Table 2.1 Worldwide Usage of Iron Powder for Sintered Parts

	Unalloyed Iron Powders				Low-alloyed Iron Powders		All Iron Powders	
	compact densities 5.5 to 7.0 g/cm^3		compact densities > 7.0 g/cm^3		compact densities > 6.7 g/cm^3		compact densities > 5.5 g/cm^3	
Year	tons	%	tons	%	tons	%	tons	%
1965	35 000	100.0	–	0.0	–	0.0	35 000	100.0
1975	120 000	92.3	10 000	7.7	–	0.0	130 000	100.0
1985	180 000	70.6	50 000	19.6	25 000	9.8	255 000	100.0
1995	300 000	53.6	200 000	35.7	60 000	10.7	560 000	100.0

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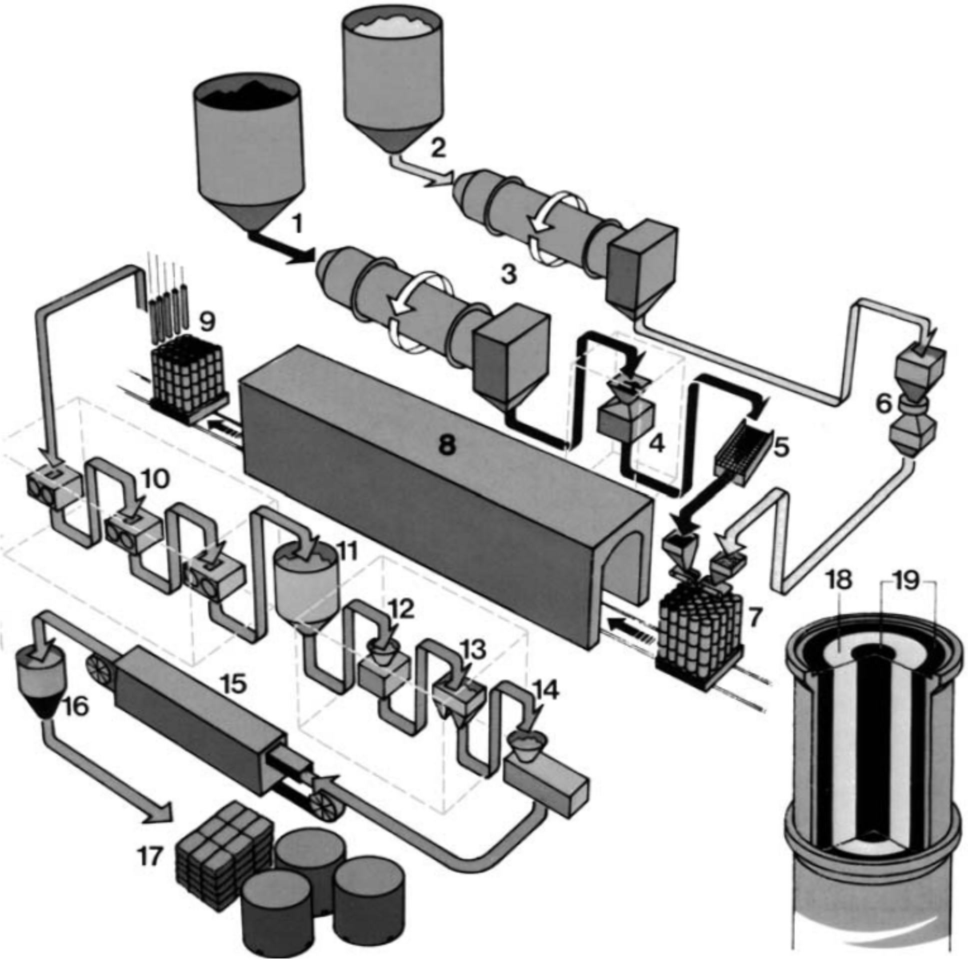
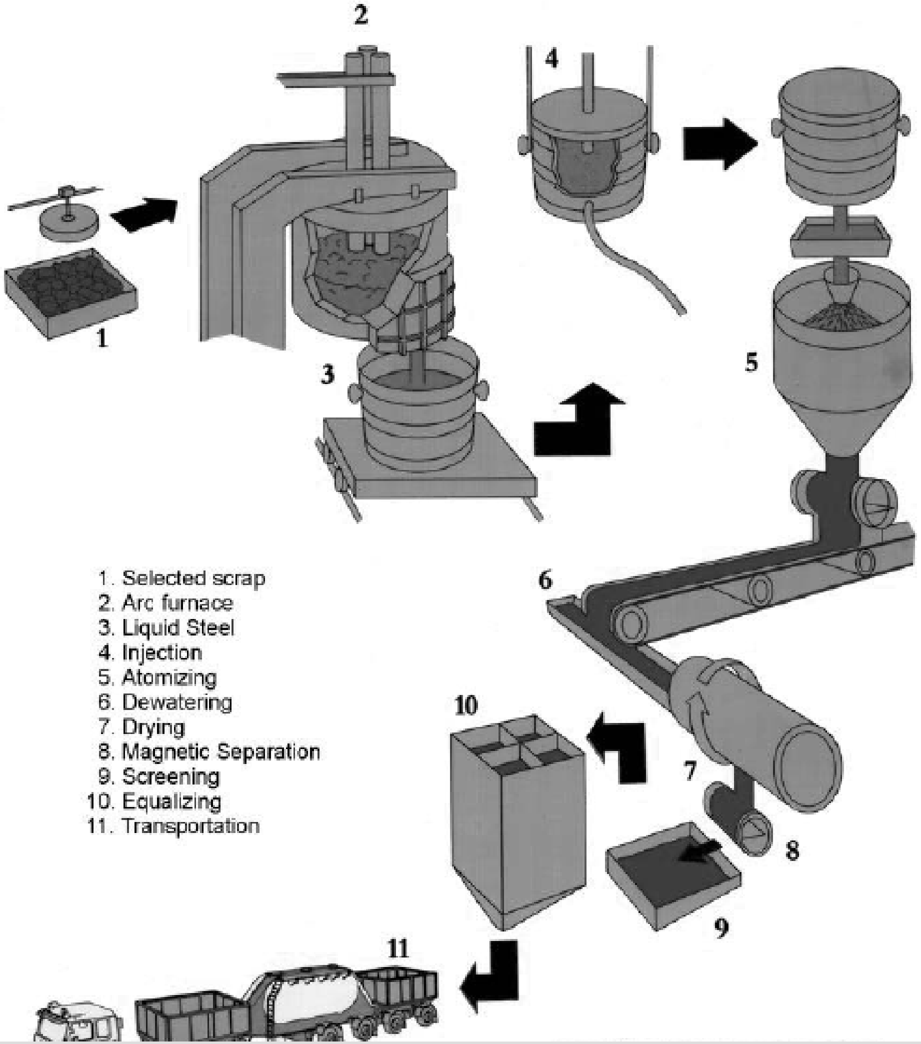
Szinter technológia



1. Reduction Mix of Coke Breeze and Limestone
2. Iron Ore
3. Drying
4. Crushing
5. Screening
6. Magnetic Separation
7. Charging in Ceramic Tubes
8. Reduction in Tunnel Kilns, Approximately 1200°C
9. Discharging
10. Coarse Crushing
11. Storage in Silos
12. Chrusing
13. Magnetic Separation
14. Grinding and Screening
15. Annealing in Belt Furnace, Approximately 800-900° C
16. Equalising
17. Automatic Packing
18. Iron Ore
19. Reduction Mix

These retorts are standing, 25 each, on rail-bounded cars which are clad with a thick layer of refractory bricks. These cars are traveling slowly through a tunnel kiln of approx. 260 m length (8) within which the retorts are gradually heated to a maximum temperature of approx. 1200°C. As the temperature inside the retorts increases, the coke breeze begins to burn forming CO which, in turn, begins to reduce the magnetite to metallic iron while itself oxidizing to CO_2.

The so generated CO_2 reacts with the remaining coke breeze forming new CO, which again reduces more magnetite to metallic iron. This reaction cycle continues until all magnetite has been reduced to metallic iron and the major part of coke breeze is burned up. Parallel to the reduction cycle, the limestone in the reduction mix binds the sulfur arising from the burning coke breeze.


1
2
3
4
5
6
7
8
9
10
11
1. Selected scrap
2. Arc furnace
3. Liquid Steel
4. Injection
5. Atomizing
6. Dewatering
7. Drying
8. Magnetic Separation
9. Screening
10. Equalizing
11. Transportation

BOSCH

Homogeneously alloyed powders.

Advantages:

- Alloying elements do not segregate when the powder is handled .
- Yield fully homogeneously alloyed sintered parts.

Disadvantages:

- Have low compressibility, because their particles are solution-hardened. (*See Figs. 2.3 and 2.5*).
- In order to change or correct the composition of a fully alloyed powder, if ever so little, a new melt (usually 50 tons at time) will have to be atomized.

Powder mixes.

Advantages:

- Have higher compressibility. (*See Fig. 2.5*).
- No additional mixing operation is required as the powder has to be admixed with a lubricant anyway.
- The composition of a powder mix can very easily be changed or corrected by re-mixing it with additional amounts of either iron powder or alloying elements.

Disadvantages:

- Yield less homogeneously alloyed sintered parts, because the admixed alloying elements (except carbon) diffuse very slowly in solid iron.
(*ref. Chapter 6, Figs. 6.9 and 6.10*).
- Alloying elements tend to segregate when the powder mix is transported and handled. (However, powder mixes can be made segregation-proof by means of special treatments as described in the following paragraph).

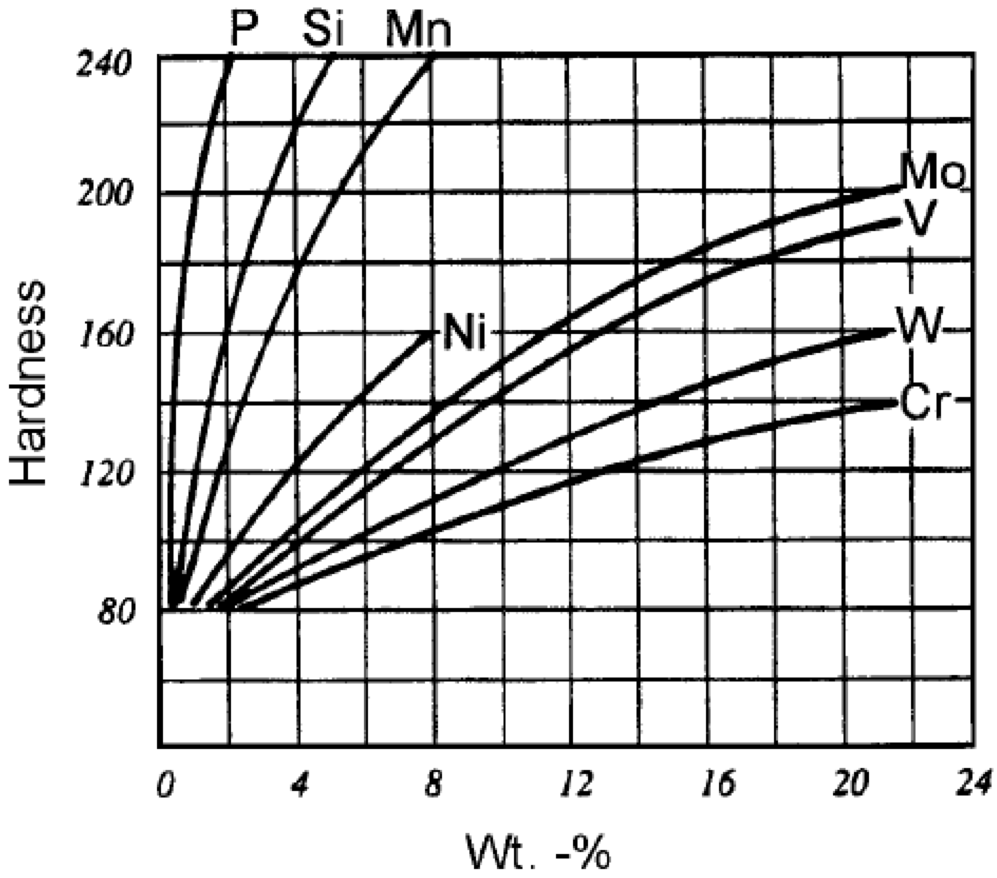
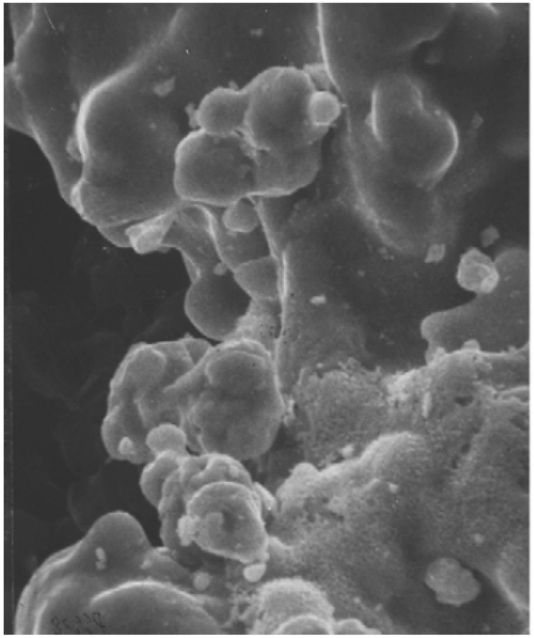
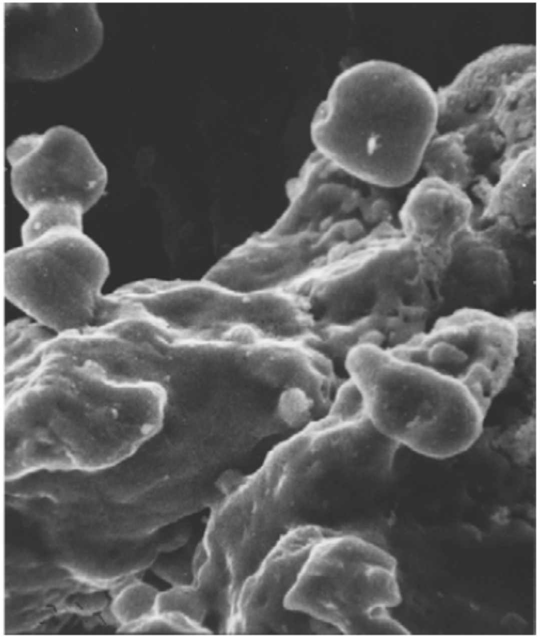


Figure. 2.3. Influence of some alloying elements on the hardness of iron.

The Distaloy™ process can be described as follows:
Alloying elements used in the Distaloy™ process are mainly copper, nickel and molybdenum (but not graphite!) in the form of very finely grained powders. The process starts with weighing-in a production lot of 30 tons of iron powder and alloying powders in exactly controlled proportions. This lot is mixed in a double-cone mixer. Special precautions are taken to prevent segregation of the mix when discharged from the mixer.





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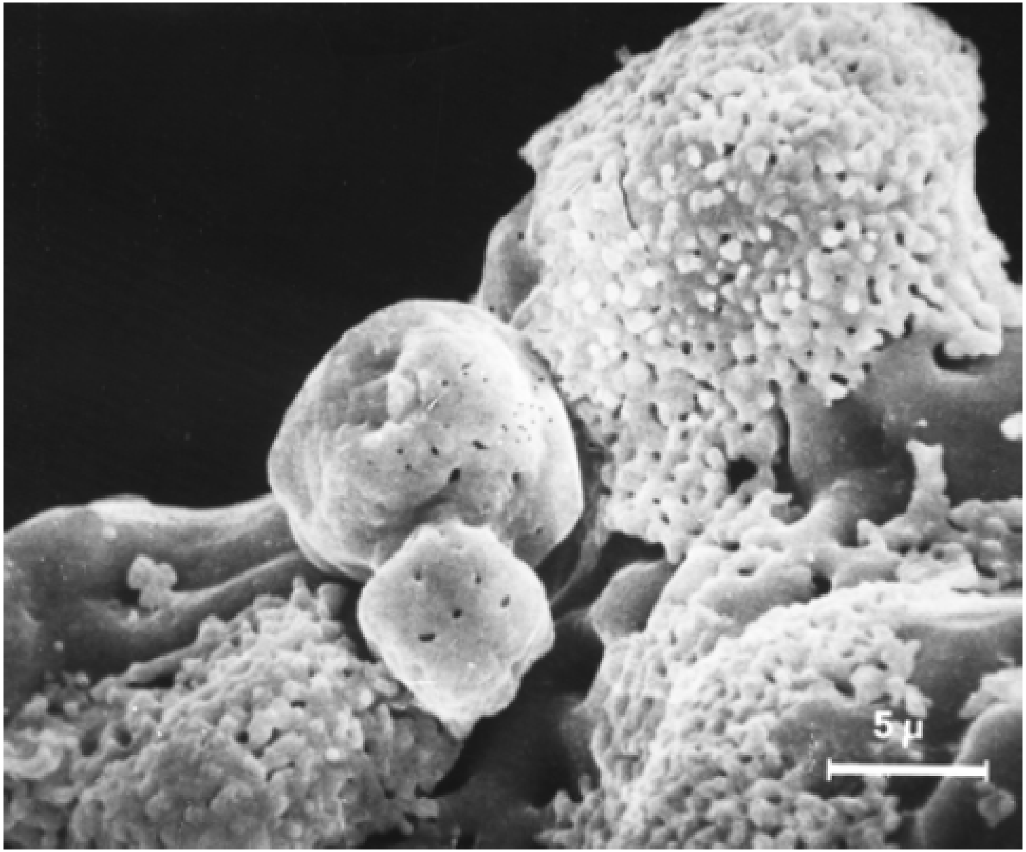

5 µ

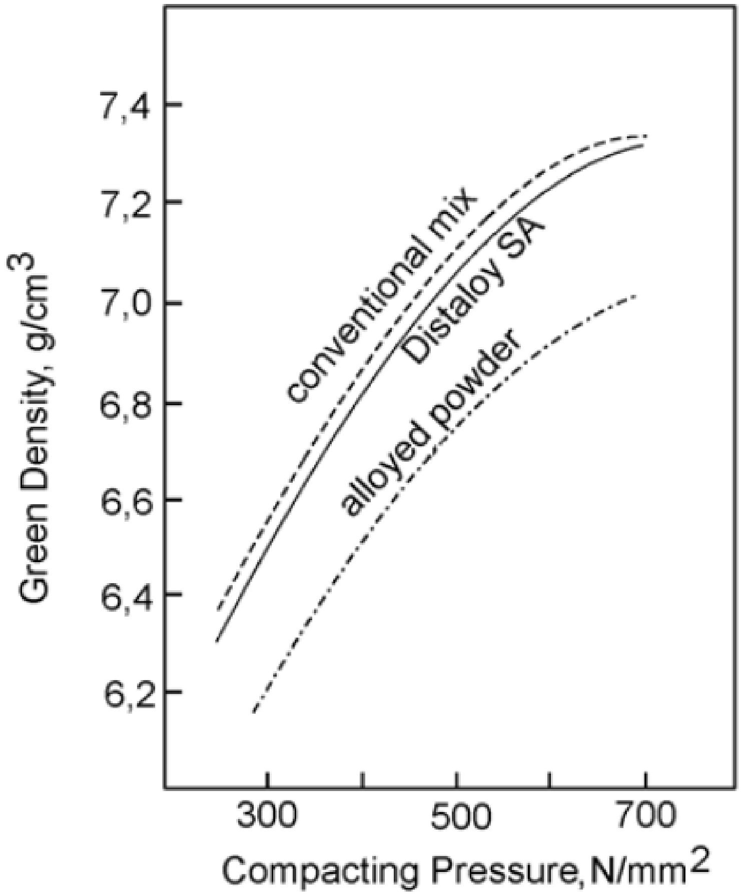


Figure. 2.5. Compressibility curves for three ferrous powders produced by different methods but having the same chemical composition: 1.75% Ni, 1.5% Cu, 0.5% Mo, remainder Fe.

The Starmix process uses special types of organic binders to glue graphite and lubricants to the iron powder particles during the mixing procedure.
See SEM-photograph at Fig. 2.6.

