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Modelling and Part Manufacture

P.Brewin[1], O. Coube[2], J.A. Calero[3], H. Hodgson[4], R. Maassen[5] and M. Satur[6]

[1]European Powder Metall Association, Talbot House, Market St., Shrewsbury SY1 1LG, UK.
[2]PLANSEE SE, Technologiezentrum (TZIK), A-6600 Reutte, Tirol, Austria.
[3]AMES S.A, Ctra.Nac. 340 Km 1.242 Pol.Ind."Les Fallulles", 08620 Sant Vicenc dels Horts, Barcelona, Spain.
[4]Dynamic-Ceramic Ltd., Crewe Hall Enterprise Park, Weston Road, Crewe, Cheshire CW1 6UA, UK.
[5]GKN Sintermetals Service, Krebsoge 10, D-42477 Radevormwald, Germany.
[6]Swift Levick Magnets Ltd., High Hazels Rd., Barlborough Links, Barlborough, Derbys S43 4TZ, UK.

2.1 Introduction

Compaction is the central stage of the Powder Metall shaping process. Powder blends must balance free flow with high green strength and good compressibility (of special interest to powder makers); tooling must be of sufficient strength to withstand the stresses of production, and must incorporate design features that take into account not only finished-part geometry but also die fill, powder-transfer stages, press kinematics and ejection to achieve uniform pressed density and to avoid generation of shear or tensile cracks as a result of the compaction process (of special interest to tool designers and press makers).

Where parts are to be sintered to full density, sintered-part accuracy will substantially be determined by uniformity of pressed density; where final-part properties are to be achieved without dimensional change by sintering at lower temperatures, parts can be more complex in shape (of special interest to component producers). Where parts are to be marketed in the as-pressed condition (such as in pharmaceuticals) they must have sufficient strength to withstand post-compaction operations and delivery to the customer. In this process the pressed part may incorporate necessary geometrical features (such as embossed letters) which weaken the component (see Chapter 14).

Developments in compaction modelling ("CM") offer the component manufacturer an advanced tool to calculate stresses and pressed part qualities for different possible tooling designs. Such a design tool can additionally be used in the selection of powder blends presses and tooling by testing alternative designs virtually and by sensitivity methods.

In addition to accurate and effective compaction modelling ("CM") industry requires

- cost-effective methods of generating the input data required for the compaction models, this to include powder blend constitutive data, friction and die fill characteristics.
- methods of validating the predictions on experimentally produced parts including predictions of pressed density, tooling loads and cracks.

This chapter considers the requirements of industry for both:

- *how CMs should improve the PM production process*
- *how the operational aspects of CMs should integrate with industry's existing design and manufacturing methods.*

It is intended that this discussion should assist researchers in prioritising their efforts in the development of compaction modelling techniques for industrial use, while further encouraging industry to implement them.

2.2 Requirements for Improving the PM Production Process

2.2.1 Introduction

Because of its inherent flexibility, Powder Metall often offers several different processing routes to solve a single design problem. The increasing success of computers to model the compaction process is also a measure of our improved understanding of the process itself; for example, our understanding of the mechanisms controlling the filling of dies has greatly improved in recent years as a direct result of CM studies. CM also offers the ability to carry out computer studies to determine the sensitivity of a key parameter such as part density distribution to an independent variable such as die wall friction and tooling motion [1]. The results of such studies can be used better to focus engineering effort in terms of raw material selection, engineering design or processing route. Recent developments in CM have been greatly assisted by the continuing and fast improving power and processing speed of the desktop PC, these have made it possible to carry out simulations in a few hours that previously would have taken several days, and have opened up the possibility of using discrete element models.

It is significant that many major industries converting particulates to components by die compaction have no direct experience of CM - indeed it is only recently that CM has started to be used in pharmaceuticals, one of the largest industries employing powder compaction.

Industry requirements for CMs are as numerous as the number of in house functions involved [2]. Overall, however, industry wishes to use CM in all in-house functions for calculating density distribution, crack prediction, tooling loading and press movements.

