nificance. Any reaction between the particles or between the powder and its environment starts at these surfaces. This affects sinterability. For a very irregular shaped particle with a high degree of surface roughness, the specific surface area can be very high.

The surface area of a given powder is measured by the BET method, in which an adsorption of a species in solution may be used to obtain a value of specific surface (S_W) if the surface is completely covered by a monomolecular layer of the solute. From a knowledge of the area occupied by one molecule, the total area of the powder sample and, finally, S_W can be obtained. The amount of gas adsorbed in a monomolecular layer in m^2 is calculated from an adsorption isotherm, i.e. a series of measurements of the volume V of gas adsorbed as a function of pressure p.

The BET method of determining the specific surface is widely used for catalysts. Its use for metal powder is primarily for very fine powders, particularly those of the refractory metals and for characterizing the total surface area of porous powders.

3.6 Apparent and Tap Density

The apparent density of a powder refers to the mass of unit volume of loose powder usually expressed in g/cm^3. It is one of the most critical characteristics of a powder, because of following reasons:

(*a*) It determines the size of the compaction tooling and the magnitude of press motions necessary to compact and densify the loose powder;

(*b*) It determines the selection of equipment used to transport and treat the initial powder;

(*c*) It influences the behaviour of the powder during sintering;

Other characteristics which have direct bearing on apparent density are the density of the solid material, particle size and shape, surface area, topography and its distribution.

Apparent density is determined by the Hall flowmeter, where a container of known volume (25 ml) is completely filled by flowing metal powder through a Hall funnel (Fig.3.3).

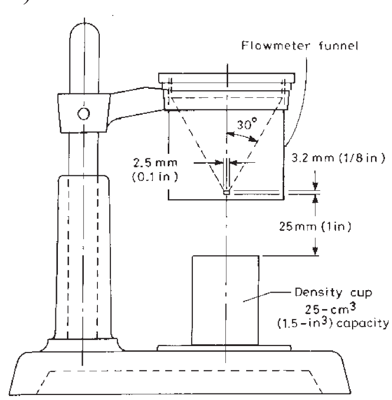

Fig.3.3 Hall flowmeter.

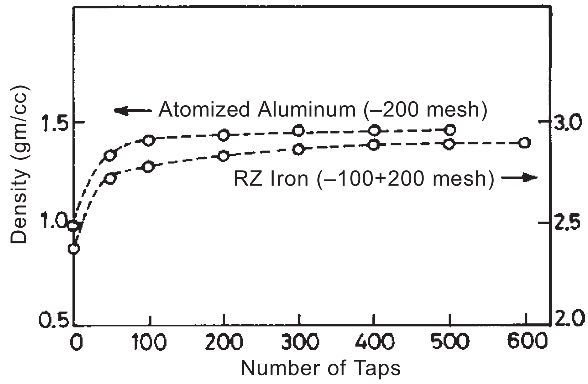

Fig.3.4 The density of loose powder as a function of the number of taps, for atomized aluminium and atomized/reduced iron powders[2].

Very often a mass of loose powder is mechanically vibrated or tapped. The density of the loose powder increases due to this treatment and is always higher than the apparent density. The greatest increase in density occurs during the initial tapping period and eventually the density becomes constant. The final stable density is the value reported as the tap density (Fig.3.4). The amount of increase in density due to tapping depends on the extent of original friction forces between the particles. The greater the frictional conditions in the original powder (small sizes, irregular shapes and roughened surface), the greater the increase in density due to tapping.

Table 3.4 gives some typical data of apparent and tap densities of iron powder produced by different methods.

3.7 Flow Rate

Rapid rates of P/M parts production require a relatively rapid flow of pow-

Table 3.4 Apparent and tap densities of various powders[2]

Material	Apparent density (g/cc)	Tap density (g/cc)	Percent increase
Copper (a)			
spherical	4.5	5.3	18
irregular	2.3	3.14	35
flake	0.4	0.7	75
Iron (–100+200 mesh)			
electrolytic	3.31	3.75	13
atomized	2.66	3.26	23
sponge	2.29	2.73	19
Aluminium (–200 mesh)			
atomized	0.98	1.46	49

(a) all copper powders with same size distribution; from H.H. Hausner, in: Handbook of Metal Powders, A.R.Poster, editor, Reinhold, N.Y., 1966.

der from storage containers to dies. The standard method for its determination is by the Hall flowmeter, where the time necessary for 50 g of powder to flow through a prescribed small orifice is measured. The test offers only a means of comparison and evaluation because in the majority of operating conditions the powder does not have to flow through a small orifice. Flow times are, therefore, proportional to the reciprocal of the flow rates. Very fine powders do not flow through a small orifice. This is a result of the drastic increase in the specific surface area as the size becomes very small. For a given metal powder, the higher the apparent density, the lower the flow time. When a fine size powder is mixed in a coarse powder, because of the increase in the apparent density, the flow time is decreased irrespective of whether the particles was irregular or spherical. However, in case of irregular powder additions an amount is reached for which no flow behaviour is observed. This corresponds to the presence of an excessive amount of frictional surface area.