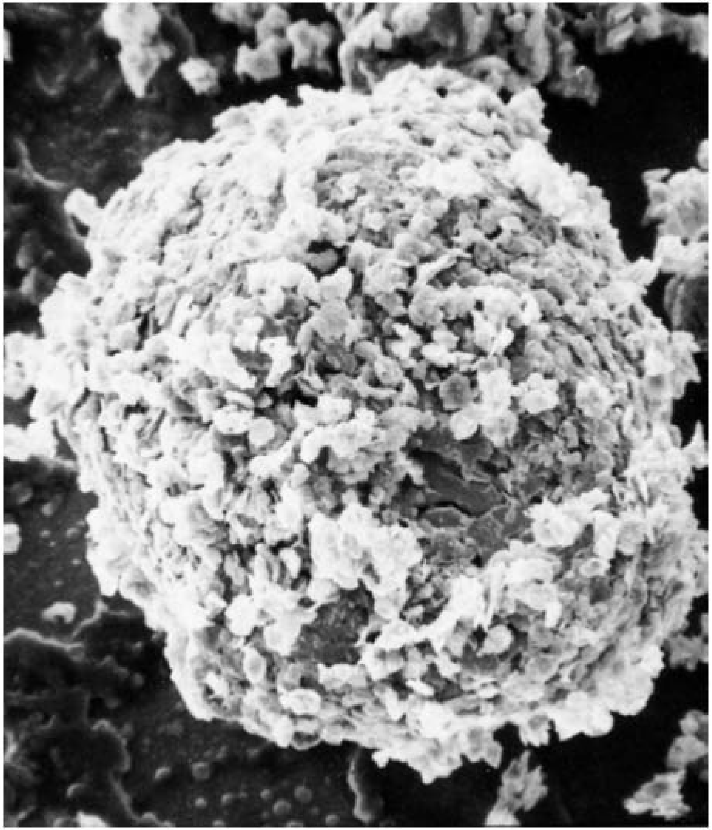
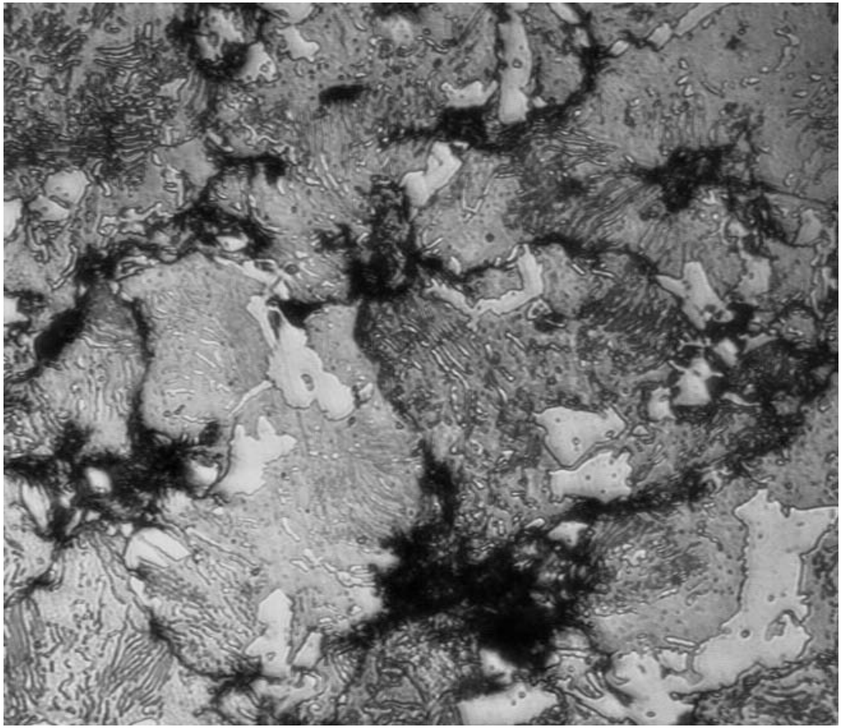
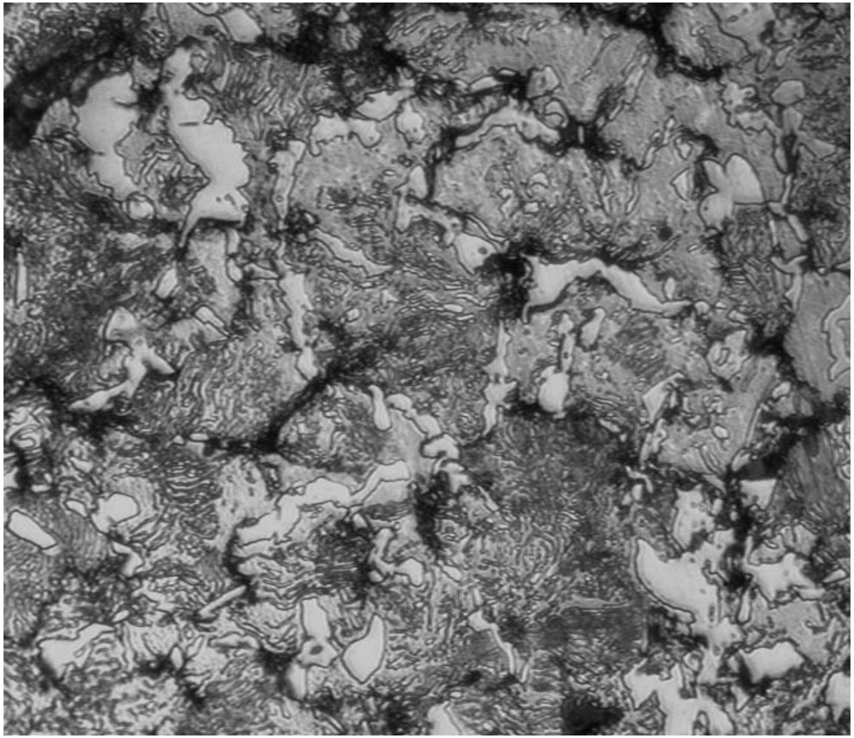


Figure. 2.6. SEM-photograph showing fine graphite particles glued, in the Starmix process, to the surface of an iron powder particle (NC100.24).

Szinter technológia





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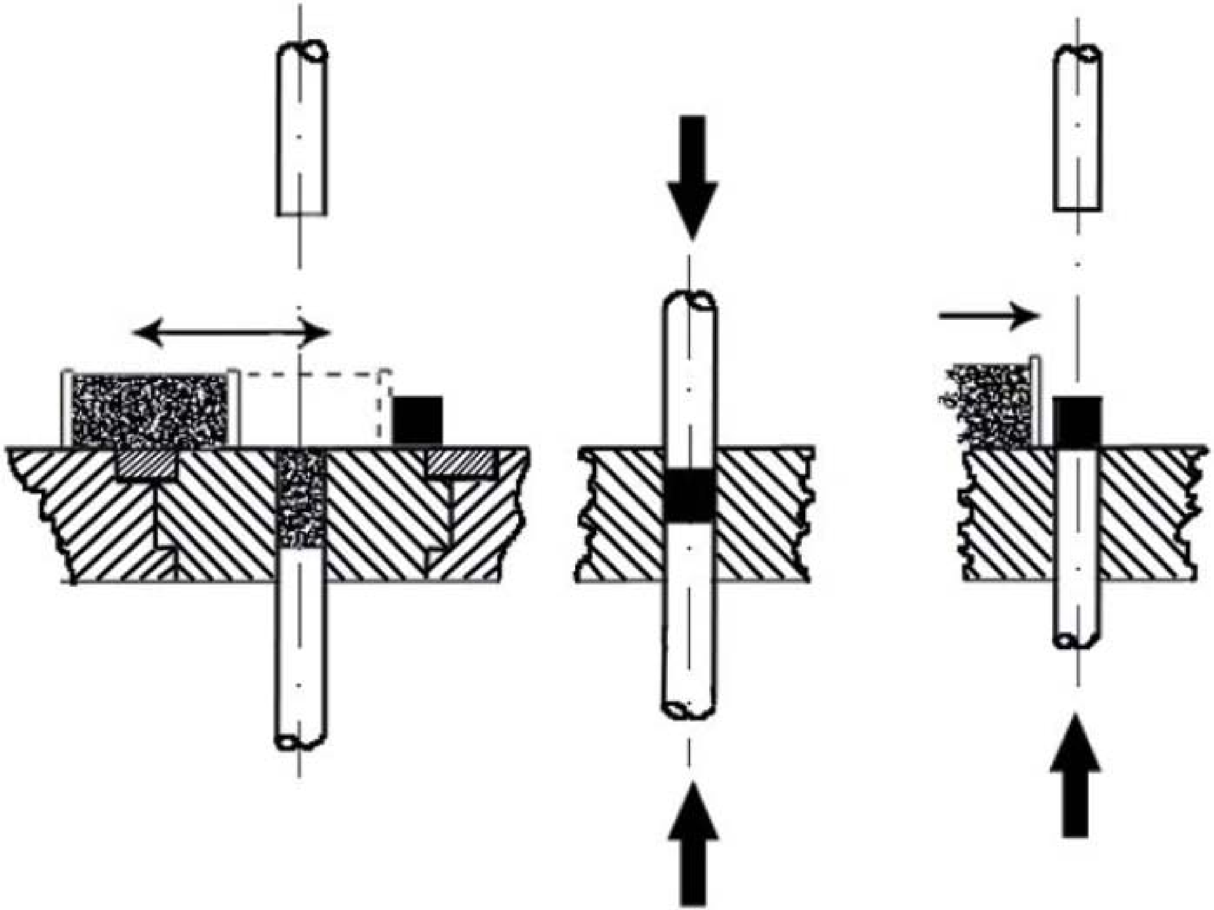

1. All portions of the die cavity must, in a reliable way, be filled with exact amounts of powder.
2. The density distribution in the compact should be as homogeneous as possible.
3. In all portions of the die cavity, the densification of the powder should take place simultaneously, in order to warrant 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.

BOSCH

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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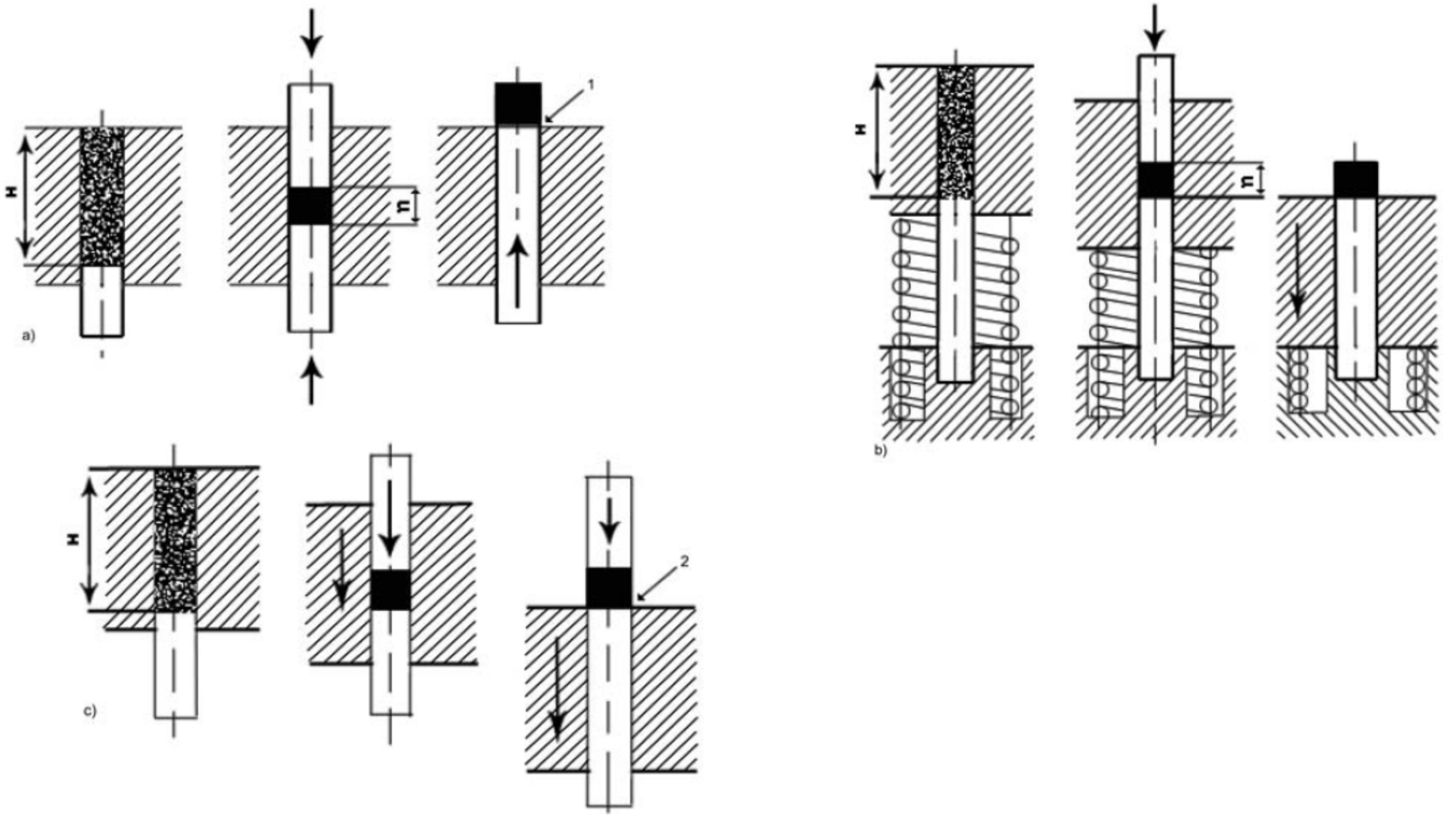
In most cases, it is best for the properties of the compact if the zone of lowest density, the *neutral zone*, is located approx. half-way between top and bottom of the compact.



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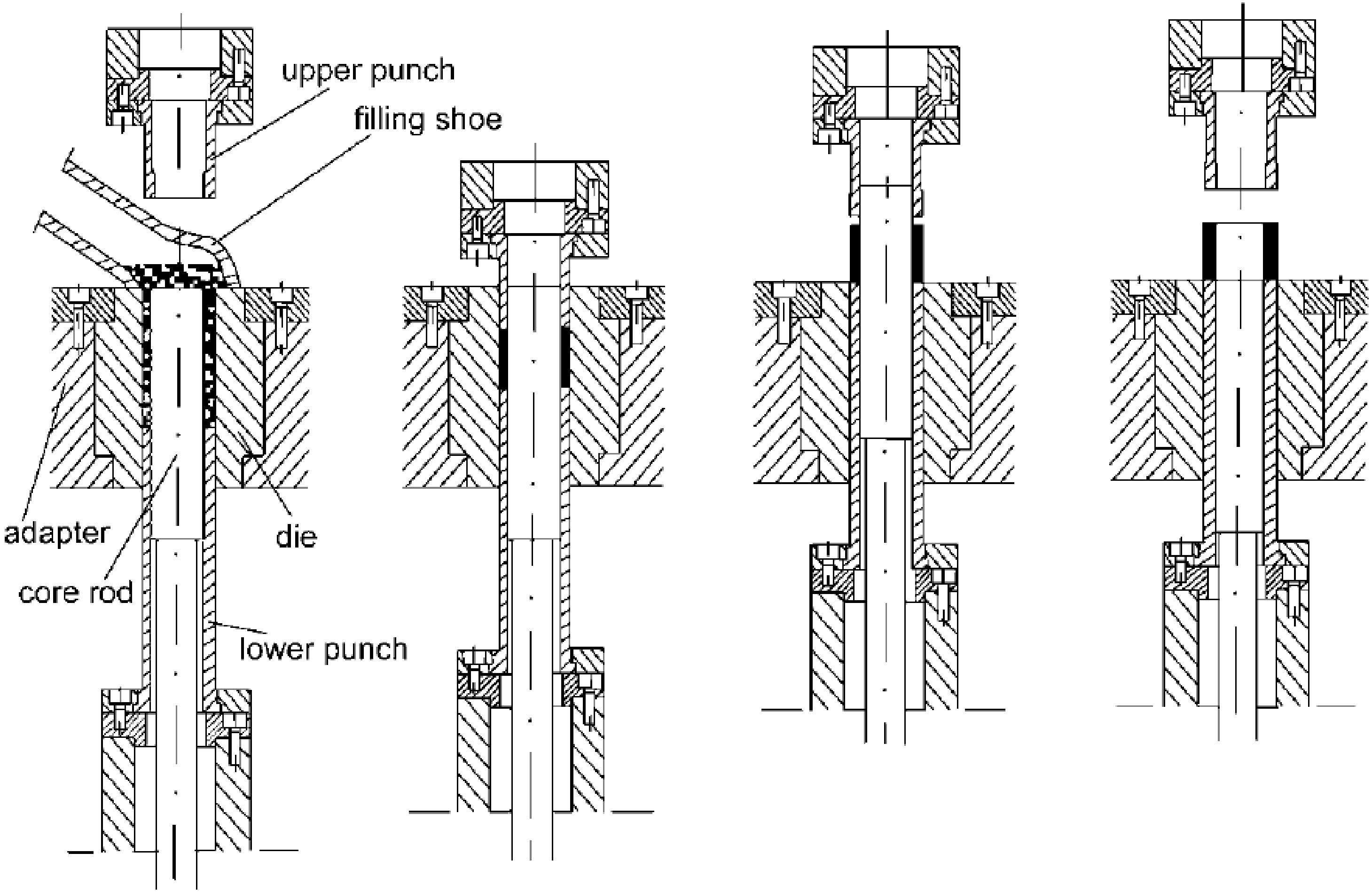