Apart from the obvious uses of CM in research and development, full implementation will be in association with the design office and to some extent by production for press setting. Achieving this will require:

- material databases
- robust FE software
- integration of the software in an automatic or semi automatic optimisation tool
- good interfaces with other computer applications (both component design and press software)
- user-friendly interfaces for non specialists.

Additionally it should be possible to generate adequate input data in-house; externally developed software should provide good quality updates and support.

Table 2.1 lists the uses and user friendly requirements by company function:

Table 2.1. Uses of compaction modelling by company function

Company function	Uses	User-Friendly requirements
R&D	Feasibility studies New materials Process development Powder development	Interfaces to FE and CAD software input data generation with in-house capabilities (instrumented die, tensile and compression tests) Interface between FE and optimisation tool
Tooling design office	Feasibility studies for different tool solutions (materials, shapes, kinematics) Die deformation Springback of the green compact	Interface between FE and CAD software Interface between FE and optimisation tool Material database Database of presses to be used
Production press setup	Press setup	Interface to press software Interface to less-controlled mechanical presses Material database Robust software Speed Visual displays of output

Until low-cost software packages are commercially available, smaller companies will likely prefer to purchase simulations from commercial agencies.

2.2.2 Selection of Powder Blends

2.2.2.1 Introduction

Industry can look to CM not only to predict pressed part density distributions and loads, but also as a tool to develop powder properties. Thus, powder makers can use CM to optimise powder properties for different component shapes; parts makers with in-house powder production can similarly use CM to optimise powder properties; other parts makers can choose the most appropriate combination of raw material and processing parameters to suit the component and the production equipment available. Granulation and other blend modifications can be used to optimise powder blends. (Where powders require magnetic alignment following die fill but before the application of pressure, granulation may not be possible.)

2.2.2.2 Granulation

Several industries including ceramic, hardmetal, pharmaceutical and magnets use powders that are too fine to flow freely. Granulation using organic binders is used to provide relatively coarse rounded agglomerates that flow freely into dies. A variety of different granulation techniques is used [3], each producing different granule structures.

The best granulation techniques

- produce granules in which the binder is distributed uniformly
- allow granules to deform during compaction to fill all voids uniformly.

In hardmetal manufacture granulation can be used to reduce the tap:apparent density ratio to as low as 1.05 (unlubricated ferrous powders are typically 1.25) thereby improving die fill uniformity. Because the hardmetal particles are incompressible, the binder provides the compact green strength.

2.2.2.3 Fill and Flow

Recent experimental work and numerical studies have done much to improve our understanding of die filling [4]. Not least, these studies have highlighted those areas where we lack understanding of the different mechanisms, particularly the role of entrapped air.

Numerical studies are only of value if they can be validated; this has been done by:

- high speed photography of transparent dies using both monochrome powders and powders of varying colours and sizes
- sectioning and X-ray of filled dies after light sintering
- metallography of the finish sintered part.

(See Chapter 9 for further discussion.)

Discrete element modelling enables us to map the evolving powder density distributions during die filling and thereby better to optimise the die design and fill kinematics. In this respect it is clear that fill-shoe speed must be controlled to match the evolution of air from the die cavity. Failure to optimise die filling can lead to large variations in fill density through the die cavity and also to incomplete filling at the die surface.

Some key issues are as follows:

