2 = 8 \text{ mm} \) upwards. Thus, according to (5.1), the neutral zone of the right portion of the compact is located at distance \( E_2 = \frac{32 \times 11/(11+8)}{2} = 18.5 \text{ mm} \) below the upper rim of the die, i.e. 2.5 mm below the center of the right portion and 2.5 mm higher than the neutral zone of the left portion. If the neutral zones of the two portions would be too far apart, cracks might be created at the joint of the two portions during densification.

Ideally, the movements of the two lower punches should be coordinated in such a way that the two powder columns standing upon them get densified simultaneously and homogeneously. If densification in the two powder columns proceeds at different rates, unsymmetrical lateral pressures act upon the two parallel core rods, possibly causing unacceptable deviations from specified tolerances on central distance and parallelism of the two bores. Prematurely worn or broken core rods may also be a consequence of unsymmetrical lateral pressures.
5.3.2 Dimensions and Tolerances on Tool Members

When pinpointing the final dimensions and tolerances for the various tool members, not only the final dimensions and tolerances of the structural part, as specified on the customers’ drawing, must be considered, but also the dimensional changes which the compact undergoes during ejection from the compacting die and during subsequent sintering.

Dimensional changes of the compact’s longitudinal dimensions do not constitute any greater problem, because they can relatively easily be compensated for by slight adjustments of punch positions and movements. Much more critical are dimensional changes of the compact’s transversal dimensions, because they cannot be adjusted without disassembling the compacting tool and reground or entirely remake die and punches. Thus, before finally laying down transversal dimensions and tolerances of tool members, it is most important to very carefully establish the dimensional changes of the compact under production-like compacting and sintering conditions.

Dimensional change data from previously produced parts of similar shape and composition may be a good guidance. To rely solely on data established under laboratory conditions is risky. In this context, it must be kept in mind that dimensional changes during sintering are sensitive not only to variations in sintering temperature and time but also to variations in powder composition and compact density. We demonstrate the procedure of calculating the transversal dimensions of a compacting tool for the case of a straight bushing. The drawing of the bushing specifies:

- Outer diameter = \( D_a \), tolerance = \( +\Delta D_a \)
- Inner diameter = \( D_i \), tolerance = \( -\Delta D_i \)

From previous production of similar bushings, the following data are known: average spring-back after compacting = \( e \) %, average dimensional change during sintering = \( s \) % (+ for swelling, - for shrinkage). The tool dimensions to be calculated are: inner diameter of the die = \( d_m \), and outer diameter of the core rod = \( d_k \). It is to be expected that, due to wear during production, the inner diameter of the die \( (d_m) \) increases and the outer diameter of the core rod \( (d_k) \) decreases.

In order to keep the dimensions of the sintered bushing within specified tolerances, the following limitations have to be observed when dimensioning die and core rod:

\[
\frac{D_a + \Delta D_a}{1 + e + s} > d_m > \frac{D_a}{1 + e + s} 
\]  \hspace{1cm} (5.3)

and

\[
\frac{D_i}{1 + e + s} > d_k > \frac{D_i - \Delta D_i}{1 + e + s} 
\]  \hspace{1cm} (5.4)
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Theoretically, the optimal utilization of die and core rod would be attainable if the initial value of \( d_m \) is as small as the right side of (5.3) allows, and the initial value of \( d_k \) as large as the left side of (5.4) allows. In order to make sure that the dimensions of the sintered bushings are within specified tolerances even in case dimensional changes \( e \) and \( s \) should vary, the specified tolerance ranges are narrowed at both ends by 20%. In other words, it is being assumed that the specified limits are \( D_a + 0.2\Delta D_a \) and \( D_i - 0.8\Delta D_i \) for the outer and \( D_i - 0.2\Delta D_i \) and \( D_i - 0.8\Delta D_i \) for the inner diameter of the bushing. Thus, for the inner diameter of the die and for the outer diameter of the core rod, the following relationships are stated:

\[
d_m = \frac{(D_a + 0.2\Delta D_a)}{(1 + e + s)} \quad (5.5)
\]
\[
d_k = \frac{(D_i - 0.2\Delta D_i)}{(1 + e + s)} \quad (5.6)
\]