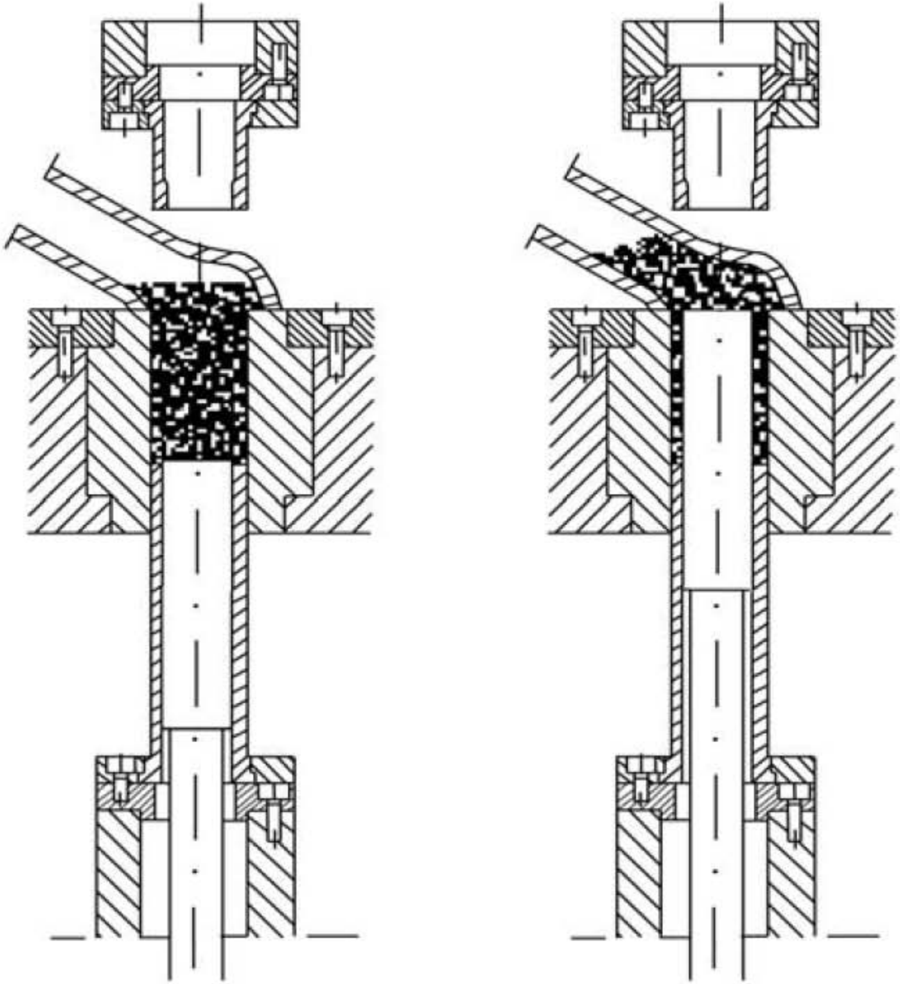
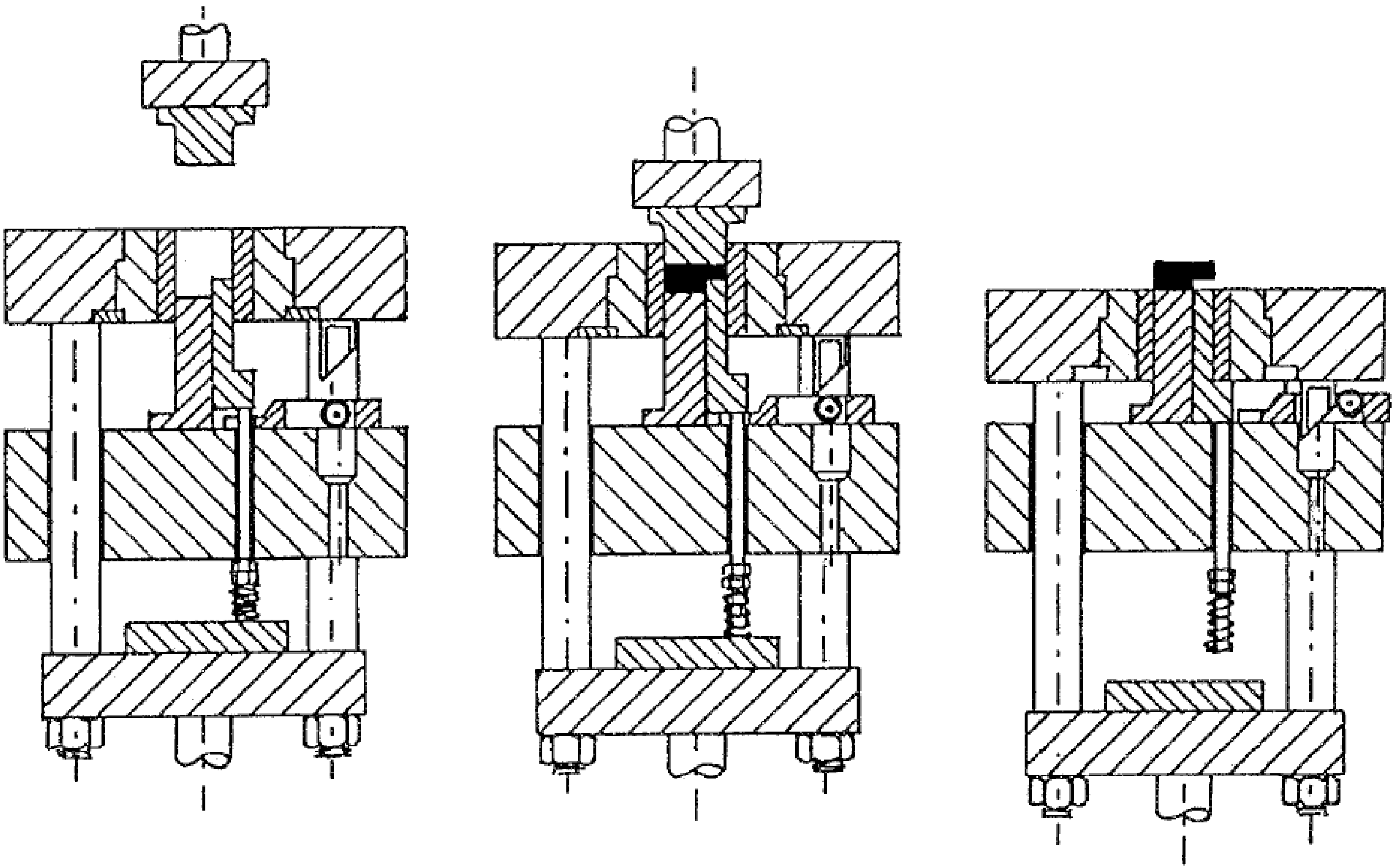
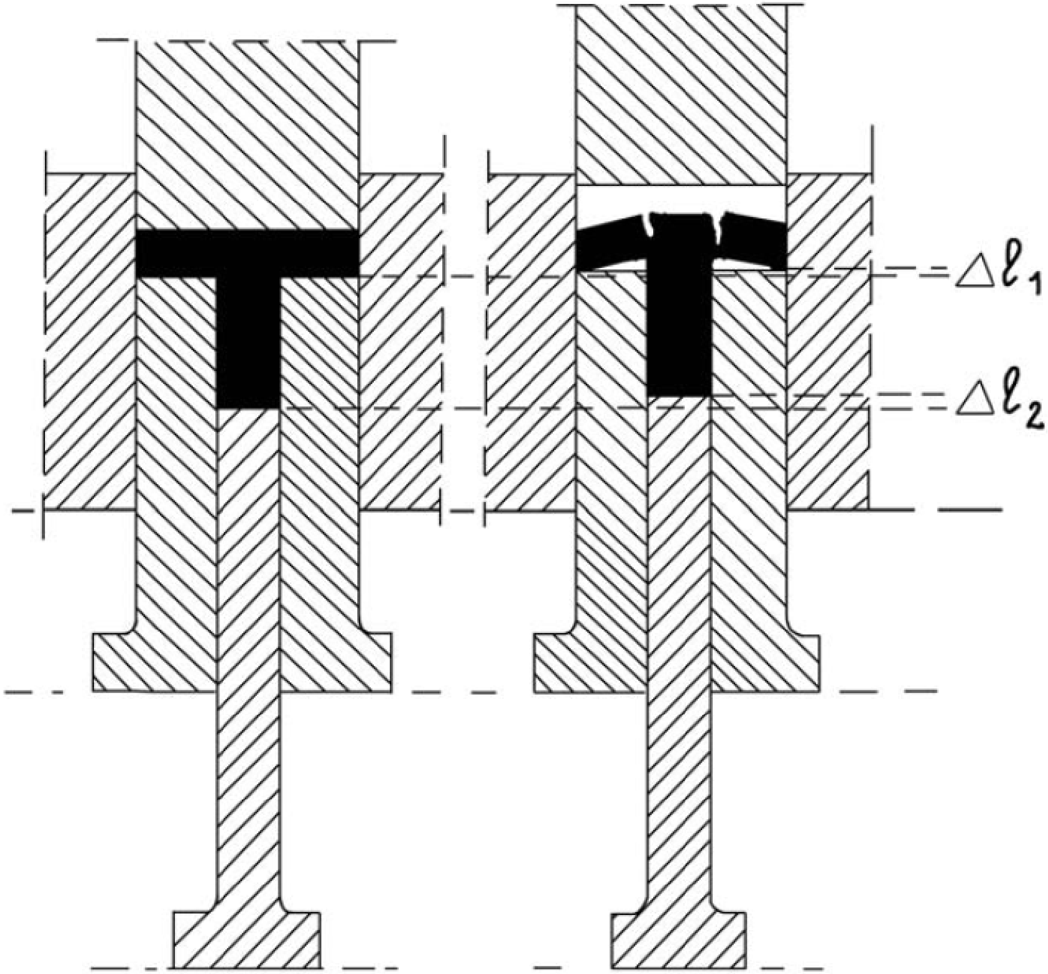


Figure. 5.5 Filling of the die cavity with the core rod withdrawn.

Szinter technológia




Δℓ₁
Δℓ₂

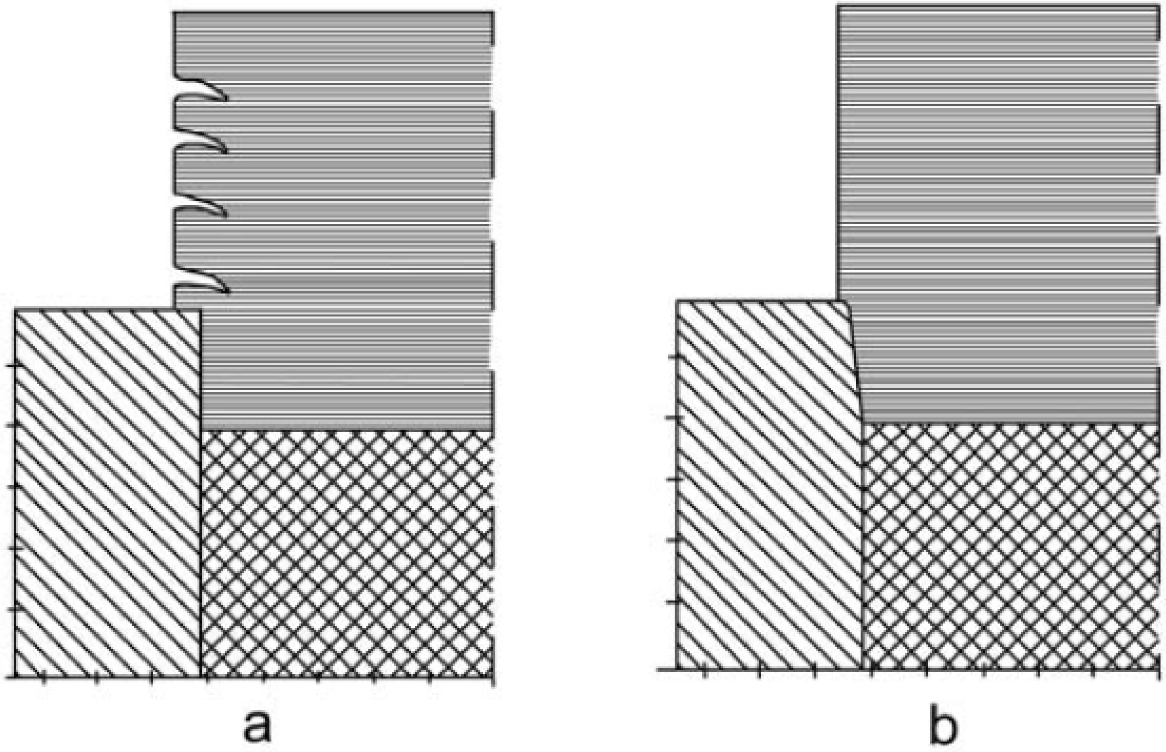


Figure. 5.8 Ejection procedure:
a) crack formation as the compact passes a sharp upper rim of the die cavity,
b) crack formation avoided by tapering the die exit and rounding-off the upper rim of the die cavity.

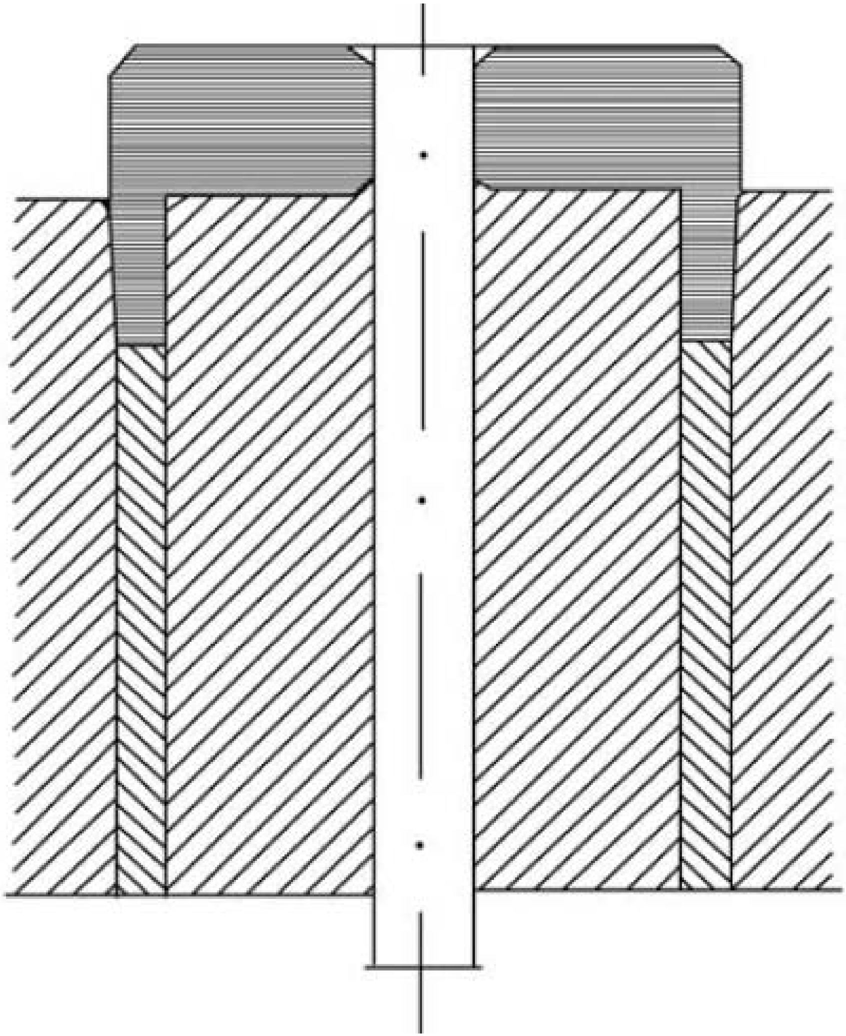


Figure. 5.9 Ejection procedure: risk of crack formation between the sturdy upper segment and the thin skirt-like lower segment of a compact (e.g. shock absorber piston).

Szinter technológia

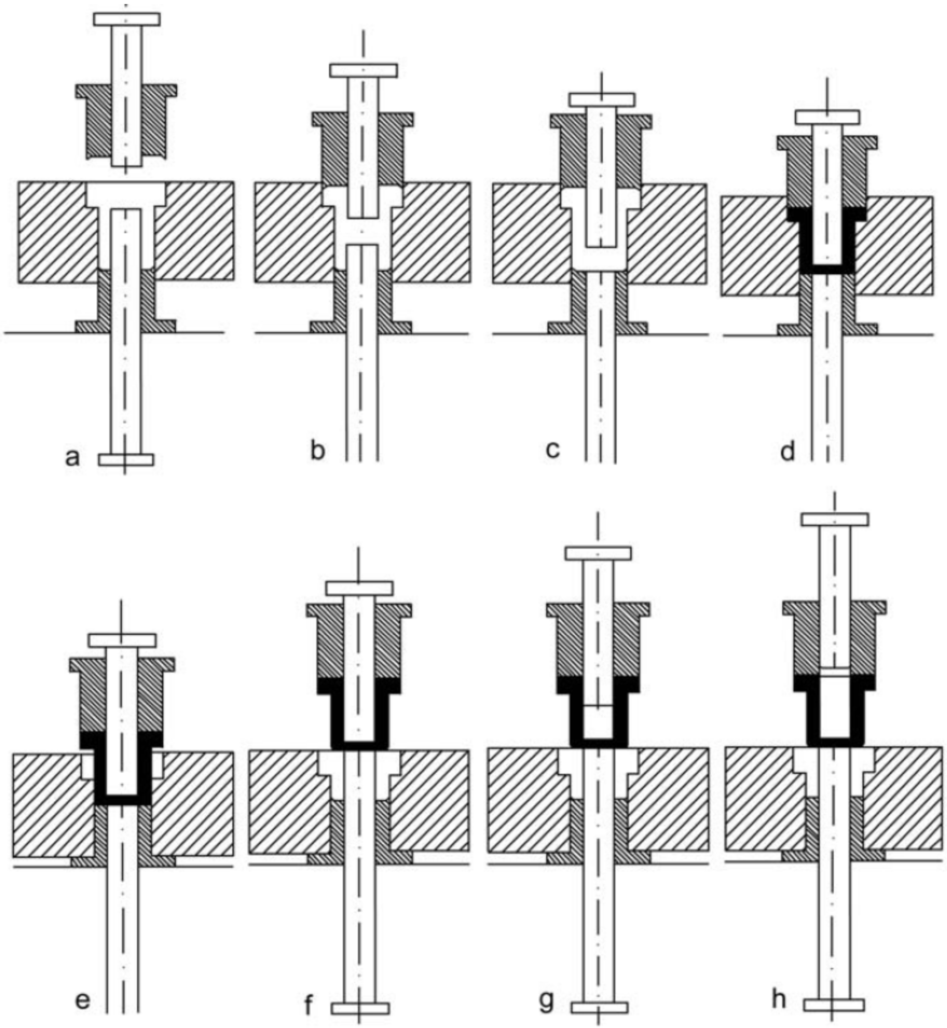
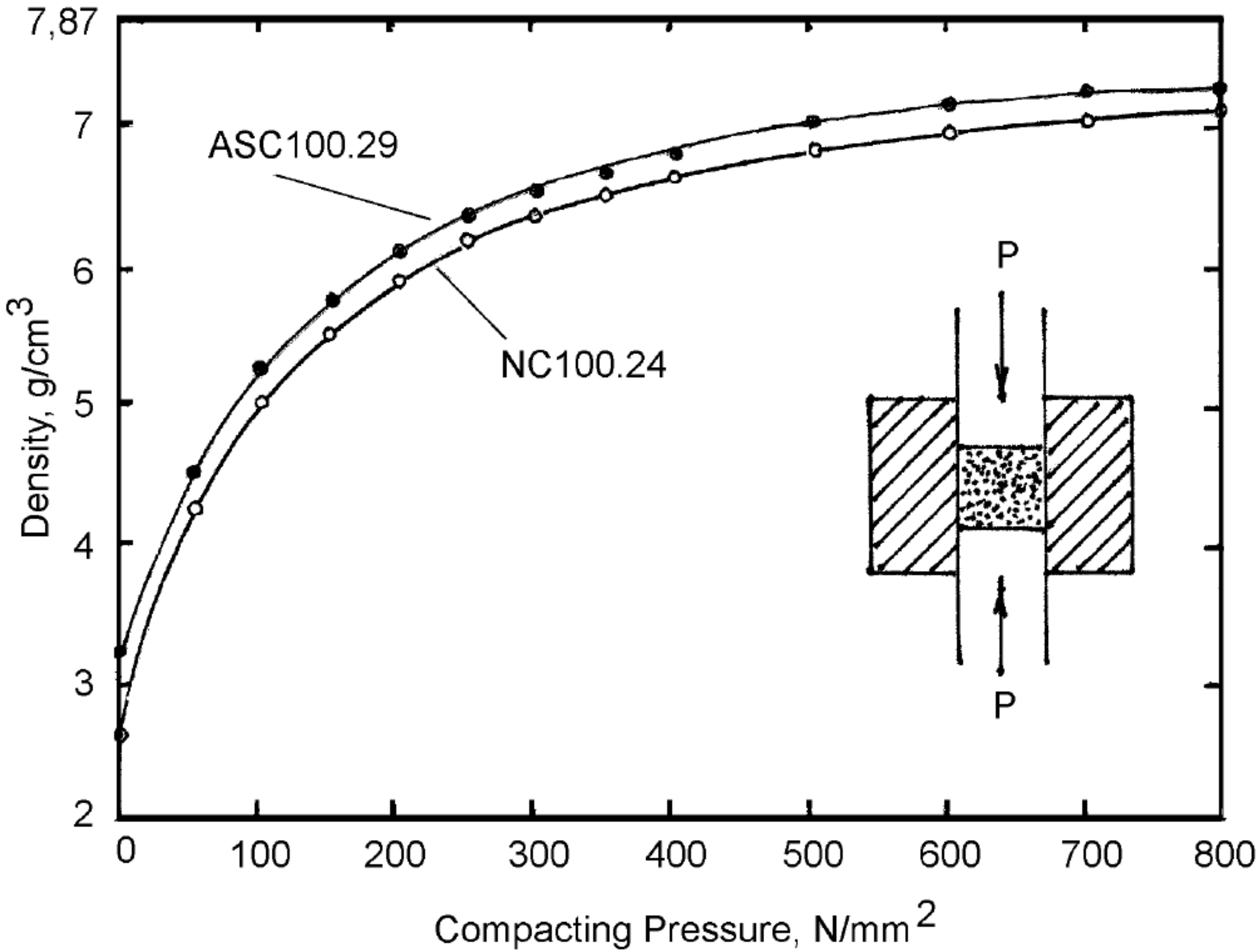


Table 5.4 Properties of Tool Steels suitable for Punches

Swedish Steel Standard	SIS 2140	–	SISI 2550
German Steel Standard	~ 105WCr6	90MnV8	50NiCr13
ANALYSIS: % C Si Mn Cr Ni Mo W V	 0,95 – 1,2 0,5 – – 0,5 0,1	 0,85 – 2,1 – – – – 0,12	 0,55 – – 1,0 3,0 0,35 – –
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
Machinability	Good	Good +	Fair -
HARDENING: Resistance to decarburization Austenitizing temperature °C Quenching medium Tempering temperature °C Hardness after tempering HRC Dimensional stability Distortion or warping stability Wear resistance Toughness	 Fair 790 – 810 oil or salt bath 250 – 260 62 – 50 Good+ Good+ Fair+ Good	 Fair 770 – 810 oil or salt bath 230 – 240 63 – 50 Good+ Medium when oil quenching. Best when salt-bath-quenching Fair Good+	 Good 790 – 810 oil or salt bath 260 – 270 58 – 50 Good+ Good when oil quenching, Good+ when salt-bath-quenching Fair Best when 2x tempe-ring

- **Specific Weight:** $\rho = m/V_t$ (measured in g/cm^3); m = mass of the material; V_t = true volume of the material.
- **Density:** $\delta = m/V_b$ (measured in g/cm^3); m = mass of the powder resp. compact; V_b = bulk volume (enveloping volume).
- **Theoretical Density:** δ_{th} = density of a (practically not attainable) pore-free powder compact (measured in g/cm^3).
- **Porosity:** $\phi = 1 - \delta/\delta_{th}$ (number without dimension).
- **Compacting Pressure (die compacting):** P = compacting force/face area of compact (measured in N/mm^2 or MN/m^2).
- **Compacting Pressure (isostatic compacting):** P = pressure of the hydraulic medium (measured in MPa or MN/m^2).