- The fluidity of powder blends has a large influence on die filling, powder transfer and the early stages of compaction [5]. Fluidity is normally measured by Hall flow, although more recent work shows that a variable-aperture flowmeter ("VAF") more closely reproduces flow into closed dies ([6] p.77). The speed of the filling shoe must also be controlled: above a critical velocity dies will only fill partially ([6] Fig 6.)
- Recent modelling studies have demonstrated that on more complex parts, high-integrity compacts can only be achieved if the powder fill is uniform. High throughput compaction presses need to operate at fastest speeds consistent with good quality product, and therefore prefer free-flowing powders. On the other hand, free-flowing powders tend to give lower pressed-part green strength and greater tendency to ejection cracks. While to some extent this can more easily be achieved by optimising tool design and press kinematics, the most important factor is achieving a satisfactory compromise between powder flow and green strength.
- Filling studies [4] show the high degree of turbulence that powder blends can experience during die filling, largely as a consequence of exhausting the air entrapped during the filling process. This is particularly important on fine irregular powders that present considerable resistance to air flowing out of the die during the filling operation ([6] p.82). A comparison of critical velocities measured in air and vacuum give an indication of the tendency of certain powders to elutriate during filling ([6] p.84).
- Where two or more different powders are to be blended, the ease of mixing is greatest where powders are similar in particle size and material density. Thus, it is difficult to mix powders of widely differing particle size and density. Unfortunately many PM production processes require the addition of sub-micrometre powders (graphite, lubricants) to coarser powders. Such blends can segregate owing to air turbulence during the filling operation, resulting in undesirable variations in chemistry through the sintered part. Where this could lead to problems in final product performance, it will be advisable to stabilise the powder blend using appropriate binders. Powder blends may also be granulated where binders used are chemically compatible with the powder, and where high compacted densities are not required [5].
- Measures such as suction fill can be used to reduce countercurrent air flow during die fill by withdrawing lower punches during powder filling.
- The abrasive action of the blending operation increases the surface activity of powders; therefore powders should always be compacted as soon as practicable after blending; where this is not practicable care must be taken to exclude moisture in storage.

2.2.2.4 Deformation Characteristics during Compaction

In cold isostatic compaction powders are placed in flexible bags. After sealing, these bags are submerged in hydraulic fluids and then pressurised to the required pressure. Each powder particle sees the same pressure in all directions, and the compact shrinks approximately isotropically during compaction.

In die compaction this is not so; axial pressure only is used to densify the powder, radial dimensions being constant and confined by the die wall. Powder particles are subjected to different pressures radially from axially, typical radial pressures being half the axial pressures.

Compaction modellers have developed several basic methods of establishing the deformation characteristics of powders subjected to these non isotropic more complex stress systems (for more details see Chapters 3 and 4).

To measure the densification and hardening of the powder during compaction three laboratory rigs are commonly used:

1. High-pressure Triaxial Stress Rigs

Depending upon the design, these either measure the compaction characteristics of loose powders, or of a previously compacted part. These can work at pressures up to 1200 MPa axial and 700 MPa radial.

2. Low-pressure Triaxial Stress Rigs

Similar in design to high-pressure rigs compacting loose powders, these measure the deformation characteristics below 1 MPa.

Both the above are capital-intensive items unlikely to be purchased by industry for in-house use.

3. Instrumented Die

A plain cylindrical die is used to compact the powder; sensors in the die wall measure radial pressures during compaction at different heights.

To measure the green strength achieved by the powder during compaction, cylindrical or beam samples are first die compacted in order to reach several strategic densities and are then tested using one of the following methods:

- Compression test

a cylinder is compressed again in the axial direction (the original pressing direction). Fracture stress is measured at different densities.

- Brazilian disc test

a cylinder is compressed in the radial direction. Fracture stress is measured at different densities.

- Four-point bend test

a beam sample undergoes a four-point bend test. Fracture stress is measured at different densities.

Our improved understanding of the material processes underlying compaction now enables us better to select powder blends for the more demanding applications. In the early stages of compaction, powders need to transfer more readily to the geometrical shape of the final part. This reflects in large axial strains for a given pressure (in [7] slide 23 the lubricant addition causes deterioration in low-pressure response).

Finer spherical powders can transfer in the early stages of compaction by a series of collapsing bridges, explaining why good compacts can only be achieved at compaction speeds of 50% or less of normal ([7] slide 24).

While granulates can exhibit superior powder-transfer characteristics, granulation has a significant effect on low-pressure compaction response. Thus, granulates deform and break down at lower pressures than non granulates giving rise to greater strains at a given pressure and a more complex low-pressure response ([7] slide 25).