Consequently, the allowable wear on the die is:

\[
\Delta d_m = 0.6\Delta D_a/(1 + e + s) \quad (5.7)
\]

and the allowable wear on the core rod is:

\[
\Delta d_k = -0.6\Delta D_i/(1 + e + s) \quad (5.8)
\]

Applying equations (5.5) to (5.8) to the structural part shown at Fig. 5.15, we can now calculate the final transverse dimensions of the compacting tool. According to specifications on the drawing, the outer diameter of the higher portion of the part is \( D_a = 23.90 \) mm with tolerance \( \Delta D_a = +0.20 \) mm, and its inner diameter is \( D_i = 12.00 \) mm with tolerance \( \Delta D_i = -0.018 \) mm. We assume that the average spring-back is \( e = +0.1\% \) and the average dimensional change during sintering is \( s = +0.4\% \). On the basis of these data, we obtain for the initial values of the inner diameter \( d_m \) of the die and of the outer diameter of the core rod \( d_k \):

\[
d_m = (23.90 + 0.2/5)/1,005 = 23,821 \ mm
\]
\[
d_k = (12 - 0.018/5)/1,005 = 11,937 \ mm
\]

and for the allowable wear:

\[
\Delta d_m = (0.6/5)/1,005 = 0,119 \ mm
\]
\[
\Delta d_k = -(0.054/5)/1,005 = -0,011 \ mm
\]
5.3 DESIGNING A COMPACTING TOOL

The remaining tool dimensions can be calculated analogously. A small computer program takes quickly and reliably care of these calculations. It is recommendable to collect, in a synoptical table, all important dimensional data, pertaining to a structural part to be produced or already in production. See e.g. Table 5.2.

Table 5.2 Dimensional data pertaining to the component shown at Fig. 5.15

<table>
<thead>
<tr>
<th>B</th>
<th>Z (mm)</th>
<th>S (mm)</th>
<th>P (mm)</th>
<th>K (mm)</th>
<th>W (mm)</th>
<th>V (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D₁(1)</td>
<td>23.90+0.20</td>
<td>≥23.940</td>
<td>≥23.845</td>
<td>23.821</td>
<td>23.817*0.009</td>
<td>+0.119</td>
</tr>
<tr>
<td>D₁(1)</td>
<td>12.00-0.018</td>
<td>≤11.996</td>
<td>≤11.949</td>
<td>11.937</td>
<td>11.943*0.006</td>
<td>-0.011</td>
</tr>
<tr>
<td>D₁(2)</td>
<td>15.90+0.20</td>
<td>≥15.940</td>
<td>≥15.861</td>
<td>15.877</td>
<td>15.856*0.008</td>
<td>+0.119</td>
</tr>
<tr>
<td>D₁(2)</td>
<td>6.00+0.011</td>
<td>≤5.997</td>
<td>≤5.973</td>
<td>5.976</td>
<td>5.978*0.009</td>
<td>-0.009</td>
</tr>
<tr>
<td>L</td>
<td>16.95+0.10</td>
<td>17.00</td>
<td>16.932</td>
<td>16.916</td>
<td>16.912*0.008</td>
<td>0.000</td>
</tr>
</tbody>
</table>

L = central distance of the two bores D₁(1) and D₁(2)
B = designation
Z = dimension and tolerance specified on customer's drawing
P = allowable average dimension after compacting in virgin tool
S = allowable average dimension after sintering (at the beginning of tool usage)
K = guiding measure for tool design
W = virgin tool dimension (manufacturing tolerance IT 4)
V = allowable wear
spring-back = 0.1%; dim. change after sintering = 0.4% (assumed values)

The dimensions (W) given in table 5.2 are referring to die and core rod sizes, as the die and core rods actually form the profile of the component, whereas the punches only form the faces. The punches are marked with a clearance dimension, but no tolerance, and a note is added setting the actual clearance in terms of the die or core rods. This is important, because the clearances involved are so small, that to state a separate tolerance for both die and punch, would mean a greater variation in actual clearance than is practical.