7,87
7
6
5
4
3
2
Density, g/cm3
ASC100.29
NC100.24
P
P
0
100
200
300
400
500
600
700
800
Compacting Pressure, N/mm2

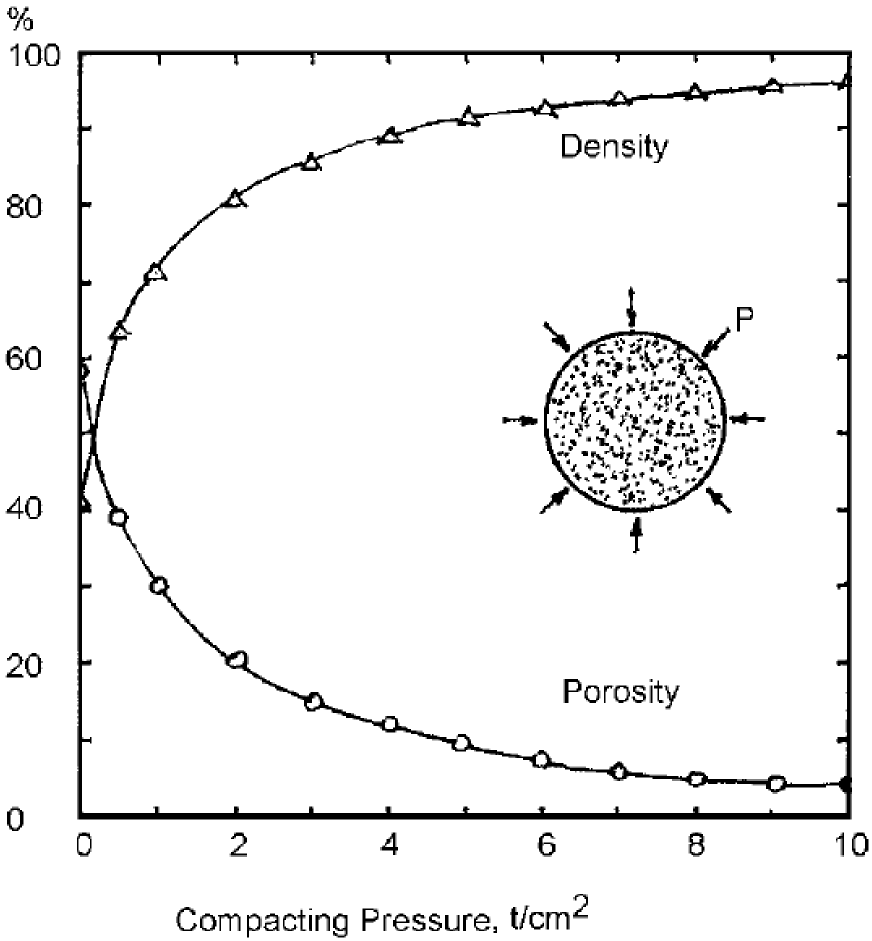


Figure. 4.2. Relative density and porosity as functions of isostatic compacting pressure. Electrolytic iron powder hermetically enclosed in thin rubber jackets subjected to hydraulic pressure. [4.2]

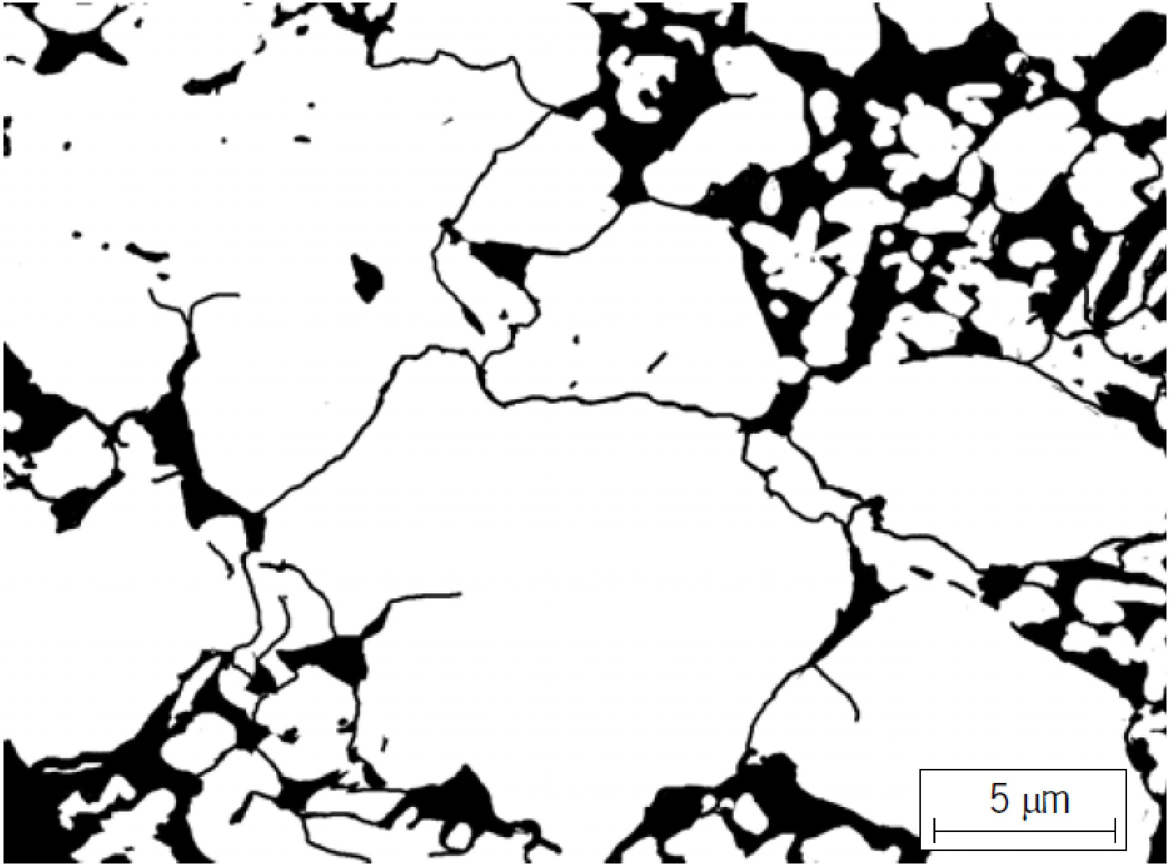


Figure. 4.3. Adaptation of surface contours due to plastic deformation of adjacent powder particles. Electrolytic copper powder compacted at 200 N/mm^2 . [4.4]

$$\sigma_r(R) - \sigma_t(R) \geq \sigma_0 \quad (4.1)$$

The radial stress $\sigma_r(R)$ and the tangential stress $\sigma_t(R)$ close to the outer surface of the hollow sphere are given by the following relations:

$$\sigma_r(R) = -P \quad (4.2)$$

and

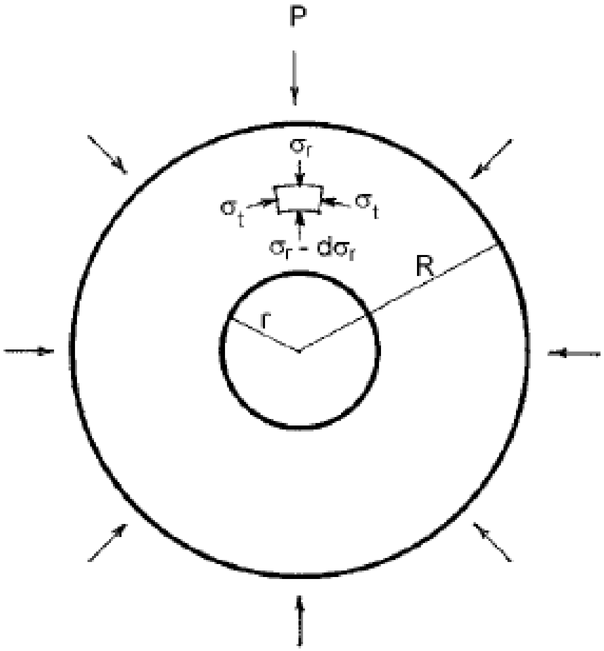
$$\sigma_t(R) = -P\frac{2R^3 + r^3}{2(R^3 - r^3)} \quad (4.3)$$

Introducing (4.2) and (4.3) into (4.1) yields:

$$P\frac{3r^3}{2(R^3 - r^3)} \geq \sigma_0 \quad (4.4)$$

or:

$$P \geq \frac{2}{3}\sigma_0 \frac{R^3 - r^3}{r^3} \quad (4.5)$$



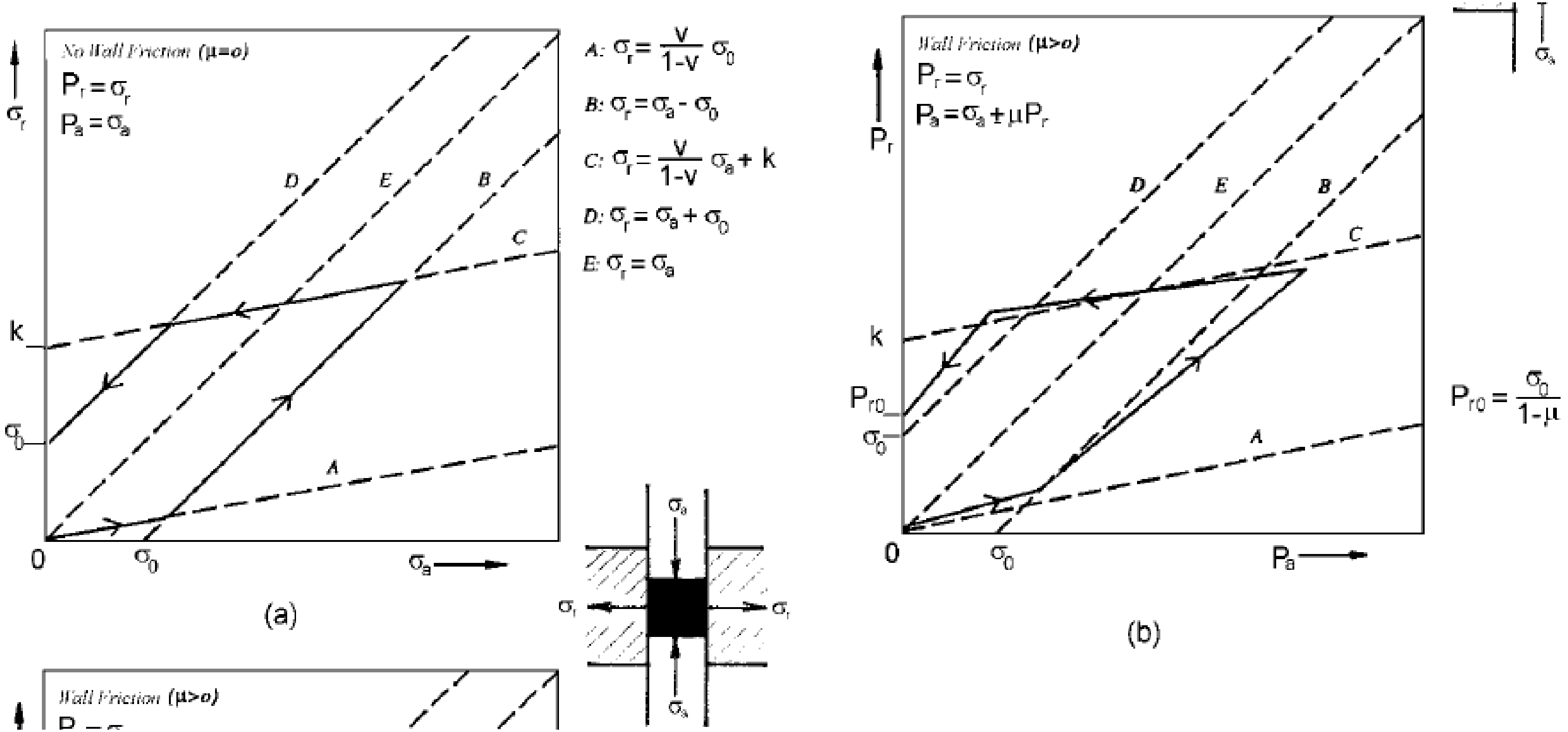
BOSCH

$w_1, w_2, w_3, \ldots$ be the weight percentages of additives and impurities.
Then, the theoretically achievable pore-free density of the powder mix is:

$$\delta_M = 100 \,/\, (w_{Fe}/\rho_{Fe} + w_1/\rho_1 + w_2/\rho_2 + w_3/\rho_3 + \ldots) \qquad (4.6)$$

Table 4.1 Specific Weights of some Metals, Additives and Impurities as occurring in Iron Powder Mixes

Metal, Additive, Impurity	Specific Weight (g/cm^3)	Metal, Additive	Specific Weight (g/cm^3)
Fe (purest iron)	7,868	NC 100.24	7,796
FeO	5,30	SC 100.26	7,807
SiO_2	2,30	ASC 100.29	7,845
Graphite	2,24	MnS	4,0
Cu (electrolytic)	8,95	Ni (pure nickel)	8,902
Zn-stearate	1,0	synthetic wax	1,0


No Wall Friction (μ=o)
P_r = σ_r
P_a = σ_a
A: σ_r = v/(1-v) σ_0
B: σ_r = σ_a - σ_0
C: σ_r = v/(1-v) σ_a + k
D: σ_r = σ_a + σ_0
E: σ_r = σ_a
(a)
Wall Friction (μ>o)
P_r = σ_r
P_a = σ_a ± μP_r
P_r0 = σ_0/(1-μ)
(b)

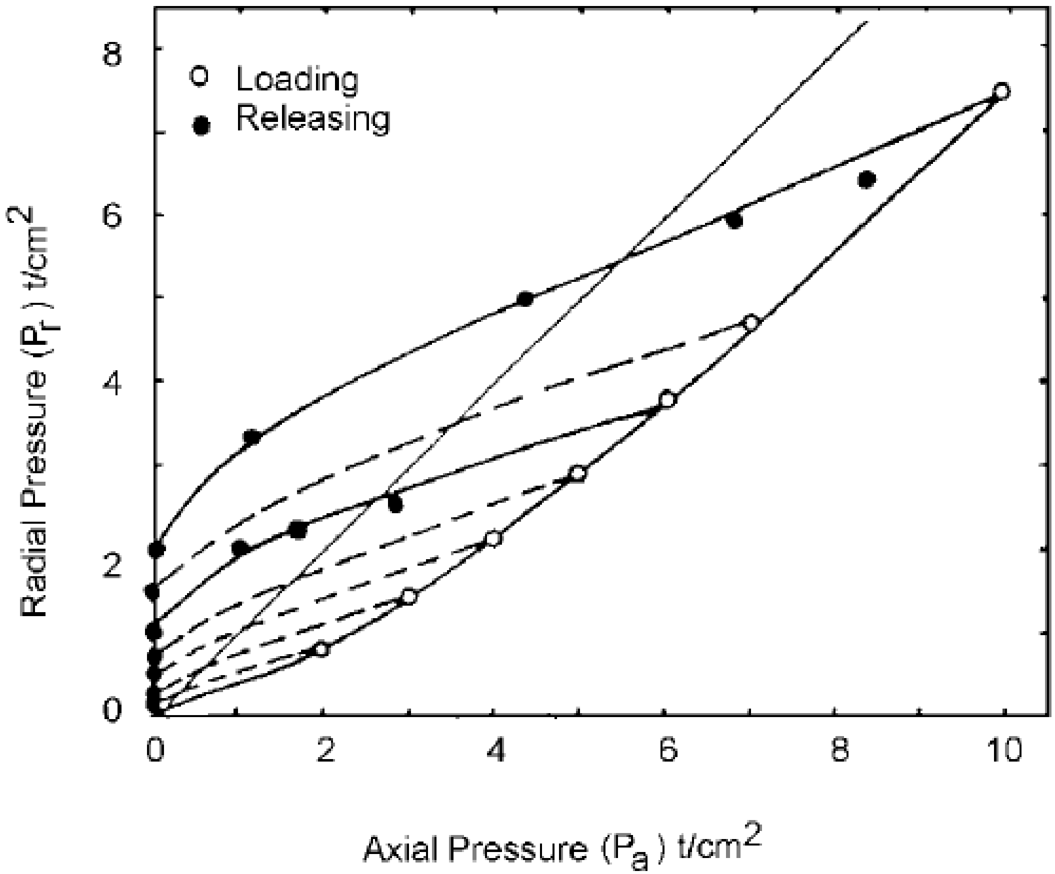
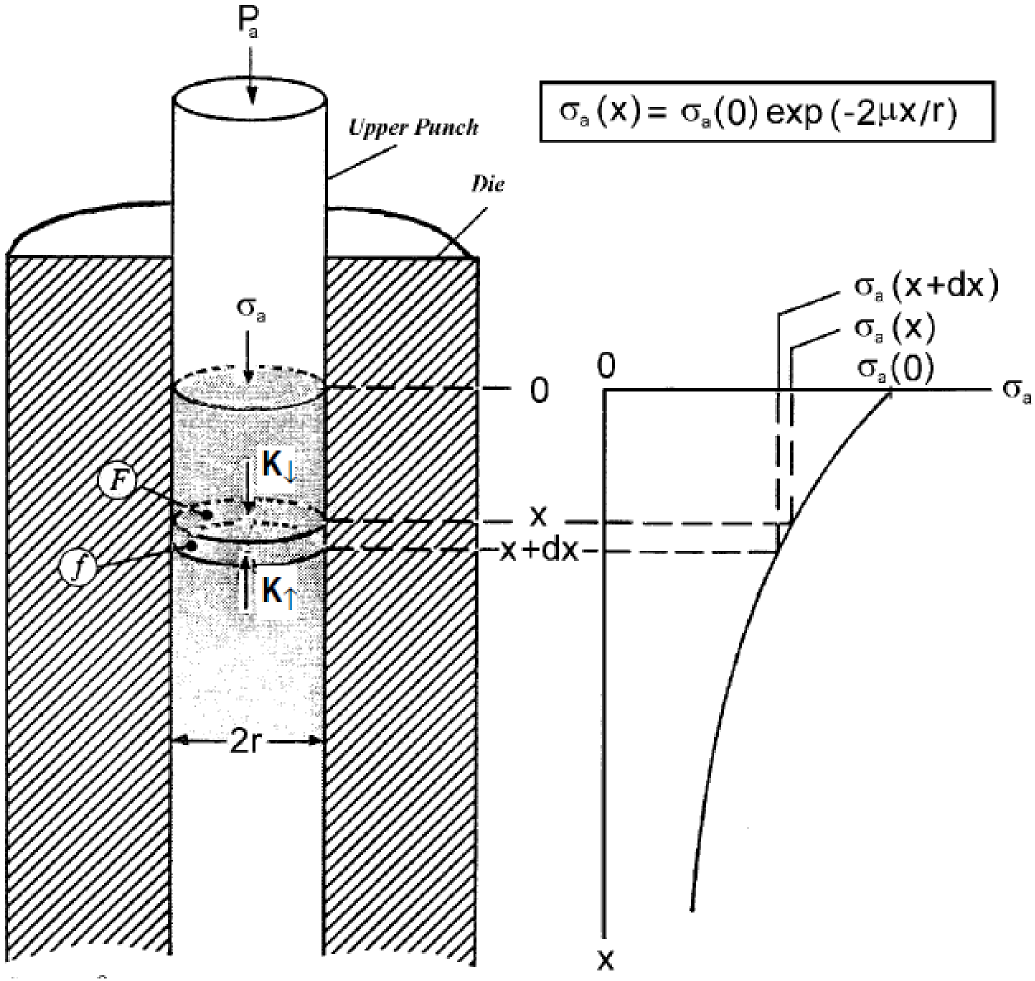


Figure. 4.8. Radial and axial pressures measured on compacts of sponge iron powder during a loading releasing cycle in a cylindrical die. [4.7]



P_a
Upper Punch
Die
$\sigma_a(x) = \sigma_a(0)\exp(-2\mu x/r)$
σ_a
$K_\downarrow$
F
f
$K_\uparrow$
2r
0
x
x+dx
0
$\sigma_a(x+dx)$
$\sigma_a(x)$
$\sigma_a(0)$
σ_a
x

BOSCH

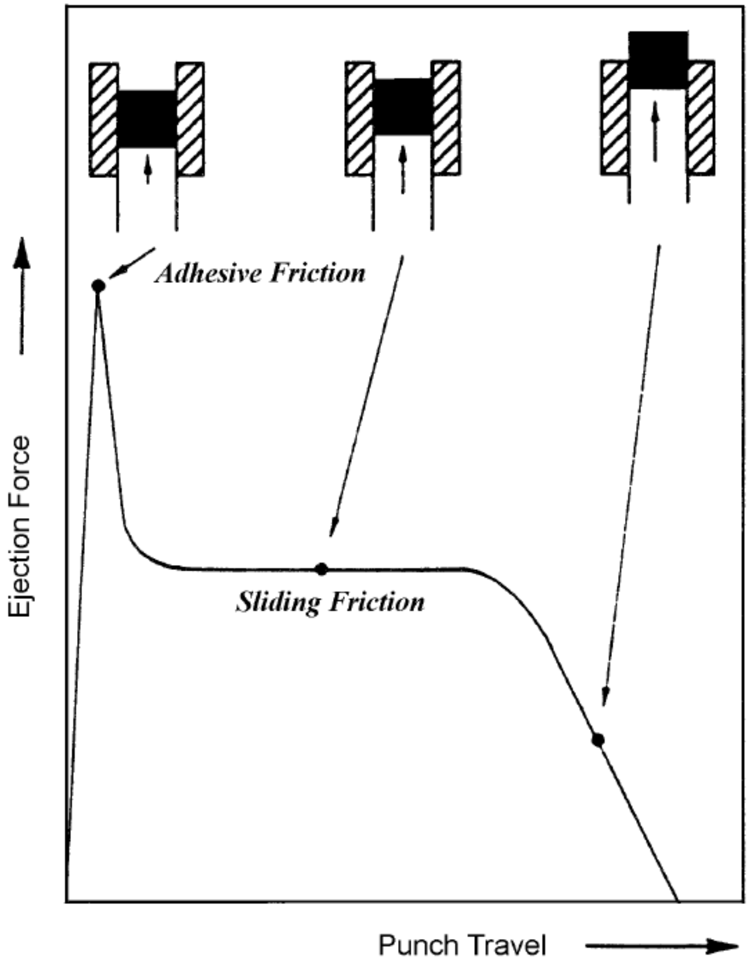


Figure. 4.12. Ejecting force as a function of the movement of the ejecting bottom punch; schematic.