3.8 Compressibility

Compressibility is a measure to which a powder will compress or densify upon application of external pressure. Compressibility is reported as the density in g/cm^3, rounded to the nearest 0.01 g/cm^3, at a specified compaction pressure, or as the pressure needed to reach a specified density. Typically, a cylinder or rectangular test piece is made by pressing powder in a die, with pressure applied simultaneously from top and bottom.

Compressibility of the powder is influenced by factors like: inherent hardness of the concerned metal or alloy, particle shape, internal porosity, particle size distribution, presence of nonmetallics, addition of alloying elements or solid lubricants.

Compressibility, alternatively, is defined in terms of the densification parameter, which is equal to:

$$\text{Densification parameter} = \frac{\text{Green density} - \text{Apparent density}}{\text{Theoretical density} - \text{Apparent density}}$$

Compressibility, in general, increases with increasing apparent density. A rather large amount of densification occurs at relatively low compaction pressure. Another term, which is very important for tooling design, is the compression ratio. It is the ratio of the volume of loose powder to the volume of the compact made from it. A low compression ratio is desirable because of following reasons:

- Size of the die cavity and tooling can be reduced
- Breakage and wear of tooling is reduced
- Press motion can be reduced
- A faster die fill and thus a higher production rate can be achieved.

Table 3.5 Green density and green strength for various types of iron powders

Powder	Apparent density (g/cm^3)	Compaction pressure (N/mm^2)	Compaction pressure (tsi)	Green density (g/cm^3)	Green strength (psi)	Green strength (N/mm^2)
Sponge [a]	2.4	415	30	6.2	14.41	2100
		550	40	6.6	22.05	3200
		690	50	6.8	28.25	4100
Atomized sponge [b]	2.5	414	30	6.55	13.09	1900
		550	40	6.8	18.80	2700
		690	50	7.0		
Reduced [a]	2.5	415	30	6.5	15.85	2300
		550	40	6.7	20.67	3000
		690	50	6.9	24.11	3500
Sponge [a]	2.6	415	30	6.6	18.60	2700
		550	40	6.8	24.80	3600
		690	50	7.0	26.87	3900
Electro [c]	2.6	415	30	6.3	31.69	4600
		550	40	6.7	42.72	6200
		690	50	6.95	53.74	7800

[a] powders contained 1% zinc sterate blended in
[b] powders contained 0.75% zinc stearate blended in
[c] unlike the other powders, this one was isostatically pressed (from C.E.Buren and H.H.Hirsch, in: Powder Metallurgy, Interscience, New York, 403–440)

3.9. Green Strength

Green strength is the mechanical strength of a green – i.e. unsintered powder compact. This characteristic is very important, as it determines the ability of a green compact to maintain its size and shape during handling prior to sintering.

Green strength is promoted by:

– increasing particle surface roughness, since more sites are available for mechanical interlocking;

– increasing the powder surface area. This is achieved by increasing the irregularity and reducing the particle size;

– decreasing the powder apparent density. This is a consequence of first two factors;

– decreasing particle surface oxidation and contamination;

– increasing green density (or compaction pressure);

– decreasing the amount of certain interfering additives. For example, the addition of small alloying elements, such as soft graphite to iron and lubricant, prevents mechanical interlocking.

The standard green strength test is a transverse bend test of a 12.7 by 31.7 mm (0.50 by 1.25 inch) rectangular specimen 6.35 mm (0.25 inch)

Table 3.6 Typical maximum levels for occupational exposure (8 hour day)

Material	Concentration (μg/m³)
Plutonium	0.0001
Beryllium	2.0
Nickel-carbonyl	7.0
Uranium	80.0
Cadmium	100.0
Chromium oxide	100.0
Mercury	100.0
Tellurium	100.0
Thorium	110.0
Lead	150.0
Arsenic	500.0
Zirconium oxide	5000.0
Iron oxide	15000.0
Titanium oxide	15000.0
Zinc oxide	15000.0

from F.Clark, Advanced Techniques in Powder Metallurgy, p.161, Rowman and Littlefield, N.Y., 1963.

thick. It is the stress calculated from the flexure formula, required to break the specimen, which as follows:

$$\text{Green strength} = \frac{3PL}{2wt^2}, \text{N / mm}^2$$

where P is the breaking load, N; L is the distance between the supporting rods, mm; t is the specimen thickness, mm; w is the width of the specimen, mm

Table 3.5 shows the relationship among green strength, apparent density, compacting pressure and green density for several types of iron powders.