As an example, a circular die cavity can be ground and lapped to a tolerance 0.005 mm and a circular punch can be made to a similar tolerance, thus giving a total tolerance for the two parts of 0.010 mm. If we require a clearance between die and punch of 0.010 to 0.015 mm, it is clear that it is better to state a tolerance only for the die which actually forms the profile of the compact, and give the punch size as a clearance rather than as a size with a tolerance. This method gives the toolmaker a better opportunity to produce an effective clearance without working to impossible tolerances.
5. COMPACTING TOOLS

Clearance recommendations vary, depending on compacting pressure, type of powder and other circumstances. Makers of bushings use clearances as small as 0.005 to 0.010 mm in some cases, but generally accepted clearances are given in Table 5.3.

<table>
<thead>
<tr>
<th>Tool Dimension (mm)</th>
<th>Clearance (= IT 5) (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 10</td>
<td>10 - 15</td>
</tr>
<tr>
<td>10 - 18</td>
<td>12 - 18</td>
</tr>
<tr>
<td>18 - 30</td>
<td>15 - 22</td>
</tr>
<tr>
<td>30 - 50</td>
<td>18 - 27</td>
</tr>
<tr>
<td>50 - 80</td>
<td>21 - 32</td>
</tr>
<tr>
<td>80 - 120</td>
<td>25 - 38</td>
</tr>
</tbody>
</table>

When applying the approximate clearances recommended in Table 5.3, it must be kept in mind that punches expand elastically under the compacting load. This means that the clearance between die and punches decreases and the clearance between core rod and punch increases. The application of such narrow clearances to profiled dies and punches presents a difficult toolmaking problem, but the satisfactory running of the tool over a reasonable period does not permit greater clearances.

A prerequisite for a long tool-life is an extremely good finish on all sliding surfaces (typical: 0.2 μm) and a proper pairing of the surface hardnesses of the sliding partners. Here applies an old rule from mechanical engineering: Sliding partners should not be made from exactly the same material and must have different surface hardnesses.

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5.3 DESIGNING A COMPACTING TOOL
5. COMPACTING TOOLS

5.3.3 Tool Materials

Punches.
As has been mentioned before, powders are usually compacted with pressures between approx. 300 and 650 N/mm². All punches of the compacting tool have to withstand these high loads not only once but several 100,000 to 1,000,000 times without breaking or getting plastically deformed. Neither may they under these loads expand elastically to such extend that they jam in the die. Even an ever so small amount of plastic deformation during one compacting cycle would, after a number of cycles, lead to a sizable shortening and thickening of the punch. It does not take much imagination to realize the consequences: As the punch gets shorter, the height of the compacts increases correspondingly, and as the punch gets thicker, it eventually jams in the die and breaks and possibly damages the entire tool.

Thus, punches must possess high compressive yield strength, high toughness and high fatigue strength. In cases where punches form part of the side walls of the compacting tool, they must, in addition to the mentioned properties, have a sufficiently high surface hardness. Surface-hardening of punches, if necessary, has to be carried out with great care, in order to avoid embrittlement and surface cracking. Only the toughest types of tool steels are suitable for punches. Ideally, they should combine the following properties:

- Good machineability when soft-annealed.
- Highest possible toughness and fatigue strength after hardening.
- Highest possible dimensional stability and lowest possible susceptibility to cracking in the hardening procedure.
- Highest possible wear resistance.

Selecting the right tool steel for a particular punch, and choosing the appropriate heat-treatment, is mainly a matter of experience. Specification charts and heat-treating suggestions provided by steel makers can be helpful.
5.3 DESIGNING A COMPACTING TOOL

Properties and heat-treating suggestions for three typical tool steels suitable for punches are presented in Table 5.4.