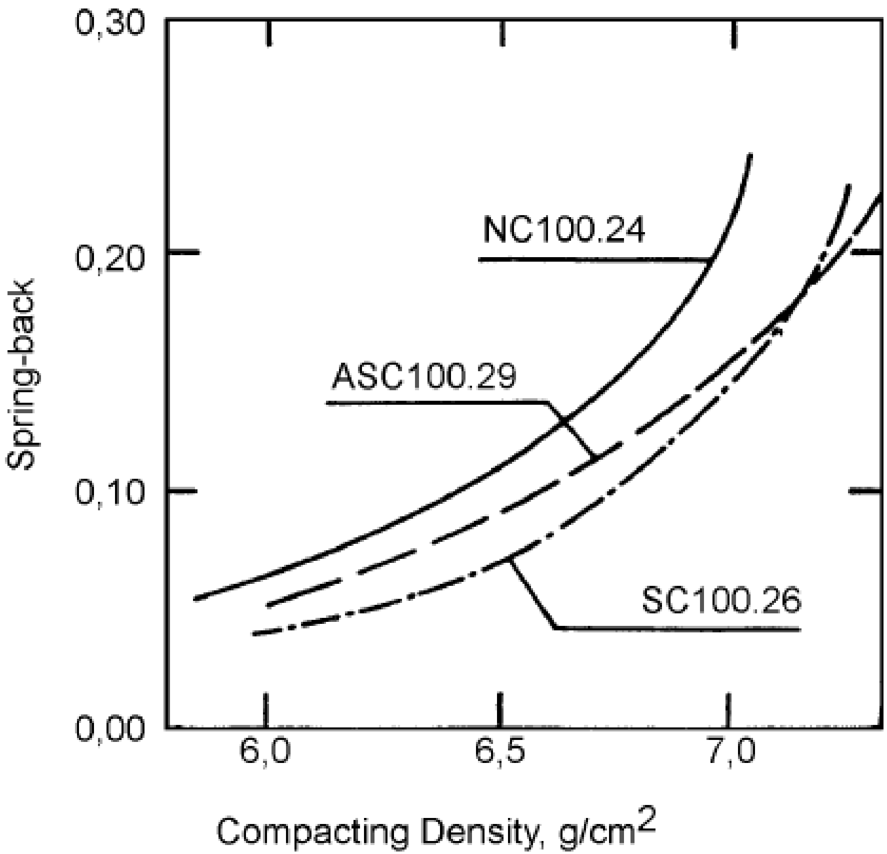


Figure. 4.14: Spring back as a function of compact density for three different iron powders. Lubricant addition: 0.8% Zn-stearate. [4.12]

SINTERING

Sintering is the process by which metal powder compacts (or loose metal powders) are transformed into coherent solids at temperatures below their melting point. During sintering, the powder particles are bonded together by diffusion and other atomic transport mechanisms, and the resulting somewhat porous body acquires a certain mechanical strength.

The sintering process is governed by the following parameters:

- temperature and time,
- geometrical structure of the powder particles,
- composition of the powder mix,
- density of the powder compact,
- composition of the protective atmosphere in the sintering furnace.

In iron powder metallurgy, common sintering conditions are: 15 - 60 min at 1120 - 1150°C.

At given sintering conditions, powders consisting of fine particles or particles of high internal porosity (large specific surface), sinter faster than powders consisting of coarse compact particles. Again, we have a dilemma: Fine powders are usually more difficult to compact than coarse powders, and compacts made from fine powder shrink more during sintering than compacts made from coarse powder. Particles of commercial iron powders (spongy or compact types) for structural parts are usually ≤ 150 µm (ref. Chapter 3).

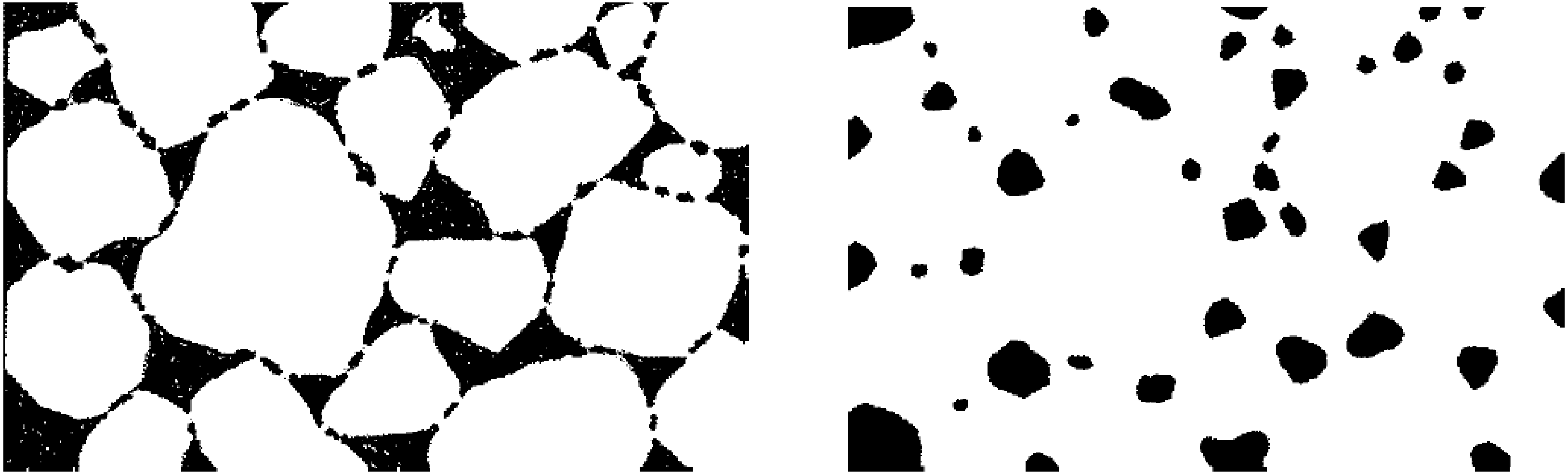
The components of powder mixes are selected and proportioned with a view to achieving desired physical properties and controlling dimensional changes during sintering (ref. Chapter 3). When mixes of two or more different metal powders (e.g. iron, nickel and molybdenum) are sintered, alloying between the components takes place simultaneously with the bonding process.

At common sintering temperatures (1120 - 1150°C), alloying processes are slow (except between iron and carbon), and a complete homogenization of the metallic alloying elements is not achievable. If the powder mix contains a component that forms a liquid phase at sintering temperature (e.g. copper in iron powder mixes), bonding between particles as well as alloying processes are accelerated.

The greater the density of a powder compact, the larger is the total contact area between powder particles, and the more efficient are bonding and alloying processes during sintering. Furthermore, these processes are enhanced by the disturbances in the particles' crystal lattice caused by plastic deformation during compaction (ref. Chapter 1, § 1.2.3,

The protective atmosphere has to fulfill several functions during sintering which in some respects are contradictory. On the one hand, the atmosphere is to protect the sinter goods from oxidation and reduce possibly present residual oxides; on the other hand, it is to prevent decarbonization of carbon-containing material and, vice versa, prevent carbonization of carbon-free material.

- reducing-decarbonizing type: hydrogen (H_2), cracked ammonia (75% H_2, 25% N_2),
- reducing-carbonizing type: endogas (32% H_2, 23% CO, 0-0.2% CO_2, 0-0.5% CH_4, bal. N_2),
- neutral type: cryogenic nitrogen (N_2), if desirable with minor additions of H_2 (to take care of residual oxides) or of methane or propane (to restore carbon losses).



a) b)

Figure. 6.1. Early (a) and late (b) stage of sintering, schematically.

- volume diffusion (migration of vacancies),
- grain-boundary diffusion,
- surface diffusion,
- viscous or plastic flow (caused by surface tension or internal stresses),
- evaporation/condensation of atoms on surfaces.

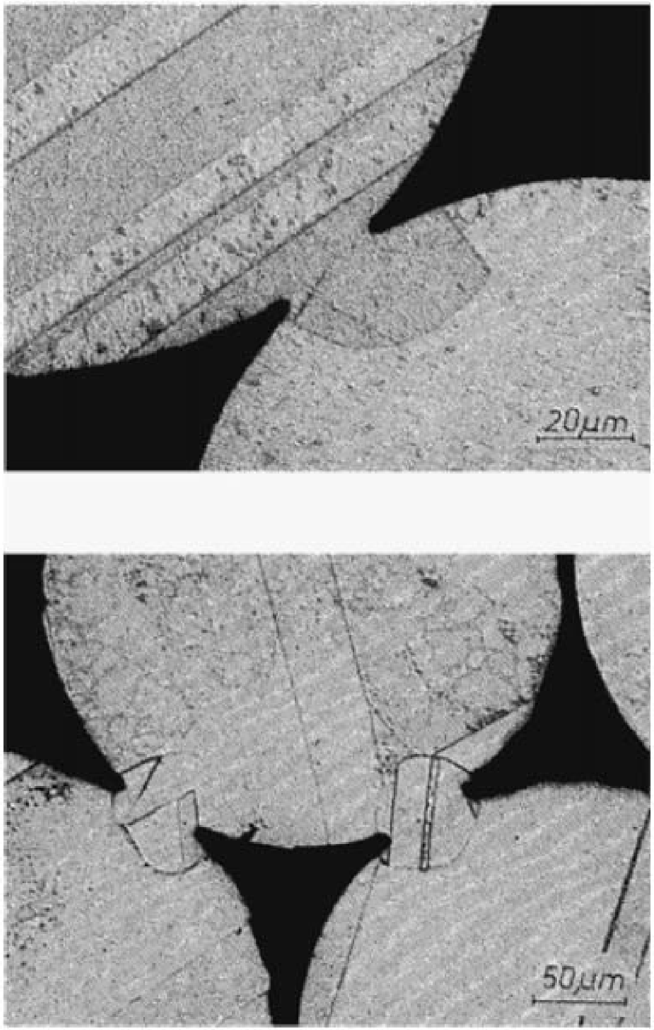
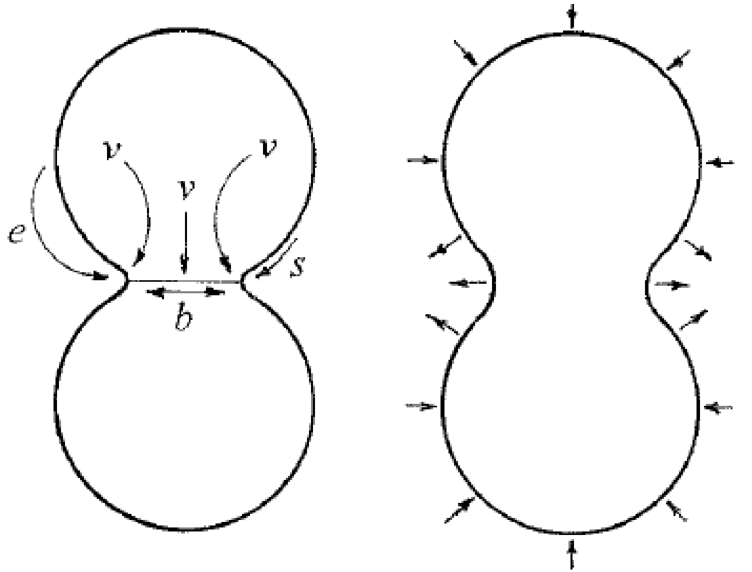


Figure. 6.2. Neck formation between sintering copper spheres. [6-1]

Szinter technológia



v = volume diffusion,b = grain boundary diffusion
s = surface diffusion,e = evaporation/condensation
← ↓ = forces from surface tension (viscous flow)

Figure. 6.3. Growth of neck width between spherical particles during sintering (according to a theoretical model by C.G. Kuczynski)**above** : time law. **below** : various mechanisms of material transport.

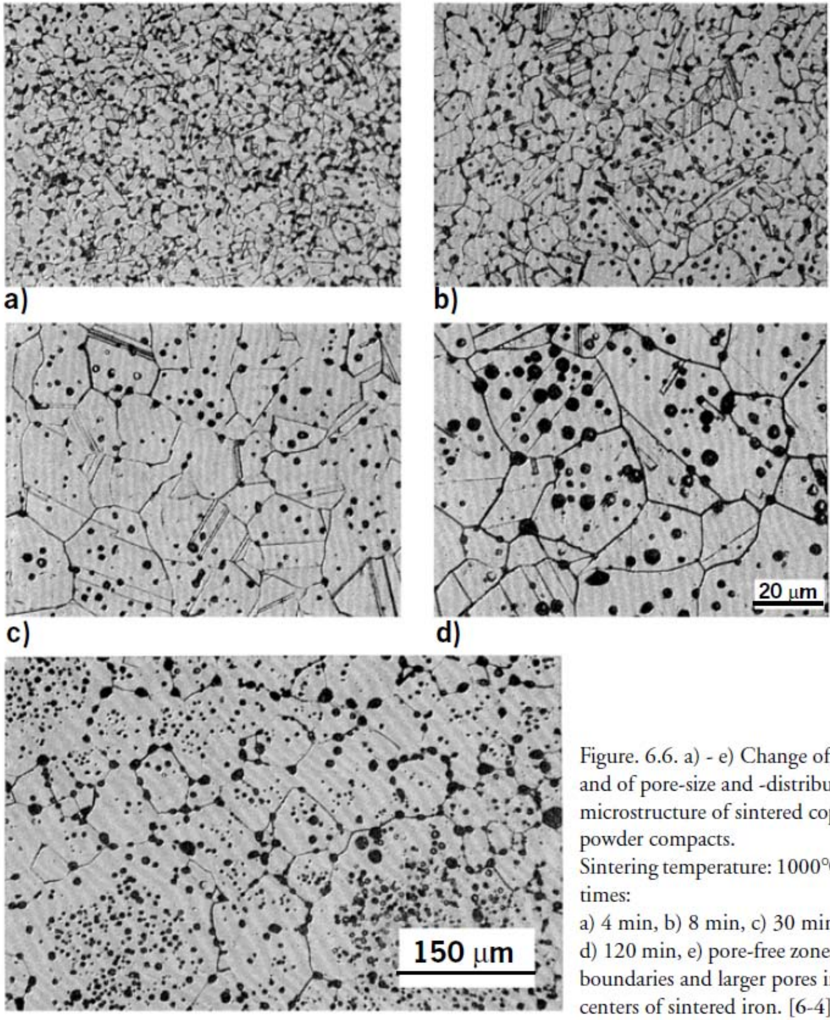


Figure. 6.6. a) - e) Change of grain-size and of pore-size and -distribution in the microstructure of sintered copper powder compacts.
Sintering temperature: 1000°C, sintering times:
a) 4 min, b) 8 min, c) 30 min,
d) 120 min, e) pore-free zones near grain boundaries and larger pores in grain centers of sintered iron. [6-4], [6-5]

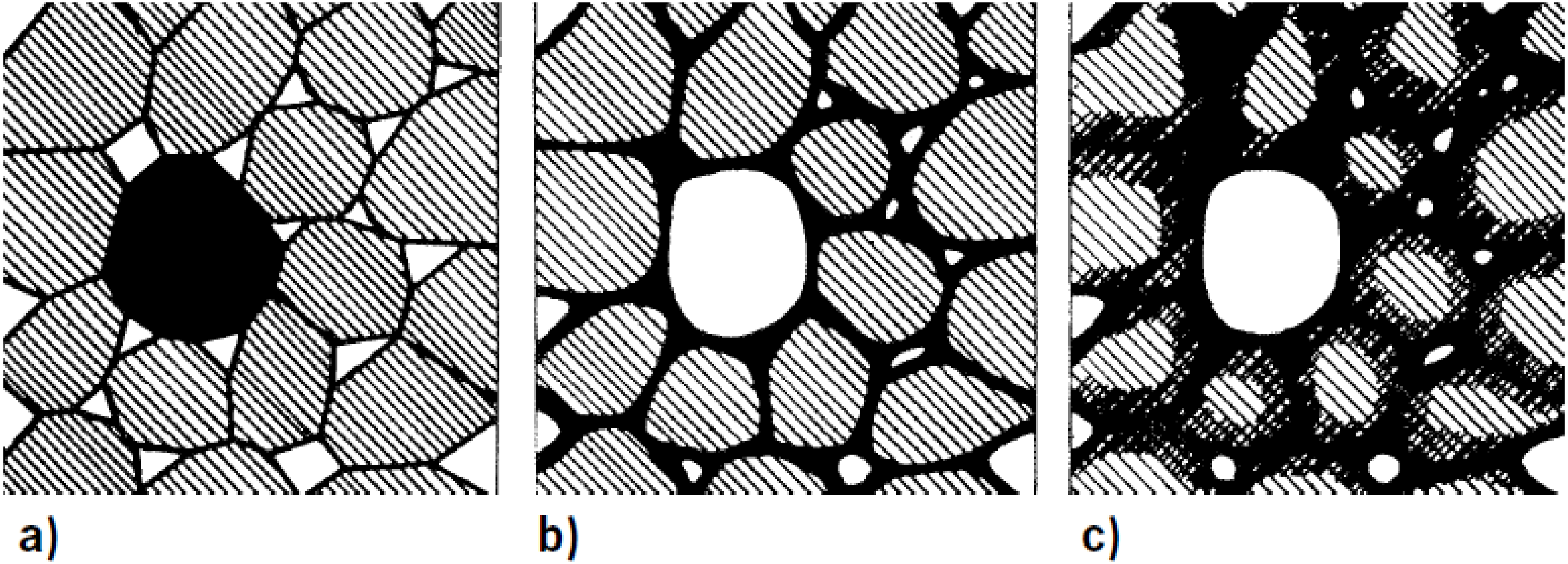


Figure. 6.11. Sintering with a transient liquid phase (schematically);
a) initial heterogeneous powder compact ,
b) one component of the powder mix melts and infiltrates the narrow gaps between the solid particles leaving large pores behind,
c) alloying takes place between liquid and solid phase, and the liquid phase gradually disappears again.