3.10 Pyrophorocity and Toxicity

Pyrophorocity is a potential danger for many metals, including the more common types, when they are in a finely divided form with large surface area-to-volume ratios. The toxicity of powder is normally related to inhalation or ingestion of the material and the resulting toxic effect. Table 3.6 shows the data for typical maximum permissible levels of toxic powders, while Table 3.7 contains data describing the explosibility and ignition conditions for some materials. The chemical reactivity of a material increases as the ratio of surface area-to-volume increases. For this reason, fine par-

Table 3.7 Ignition and explosibility of powders[2]

Material	Size, microns	Ignition temperature °C [(a)]		Minimum explosive concentration oz/ft^3	Index of explosi-bility [(c)]
		Cloud	Layer		
					Severe
Aluminium atomized	–44	650	760	0.045	>10
Al–Mg Alloy	–44	430	480	0.020	>10
Magnesium	–74	620	490	0.040	>10
Thorium Hydride	3	260	20	0.080	>10
Zirconium	3	20	190	0.045	>10
Uranium Hydride	3	20	20	0.060	>10
Titanium	10	330	510	0.045	>10
Uranium	10	20	100[(b)]	0.060	>10
Thorium	7	270	280	0.075	>10
					Strong
Zirconium Hydride	–44 (98%)	350	270	0.085	3.7
Iron Carbonyl	–74	320	310	0.105	1.6
					Moderate
Boron	–44	470	400	-0.100	0.8
Chromium	–44 (98%)	580	400	0.230	0.1
Manganese	–44	460	240	0.125	0.1
Tantalum	–44	630	300	-0.200	0.1
Tin	–53(96%)	630	430	0.190	0.1
					Weak
Lead	–53	710	270	-	<<0.1
Molybdenum	–74	720	360	-	<<0.1
Cobalt	–44	760	370	-	<<0.1
Tungsten	–74 (99%)	730	470	-	<<0.1
Beryllium	1	910	540	-	<<0.1
Copper	–44 (98%)	700	-	-	<<0.1

[(a)] These data apply to relatively coarse dust (–200 mesh) but not to submicron powder
[(b)] In this test less than one gram of powder used; larger quantities ignited spontaneously
[(c)] IE = ignition sensitivity X = explosion severity
(from M.Jacobson, A.R.Cooper and J.Nagy, Explosibility of Metal Powders, Bureau of Mines, Report 6516, 1964)

Table 3.8 Some characteristics of metal powders made by various commercial methods

Method of production	Typical purity (est.)	Particle characteristics		Compres-sibility	Apparent density	Green strength
		Shape	Meshes available			
Atomi-zation	High 99.5+	Irregular to smooth, rounded dense particles	Coarse shot to 325 mesh	Low to high	Generally	Generally low
Gaseous reduction of oxides	Medium 98.5 to 99.0+	Irregular, spongy	Usually 100 mesh and finer	Medium	Low to medium	High to medium
Gaseous reduction of solutions	High 99.2 to 99.8	Irregular, spongy	Usually 100 mesh and finer	Medium	Low to medium	High
Reduction with carbon	Medium 98.5 to 99.0+	Irregular, spongy	Most meshes from 8 down	Medium	Medium	Medium to high
Electrolytic	High +99.5+	Irregular, flaky to dense	All mesh sizes	High	Medium to high	Medium
Carbonyl decom-position	High 99.5+	Spherical	Usually in low micron ranges	Medium	Medium to high	Low
Grinding	Medium 99.+	Flaky and dense	All mesh sizes	Medium	Medium to high	Low

ticles of many materials combine with oxygen, ignite and result in explosive conditions.

3.11 Conclusion

Chapters 2 and 3 suffice to convey the message of the interrelation of the powder production methods and powder characteristics. Such a close relationship is not so prevalent in metal production methods other than for powder production. Table 3.8 summarises different types of metal powder characteristics along with their routes for production.

Reference

1. R.M. German, Powder Metallurgy Science, 2nd edition, MPIF, Princeton, 1994.
2. J.S. Hirschhorn, Introduction to Powder Metallurgy, American Powder Metallurgy Institute, New York, 1969.