Table 5.4 Properties of Tool Steels suitable for Punches

<table>
<thead>
<tr>
<th>Swedish Steel Standard</th>
<th>SIS 2140</th>
<th>-</th>
<th>SISI 2550</th>
</tr>
</thead>
<tbody>
<tr>
<td>German Steel Standard</td>
<td>~105WCr6</td>
<td>90MnV8</td>
<td>50NiCr13</td>
</tr>
</tbody>
</table>

**ANALYSIS:**

<table>
<thead>
<tr>
<th></th>
<th>%</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Si</td>
<td>Mn</td>
<td>Cr</td>
</tr>
<tr>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.95</td>
<td>-</td>
<td>1.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Si</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mn</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cr</td>
<td>0.85</td>
<td>0.1</td>
<td>0.85</td>
<td>0.12</td>
</tr>
<tr>
<td>Ni</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>Mo</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>W</td>
<td>0.5</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>V</td>
<td>0.1</td>
<td>0.12</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Normalizing temperature °C:**

- 800 – 820
- 800 – 820
- 790 – 810

**Annealing Temperature °C:**

- 750 – 770
- 690 – 710
- 740 – 760

**Hardness after anneal. HB:**

- 190 – 210
- 180 – 200
- 220 – 250

**Machineability:**

- Good
- Good +
- Fair -

**HARDENING:**

<table>
<thead>
<tr>
<th></th>
<th>Fair</th>
<th>Fair</th>
<th>Good</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance to decarburization</td>
<td>790 – 810</td>
<td>770 – 810</td>
<td>790 – 810</td>
</tr>
<tr>
<td>Austenitizing temperature °C</td>
<td>oil or salt bath</td>
<td>oil or salt bath</td>
<td>oil or salt bath</td>
</tr>
<tr>
<td>Tempering temperature °C</td>
<td>250 – 260</td>
<td>230 – 240</td>
<td>260 – 270</td>
</tr>
<tr>
<td>Hardness after tempering HRC</td>
<td>62 – 50</td>
<td>63 – 50</td>
<td>58 – 50</td>
</tr>
<tr>
<td>Dimensional stability</td>
<td>Good +</td>
<td>Good +</td>
<td>Good +</td>
</tr>
<tr>
<td>Distortion or warping stability</td>
<td>Medium when oil quenching</td>
<td>Medium when oil quenching</td>
<td>Best when oil quenching, Best</td>
</tr>
<tr>
<td>Wear resistance</td>
<td>Fair +</td>
<td>Fair</td>
<td>Good +</td>
</tr>
<tr>
<td>Toughness</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>

**Wear resistance**

- Fair +
- Good

**Toughness**

- Good

**DIES AND CORE RODS.**

Dies and core rods should best be made from cemented carbides. Although being much more expensive than steel, cemented carbides, because of their extremely high hardness and superior wear resistance, are the most economic choice for large production series.

For shorter series, however, certain high-speed steels are a less expensive alternative. Due to their high content of hard carbides embedded in a tough steel matrix, high-speed
steels are quite wear-resistant, though not on par with cemented carbides. Cemented carbide dies must always be backed up by a shrink-ring of tough steel to prevent it from bursting under the high radial pressure exerted upon its inner wall during the compacting procedure. The shrink-fitting process provokes high compressive tangential stresses in the inner wall of the die, increasing its wear resistance even further. The ratio between outer and inner diameter of the shrink-ring should be at least 2:1, or better, 4:1.

Sharp corners or incisions in the profile of the die cavity should be avoided, since they provoke high tangential tensile stresses which might burst the die. On the other hand, when the shape of the structural part requires sharp corners or incisions in the die, it is not necessarily a disaster if the die should crack, because in most cases, the shrink-ring keeps the cracked die in place.