BOSCH

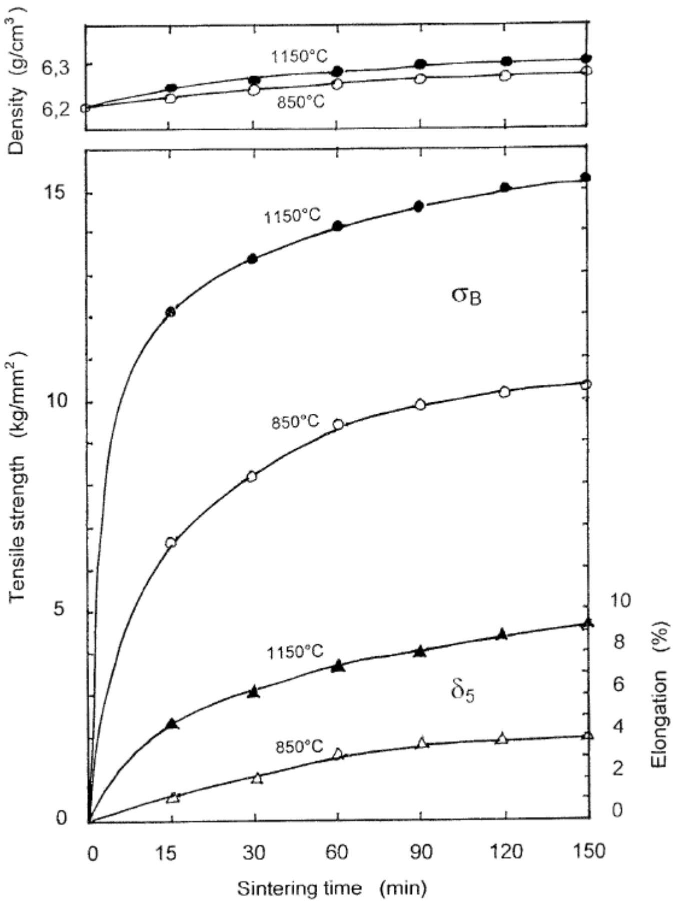
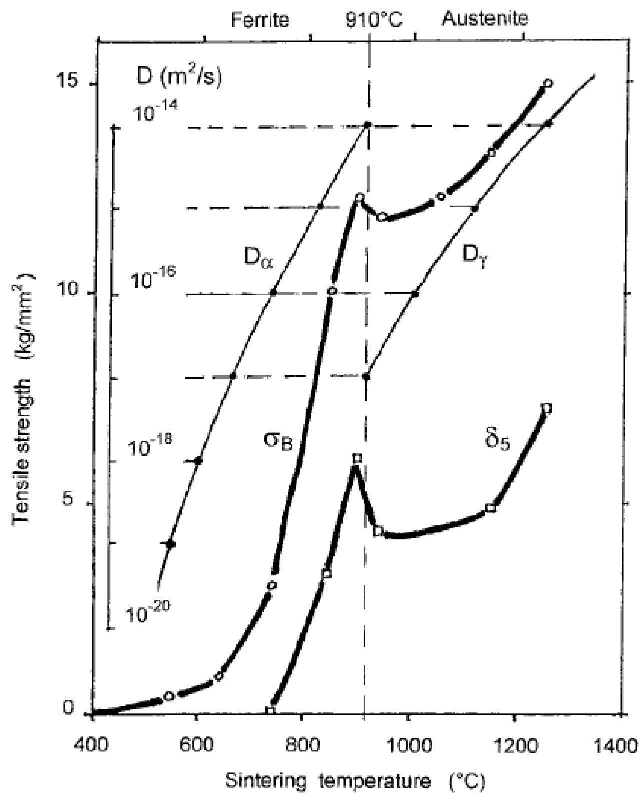


Figure. 6.16. Tensile strength, elongation and density of sintered iron (MH100.24) as functions of sintering time at two different temperatures. [6-9]



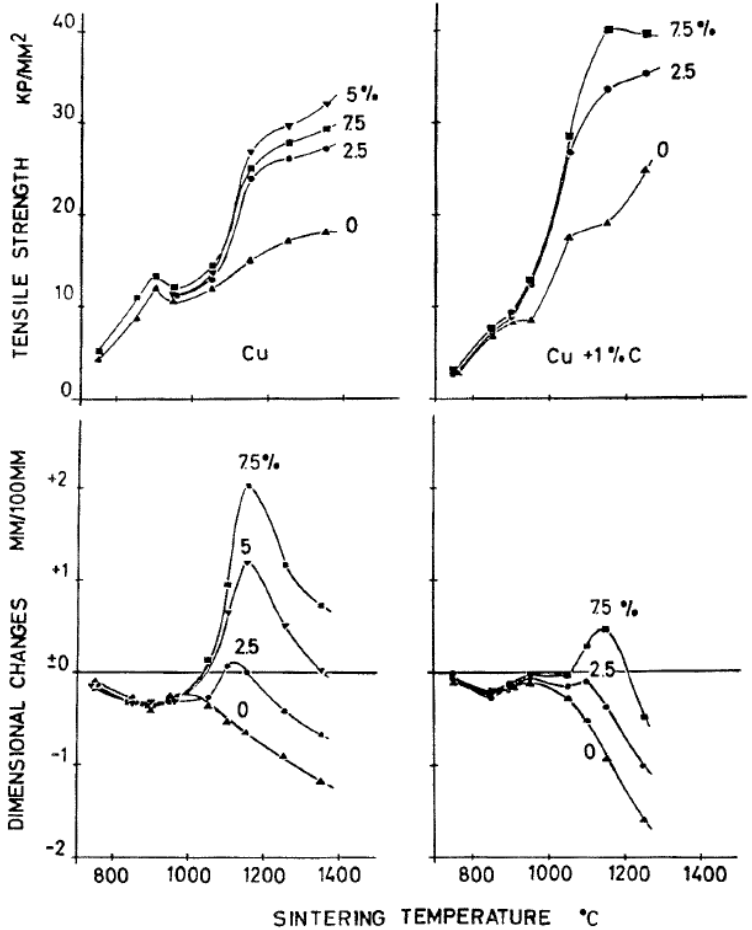


Figure. 6.18. Influence of varying additions of copper and graphite and of sintering temperature on tensile strength and dimensional changes of sintered iron (NC100.24, green density: 6,3 g/cm3, sintering: 1h in H_2), at indicated temperatures. [6-11]

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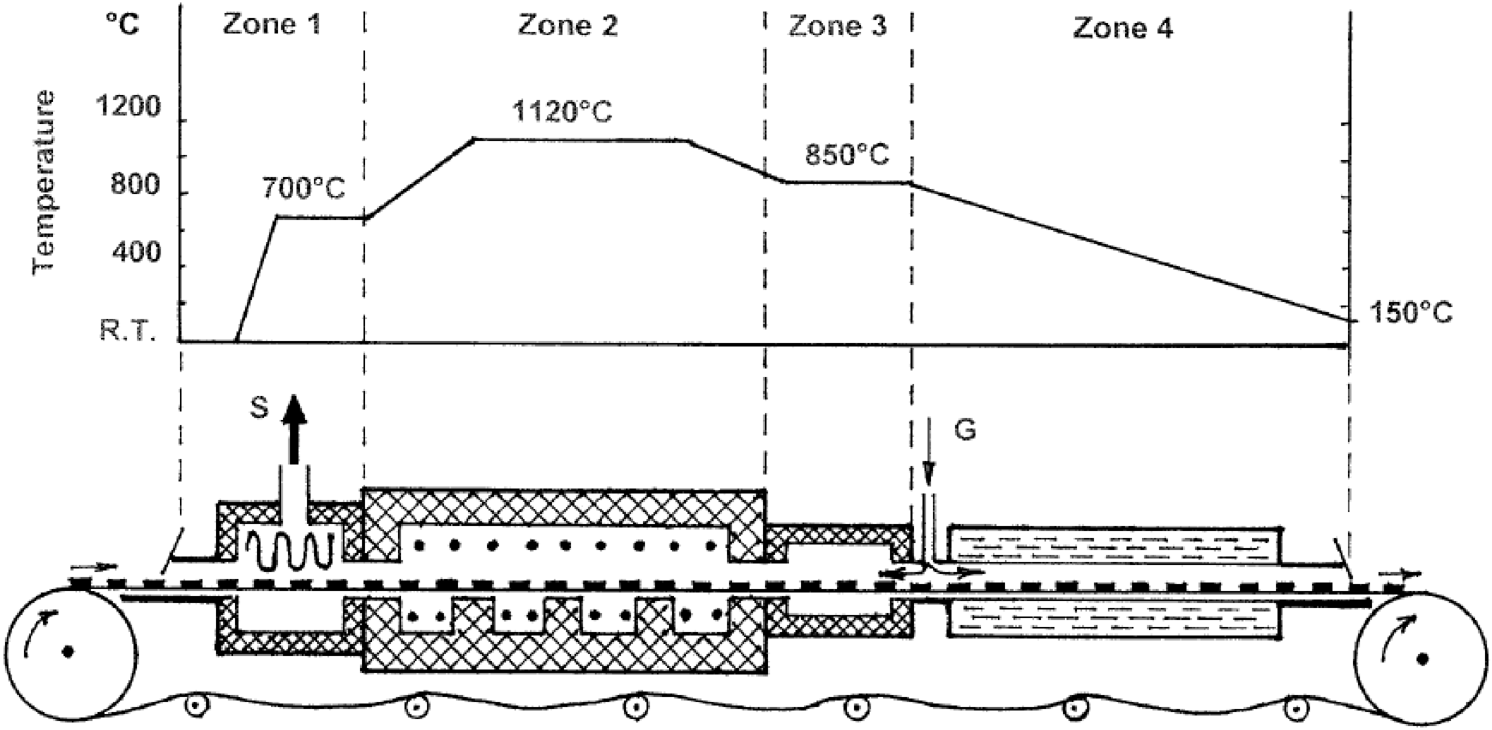


Zone 1 = Burning-off lubricants, 2 = Sintering, 3 = Re-carbonizing, 4 = Cooling
G = Gas inlet, S = Smoke and gas outlet

BOSCH

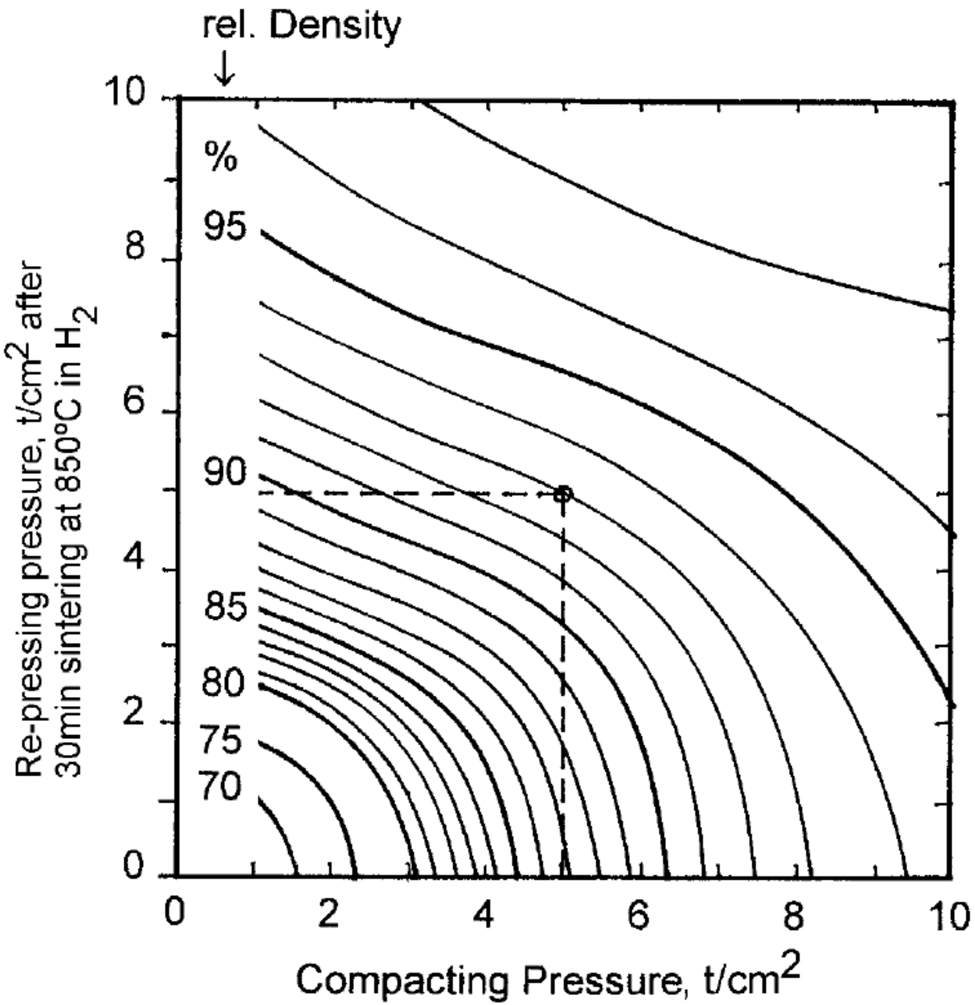


Figure. 7.2 Influence of pressing and re-pressing pressure on relative compact density. Iron powder: NC100.24-type. Pre-sintering: 30 min at 850°C in H_2 . [7-1]

$\sin \alpha = H/R$

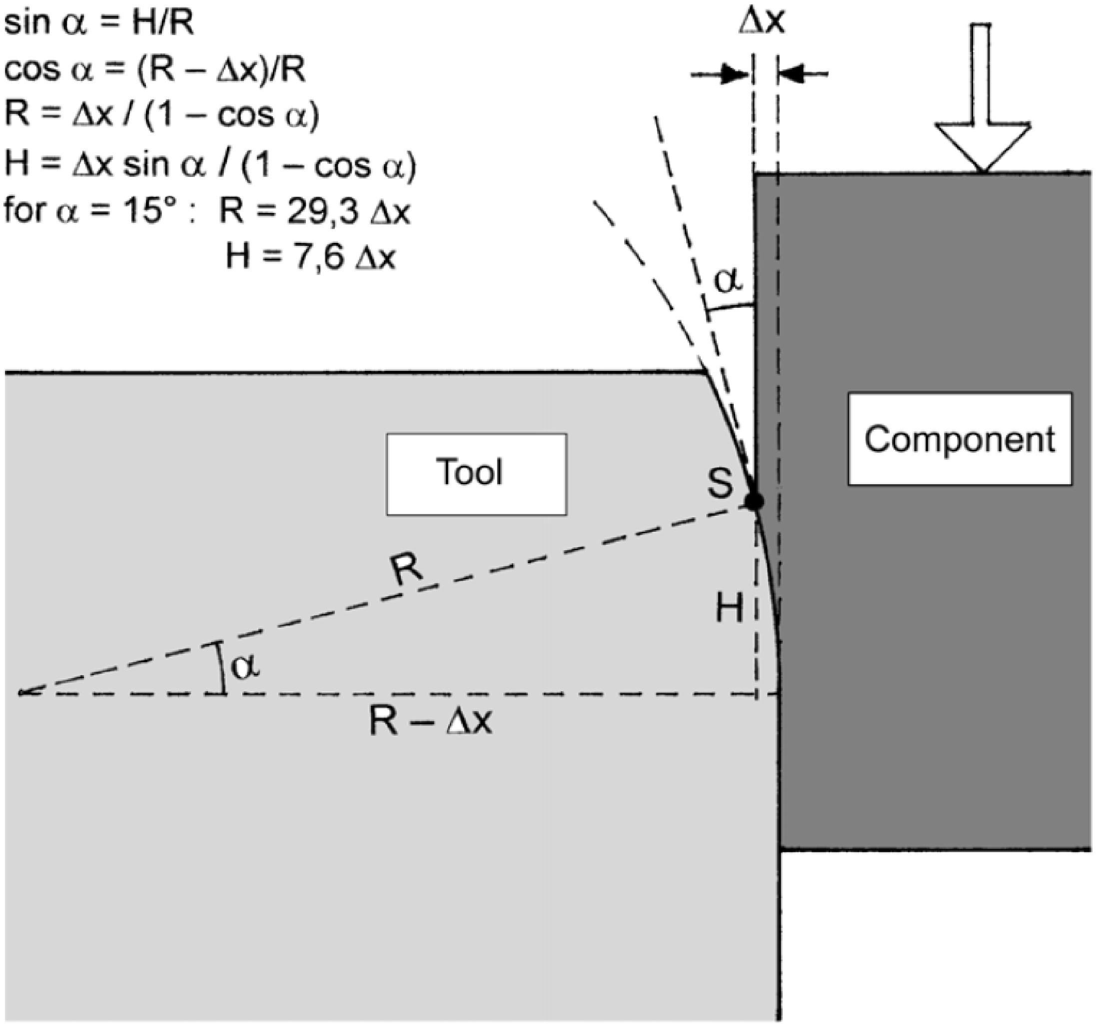
$\cos \alpha = (R - \Delta x)/R$

$R = \Delta x / (1 - \cos \alpha)$

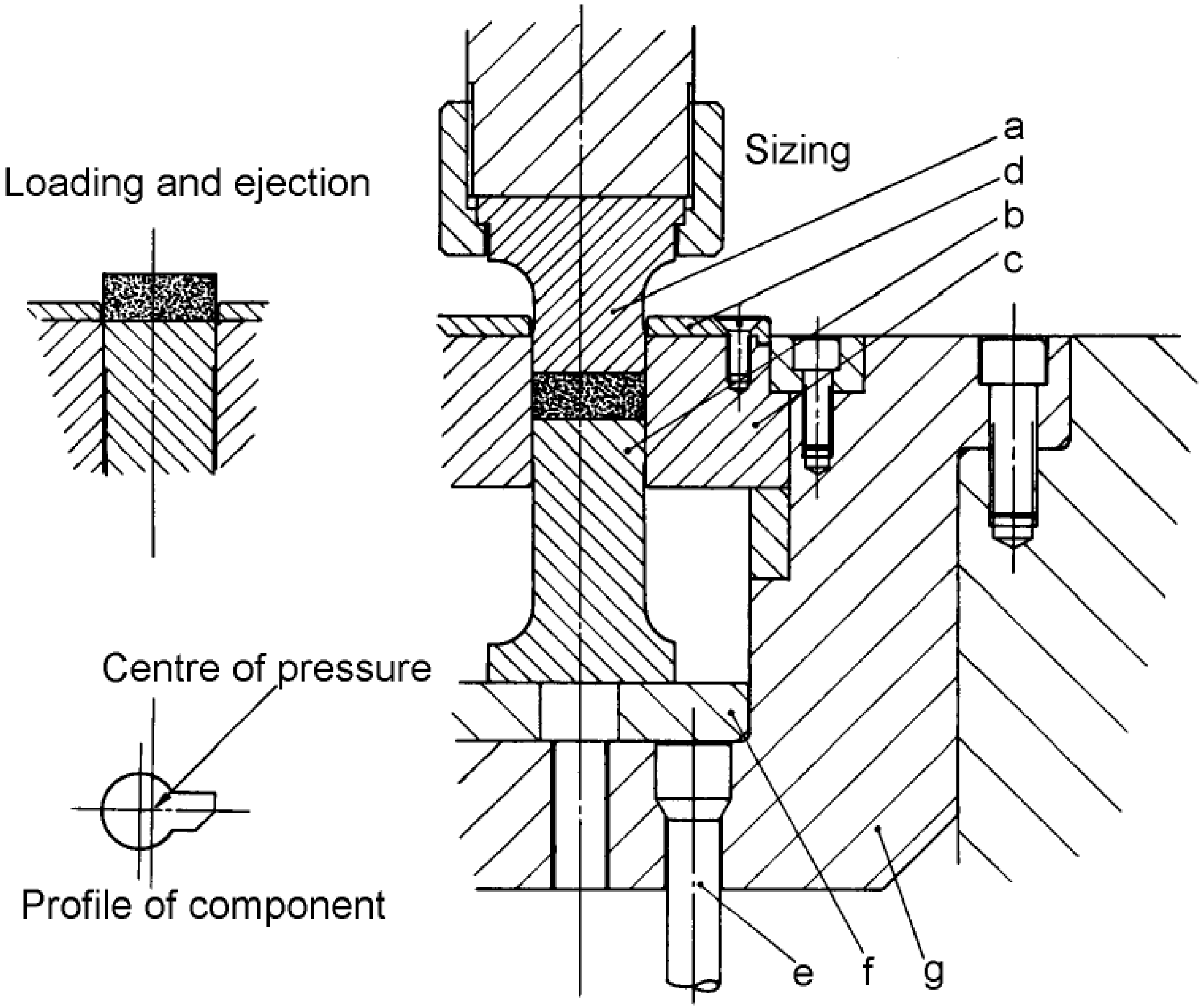
$H = \Delta x \sin \alpha / (1 - \cos \alpha)$

for $\alpha = 15°$: $R = 29{,}3\ \Delta x$

$H = 7{,}6\ \Delta x$



BOSCH


Loading and ejection
Sizing
a
d
b
c
Centre of pressure
Profile of component
e
f
g

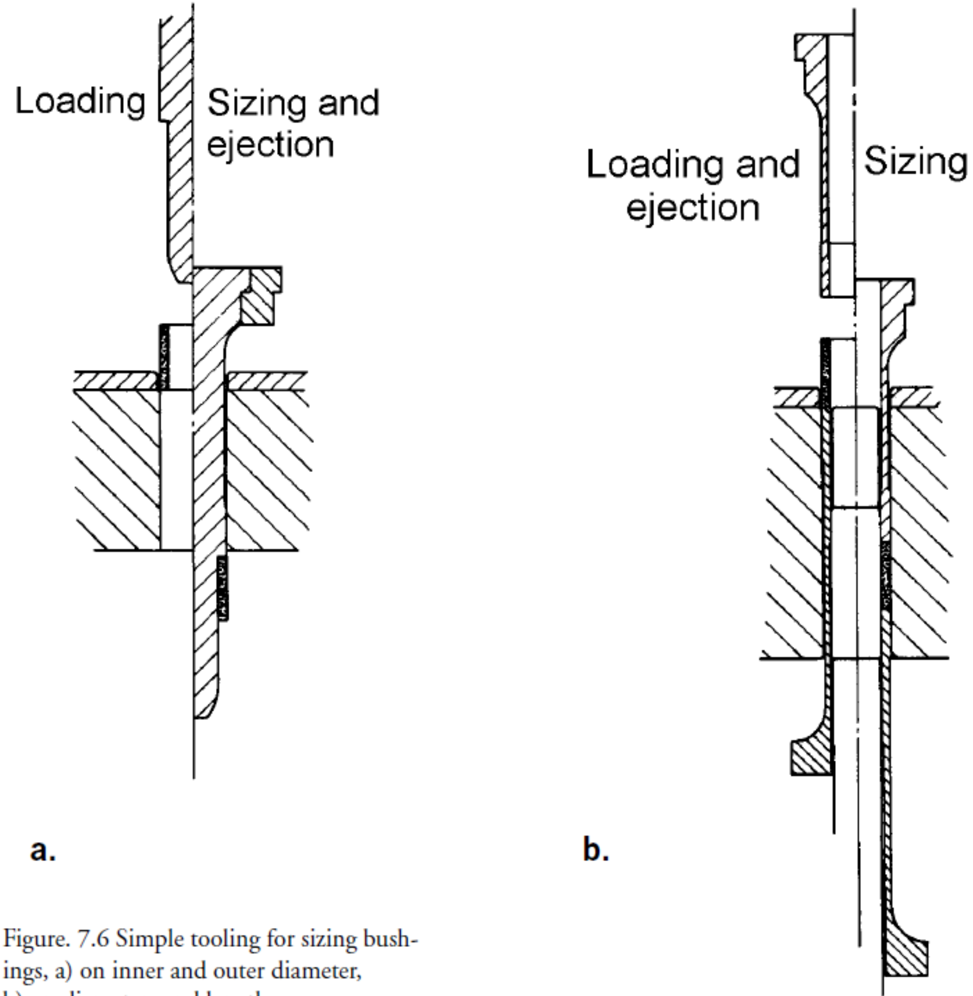
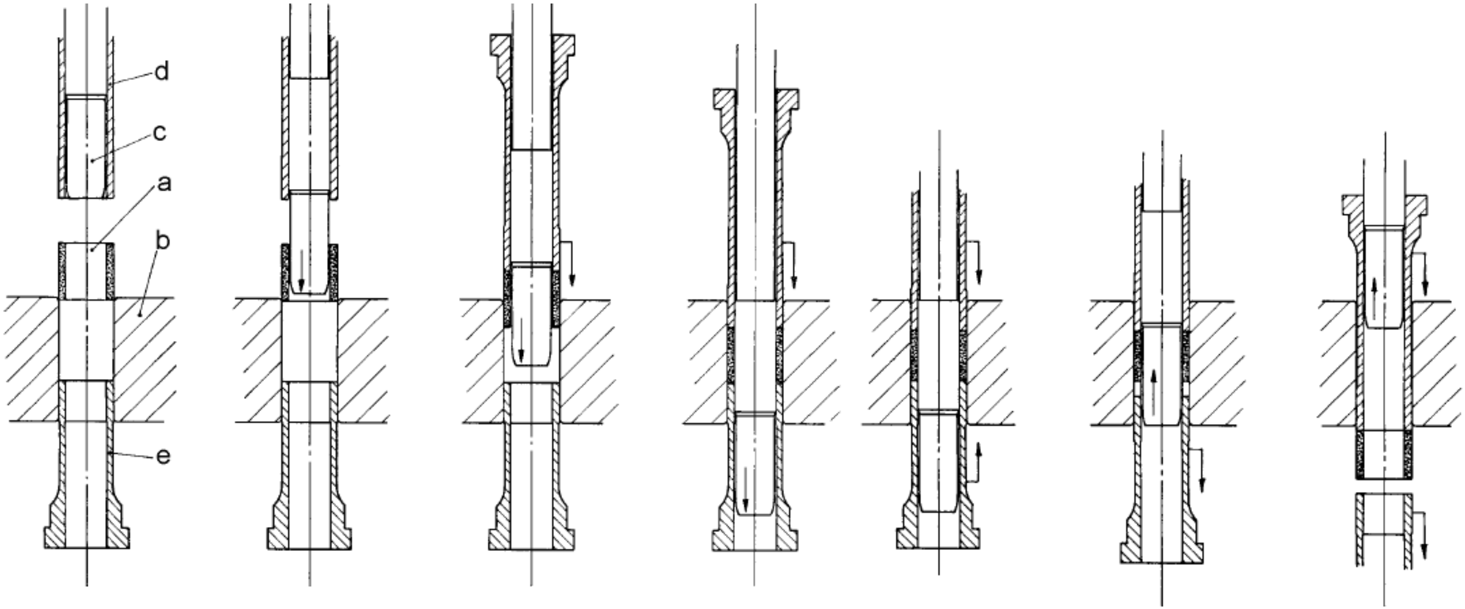


Figure. 7.6 Simple tooling for sizing bushings, a) on inner and outer diameter, b) on diameters and length.


d
c
a
b
e

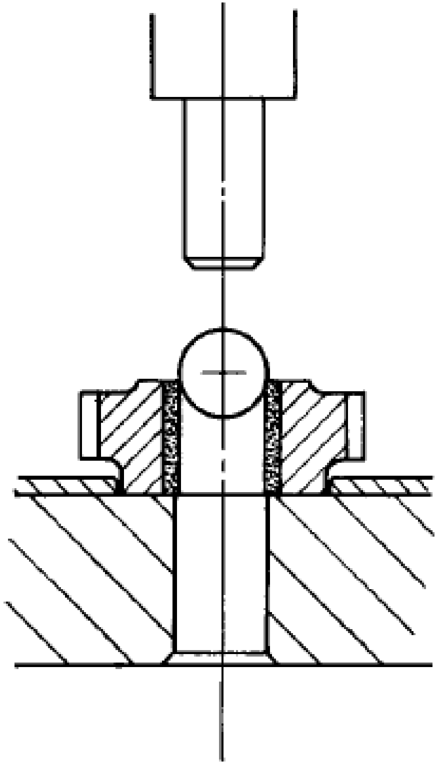
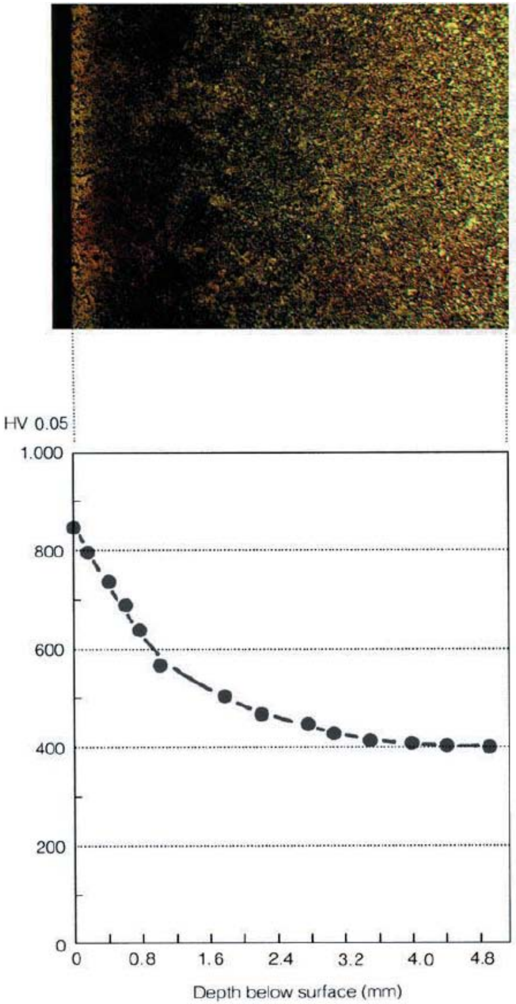


Figure. 7.12 Simple ball-sizing for assembled bushings.

Operation		Purpose
Heat-treatment	Through hardening: austenitizing, quenching, tempering	• improve cross-sectional hardness and strength
	Precipitation hardening	• see above
	Case hardening: – carbonizing – carbonitriding – nitriding – plasma nitriding – nitrocarbonizing – induction hardening	• improve surface hardness
	Annealing/Tempering	• eliminate internal stresses
Infiltration and impregna-tion	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

Operation		Purpose
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 achive a component of more complex shape
	Peening and Plating: – shot peening – peen plating – electroplating	• hardens surface and improves fatique strength • improve parts' appearence and corrosion resistance
	Corrosion Protection: – Steam treatment – Phosphatizing	• improve parts' corrosion- and wear- resistance



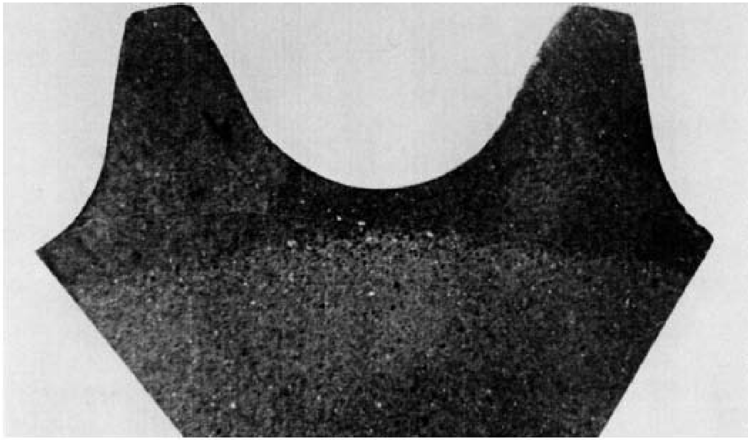


Fig. 10.15 Section of an induction-hardened chain sprocket. (Distaloy AB + 0.7 wt.% C, density 7.1 g/cm^3).
The l

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- 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.

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

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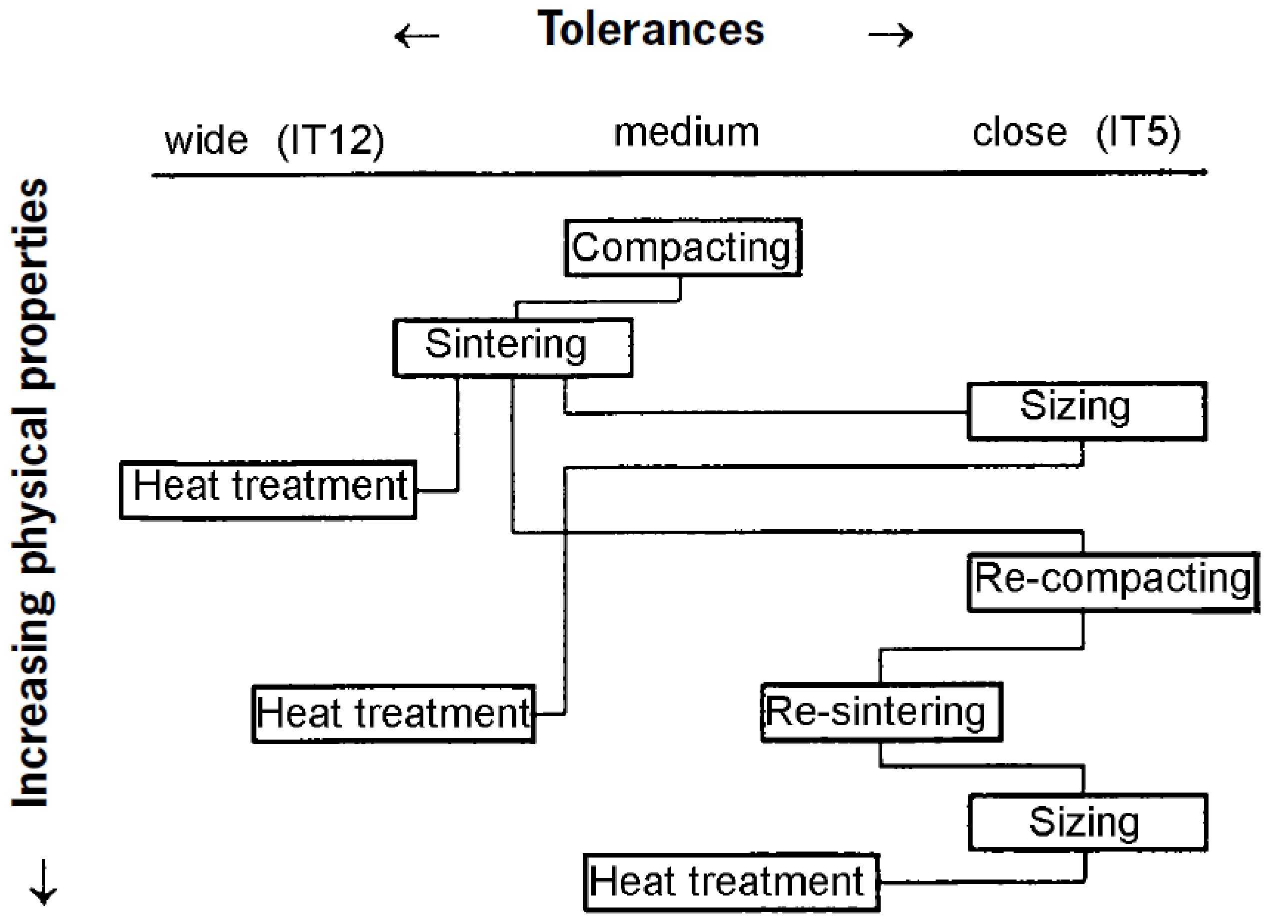

Fig. 8.1 How processing influences tolerances and physical properties of P/M-parts.

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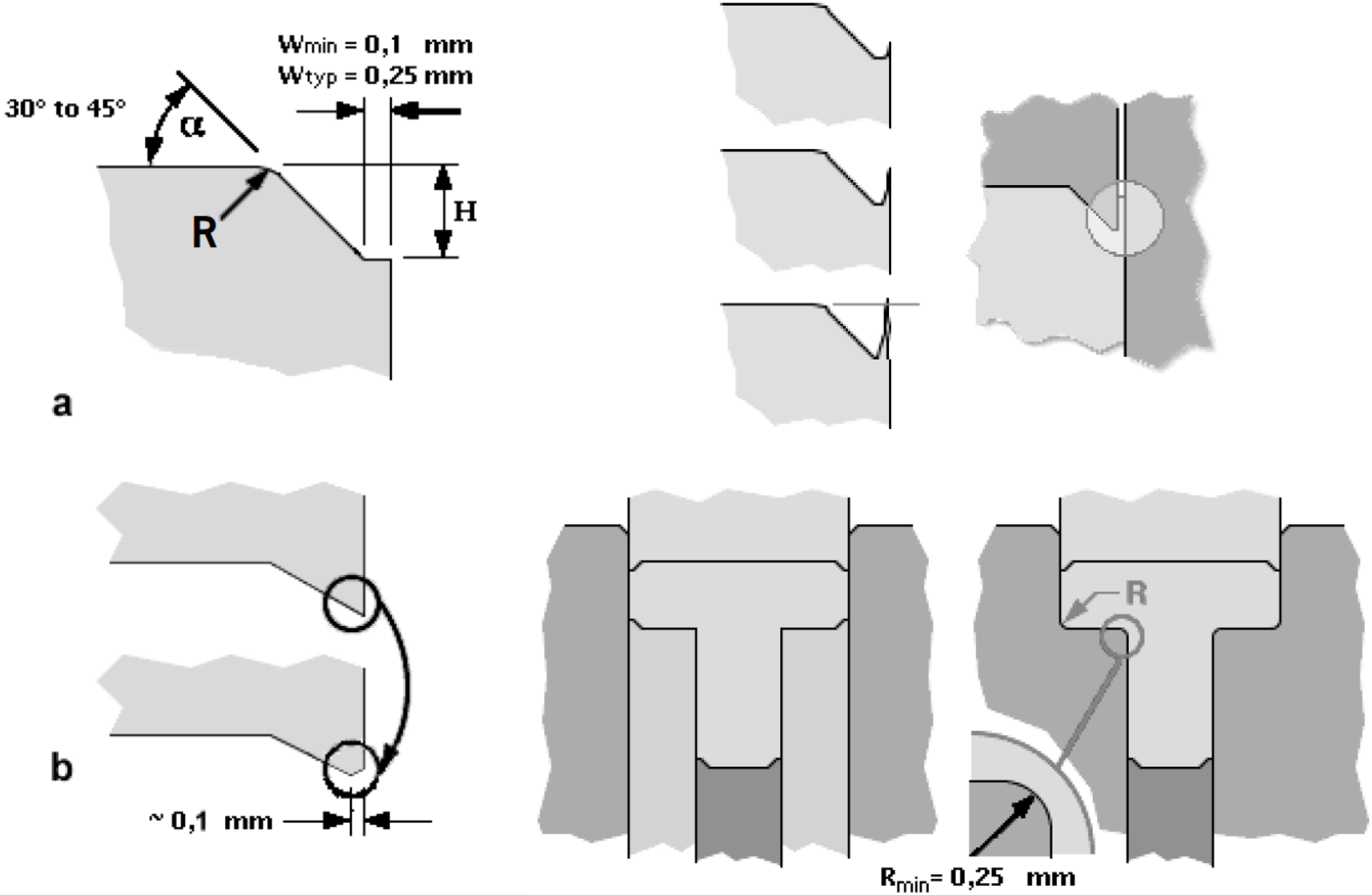
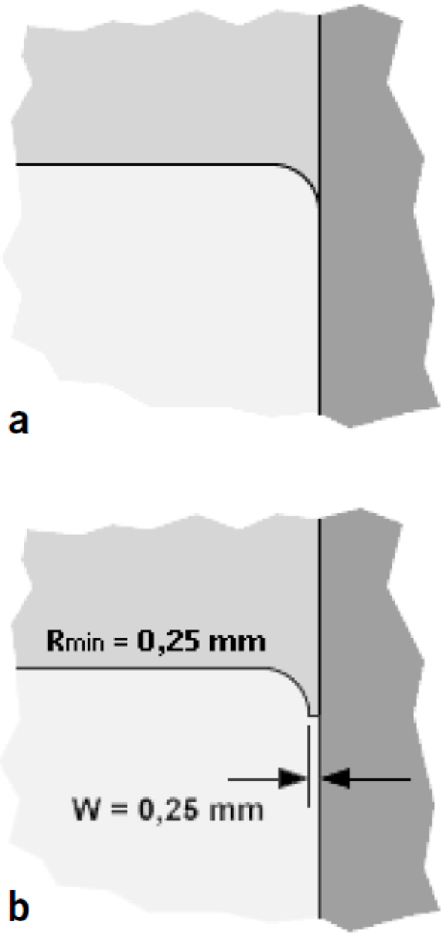
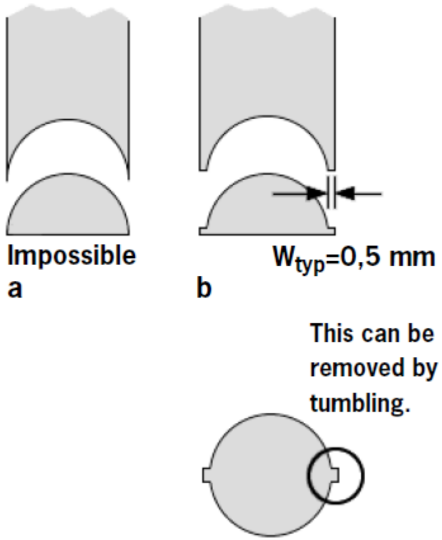
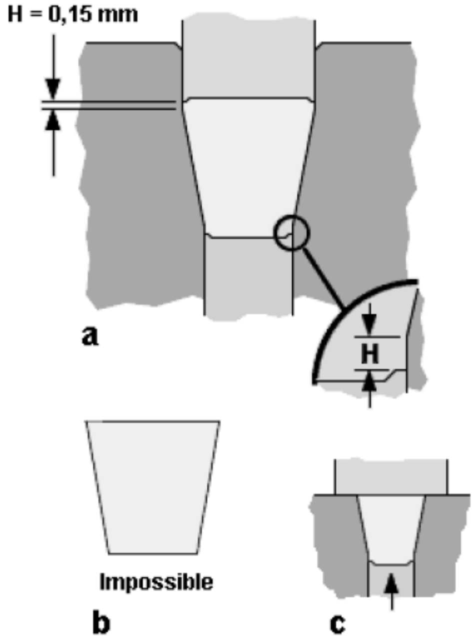