As can be seen, e.g. from the drawing at Fig. 5.17, core rods are usually much longer than the punches in which they are guided. During the compacting and during the ejecting phase, core rods are, via frictional forces, subjected alternately to high compressive and high tensile stresses, especially if they are thin and have complicated profiles. Core rods should, therefore, be as tough and fatigue resistant as possible. But this requirement is obviously in conflict with the demand for highest possible wear resistance, i.e. highest possible surface hardness. This conflict can be solved, e.g. in one of the following two ways:

a) The core rod is made in one piece, heat-treated for toughness and induction-hardened at its upper end where it is exposed to wear.

b) The core rod is made in two pieces, one short upper piece of cemented carbide which is joined, by one or another method, to a long lower piece of tough-hardened steel.
5.4 Further Recommendations

**Symmetrical Load Distribution on Punches.**

The tool assembly on the press should be carefully centered, to warrant the punches being loaded as symmetrically as possible during compacting. For punches with circular or regular cross-section, their cross-sectional center of gravity can easily be brought in line with the center line of the press, and frictional forces act symmetrically upon their lateral faces.

Achieving a symmetrical load distribution, on punches with unsymmetrical cross-sections, is a more complicated affair. Their cross-sectional center of gravity can certainly be brought in line with the center line of the press, but frictional forces do not act symmetrically upon their lateral faces. Since those frictional forces cannot be calculated very accurately in beforehand, the optimal centering of the tool assembly on the press may constitute a serious problem.

In a badly centered tool, punches get out of parallel with die and core rods when subjected to the compacting load. They scrape hard on die and core rods, causing excessive local wear which, if not detected and corrected in time, leads to a complete break-down of the tool. When loaded unsymmetrical, thin and sleeve-like punches tend to bend elastically to such degree, that clearances between them and the die wall get out of concentricity. At places of enlarged clearance, powder is being extruded into the gap, forming excessive burrs on the face of the compact. At places of narrowed clearance, punches scrape hard on die walls and core rods. This leads to excessive tool wear and increases the risk of jammed punches and broken core rods. An uneven density distribution adds to this effect.

**Influence of Profiles.**

For good functionality and long life of the various tool members it is important, not only to choose the right tool material but also to avoid profiles that provoke high stress peaks under load. Photo-elastic stress analysis with plexi-glass models can help to avoid unsuitable shapes and profiles. In particular, the following points should be observed:

- Avoid sharp corners and edges on the cross-sectional profiles of die, punches and core rods.
- Avoid sharp-edged protrusions or incisions on punch faces.
- Avoid core rod diameters smaller than 1/3- to 1/5 the length of the core rod’s portion in contact with the powder.

In order to avoid kinking under load, keep unguided portions of core rods and connecting rods as short as possible.
5. COMPACTING TOOLS

The strict observation of these recommendations helps to increase the fatigue strength and wear resistance of tool members, and to prevent stress-induced cracks during the heat-treatment of the tool and later when it is operating.

5.4.1 Tooling Costs

The manufacturing costs of compacting tools can vary between some 10 000 and 100 000 US $, depending on size and number of separately moveable parts. Tools for long series of compacts must, of course, be designed for maximal possible tool-life. This means: cemented carbides for the die and for the shaping segments of the core rods, high quality steel and optimal heat-treatment for the punches, maximum surface finish on all sliding faces, and a perfect fit between die, punches and core rods - in other words, high material and workshop costs.

The plain material costs for a compacting tool amount to approx. 15% of the total manufacturing costs (designing cost not included). With very complicated tools, the share of material costs is even smaller. This makes it clear that saving on material costs often turns out to be saving at the wrong end. Costs for waste, tool repair, production losses, and delayed delivery, as consequences of failing tool materials or sloppy tool assembling, can amount to a multiple of the total initial tooling costs.

Designing times, even when computer-aided, can easily accumulate to several weeks if the tool is of a more complicated type. Computer-aided design and machining (CAD/CAM), as well as computer-controlled production procedures, are spreading today even within the PM industry. But they are no substitute for the creativity of the tool designer or for the experience and skill of the toolmaker.

From the standpoint of economy, it is important to carefully watch the performance of any particular tool during its entire life-time, and to document pedantically character and cause of any malfunction of the tool as well as the life of each tool member. Only by such systematic routine, a reliable tool know-how can be accumulated, which helps to avoid future mistakes in tool design and toolmaking.
References