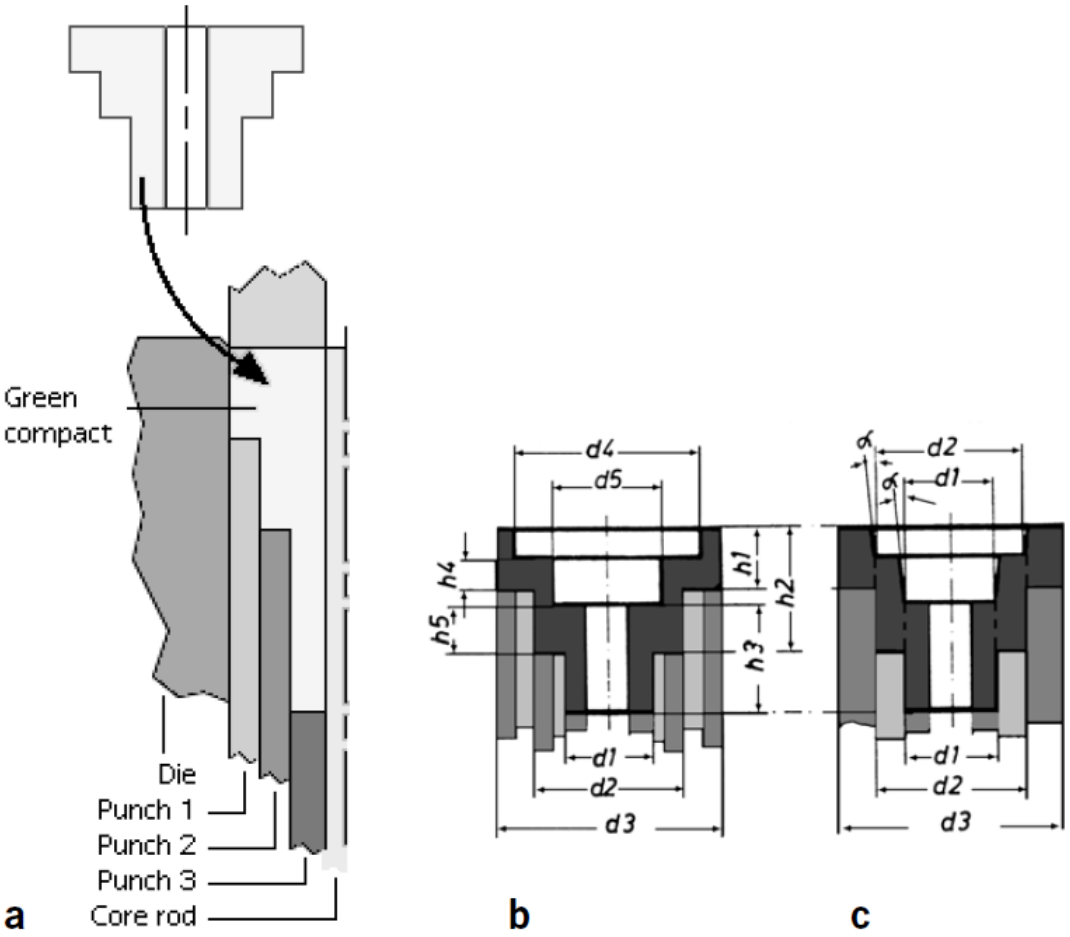
Power Tools

BOSCH


a
Rmin = 0,25 mm
W = 0,25 mm
b

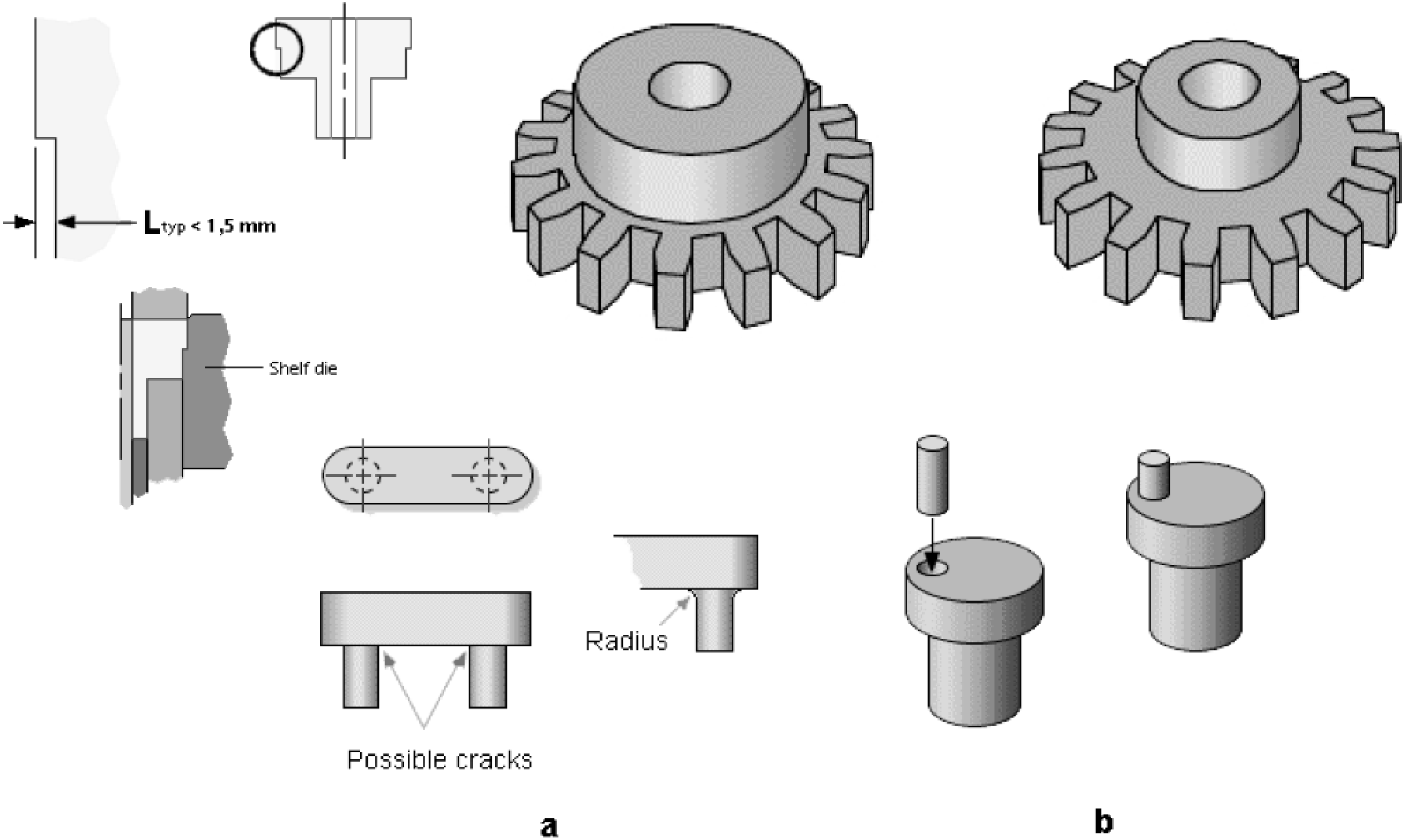

Impossible
a
b
Wtyp=0,5 mm
This can be removed by tumbling.

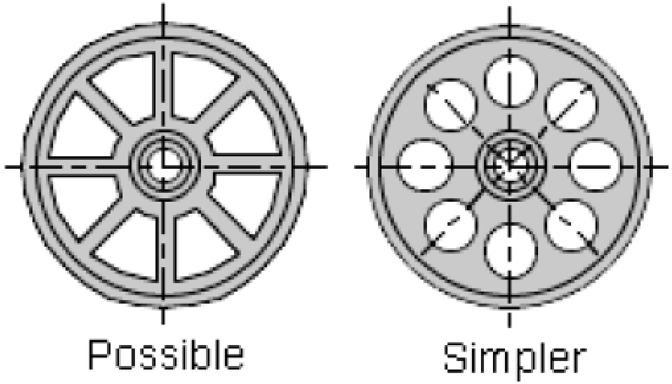

H = 0,15 mm
a
H
Impossible
b
c

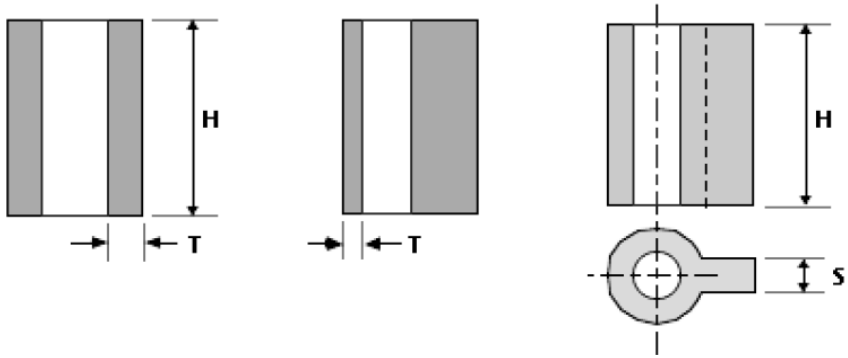

Green
compact
Die
Punch 1
Punch 2
Punch 3
Core rod
a
d4
d5
h4
h5
h1
h2
h3
d1
d2
d3
b
α
d2
α
d1
d1
d2
d3
c

BOSCH

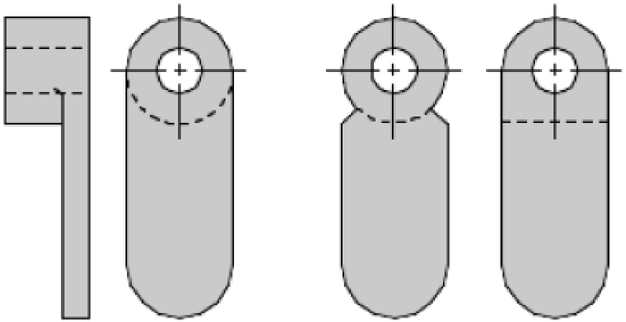
Szinter technológia

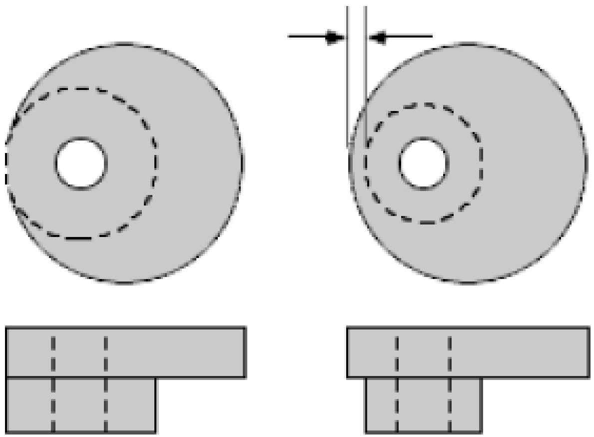






- When the ratio H/T, in sketch (a), is higher than 6.
- When thickness T, in sketch (b), is less than 0,8 mm
- When the ratio H/S, in sketch (c), is higher than 6 (





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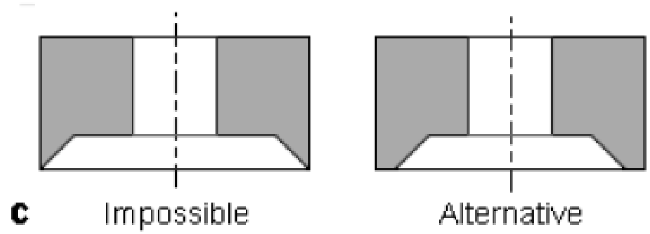

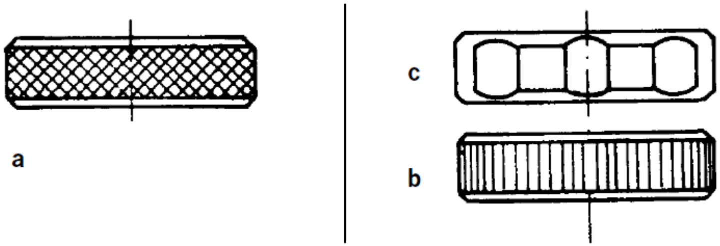

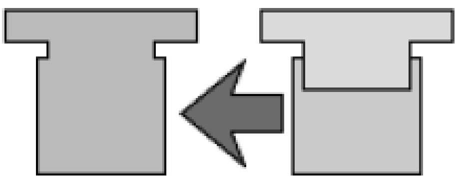

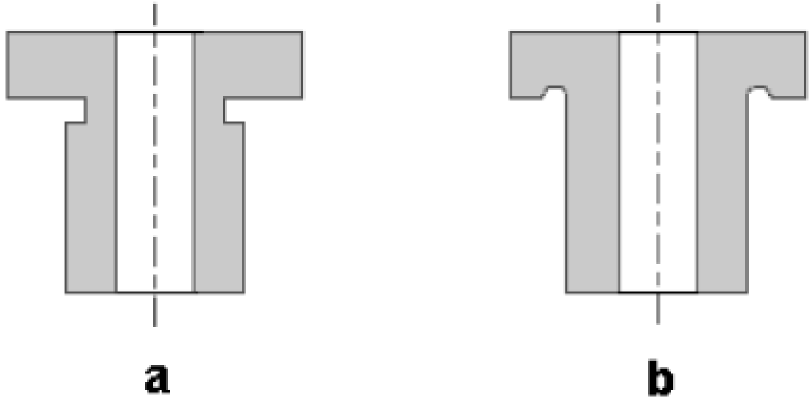

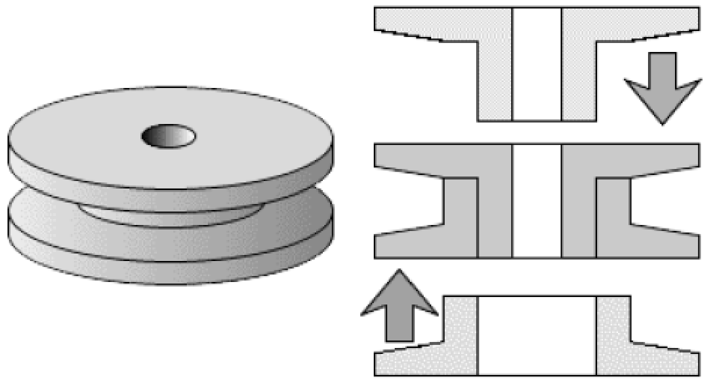

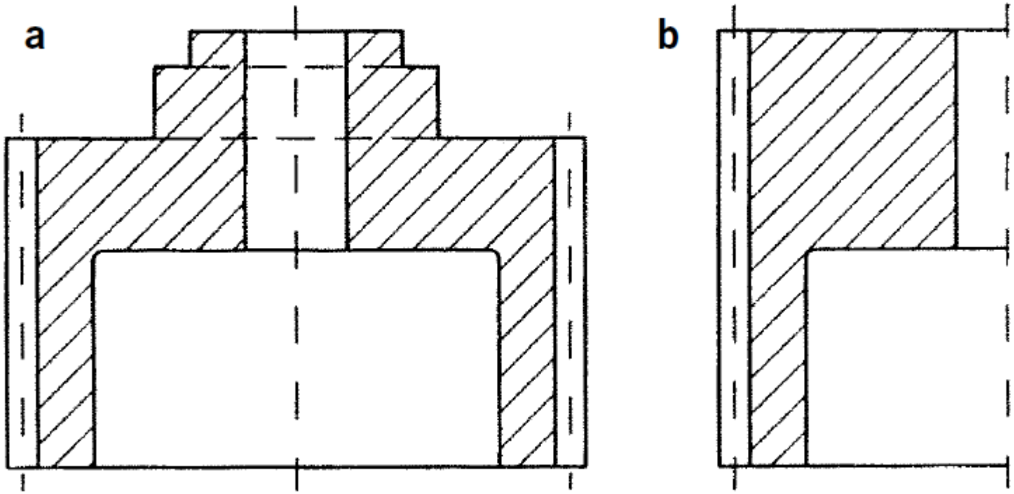

Fig. 8.32 Changing the design of a structural part for simpler P/M-tooling (in case of short production series).


4 5 6 7 8 9 10 11 12 13 14

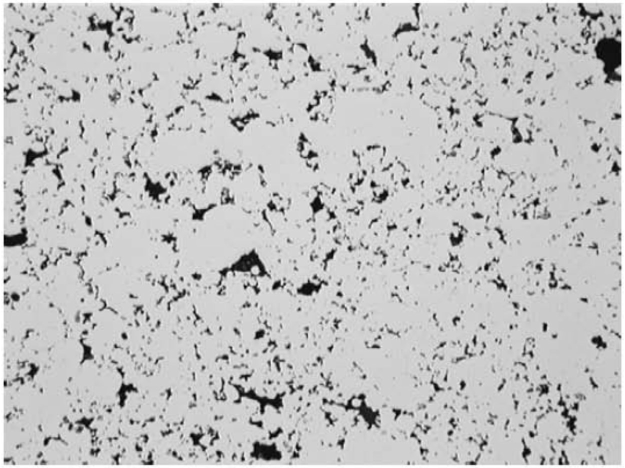

Figure 4: Sintering necks

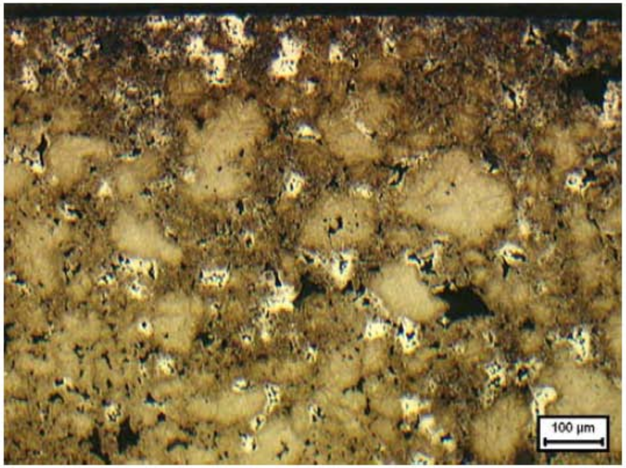

Figure 5: Etched overview

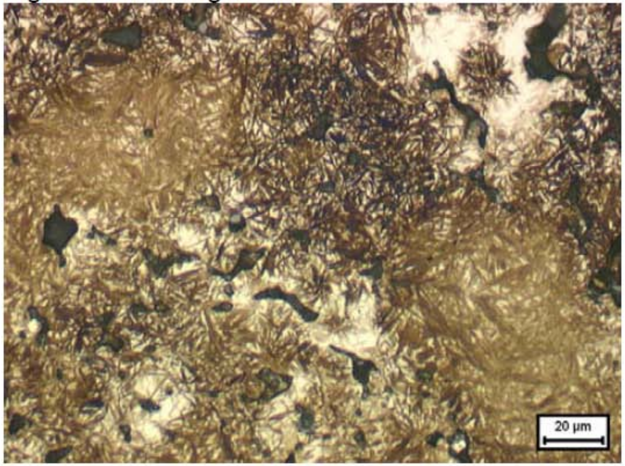

Figure 6: Etched surface

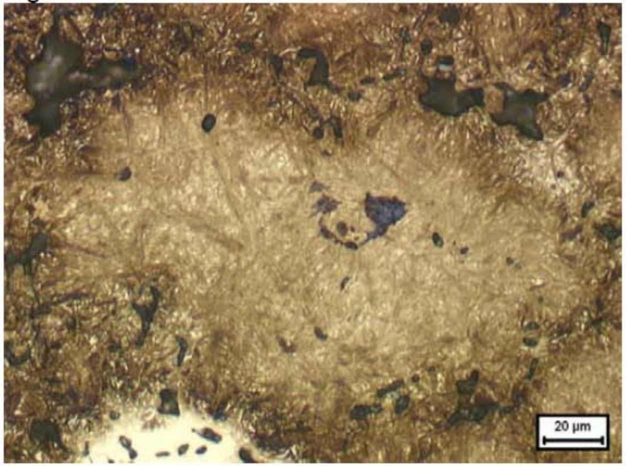

Figure 7: Etched centre

SV: Sintered gear analysis

Engström Ulf [Ulf.Engstrom@hoganas.com]

Címzett: Zima Zoltan (McP/QMM2)

Másolatot kap: Vinnerborg Fredrik; Kakuk Jozsef (PT-GEU/ENM2)

Mellékletek: Bosch-Hungary- CSI Report 2010070029.pdf (984 kB)

Dear Mr. Zima Zoltan,

We have now investigated the gear you discussed with us after the seminar and you recently sent us. I enclose our investigating report.
The conclusions you can draw are the following:

1. The material composition, analysed by EDS, is around 2.2% copper, 1.6% nickel and 1% molybdenum. Probably the base powder is pre-alloyed with 0.85% Mo and Cu and Ni added as powders.
2. There is a big crack in the part probably formed during the ejection step after compaction.
3. The sintering necks are not completely developed indicating that sintering time is not sufficient
4. A lot of retained austenite in the surface indicating to high carbon content in the surface after heat treatment.

In order to overcome the problems the manufacturer has to look over the compaction cycle and especially the ejection part.
Maybe look over the punch hold down pressure on the upper punches during ejection and or improved lubrication. It is also recommended to increase the sintering time to achieve better developed sintering necks. Finally surface carbon conditions should be adjusted.

Please observe that these are our findings and that it is a sensitive matter for us to get involved in an end user complaint vs. our customer.
Please inform us how you will go ahead to discuss with your supplier before you do so to avoid any disturbances in the value chain.

Best regards
Ulf Engström

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