Computer simulators fit the raw plasticity data to relatively simple empirical models (Cam-Clay, Drucker-Prager-Cap etc). Such models are also useful in powder selection as follows: ([7] slides 27 and 28).

- Powder *densities* are determined by a combination of mean and shear stress; different blends can be compared by comparing the respective DP failure lines, which shows the stress levels at which failure can occur.
- Powders with high cohesion* are less likely to form cracks.

*as measured by the cohesion and the cohesion angle on Drucker-Prager-Cap models ([7] and [8]). This is further discussed in Chapters 4 and 10.

2.2.2.5 Other

The pressed density selected for a component depends on several factors:

- Where ferrous parts are to be sintered, the pressed density converts roughly to the sintered density and therefore largely determines the finished part mechanical strength.
- Where hardmetal, ceramic or refractory parts are to be sintered, the minimum pressed density is used consistent with a) good green-part handleability b) adequate sinterability.
- Die-wall friction gradients increase with increasing pressed density, as do internal stresses locked up in the pressed part. Both effects mean that it is often more difficult to achieve tight dimensional tolerances on components pressed to high densities.
- While elastic recovery of compaction punches can be calculated, elastic recovery of punch holders and tool and press frames is difficult to estimate, especially in the axial direction (see Section 2.3.4). They are directly measured on modern press machines. These effects become more important at higher compaction pressures;
- Components pressed at high pressure have a greater tendency to form tensile cracks on ejection.

Powders produced in *prealloyed* (rather than elementally blended) form have the advantage of known chemical composition unaffected by segregation caused by air turbulence during die filling. The main disadvantage of prealloying, however, is the inevitable loss of compressibility, although small additions of certain elements can sometimes be made that have a strongly beneficial effect on finished-part mechanical properties without adversely affecting compressibility. (An example of this is the Fe-0.6Mo powder series.)

Powder *cost* tends to be significant on larger components; on components below (typically) 10-20 g powder content is usually masked by processing costs.

Components subjected to high stresses or other hostile environments should always be produced from *high-purity* powders with low surface oxygen. Inclusions should be minimised by taking care when manufacturing both the powder and the component, including use of magnetic separation (where possible). On materials sintered subsolidus maximum allowable inclusion size will correspond to maximum pore size; on materials sintered supersolidus maximum allowable inclusion size will generally be much finer, depending on stress levels and critical defect size.

2.2.3 Tooling Design

2.2.3.1 Introduction

Tooling design is arguably the most important function in sintered component manufacture, and the function that is most closely guarded in a competitive world.

One of the uses of CM is to make it easier for the production engineer to select the cheapest tool and simplest press consistent with a pressed component of adequate quality. In general, the part designer will strive to avoid the need for post-sinter machining; however, this may be necessary on components incorporating features such as transverse holes or where a complex tool cannot be justified on economic grounds. Post-sinter machining may also be needed where sintered dimensional tolerances are insufficiently accurate. Examples of post-sinter machining are where supersolidus sintering is used on pressed components of non-uniform pressed density, or subsolidus sintering on components pressed at high pressure.

Where distortion after sintering can be expected (uneven pressed density, slumping through gravity) it may be possible to incorporate the inverse of the anticipated distortion in the compaction tooling, to neutralise this. However, this is not usually the best practice.

The tooling designer needs accurate information on tooling stresses if he is to minimise tool breakage, to avoid over-design and to be able to use the correct figures for elastic recovery. Without CM the designer has to rely on previous experience on similar parts. The fact that tooling costs are often amongst the largest items in the maintenance budget shows the potential for improvement here.

Much of the above has to be decided at the quotation stage; CMs offer the potential to improve and accelerate this function with great benefit to the parts maker and his customer.

Tooling for use at higher compaction pressures (over 500 MPa) is usually composite, incorporating a shrink-fitted hard-wearing insert inside a steel bolster. Because hardmetal has a significantly higher elastic modulus than steel (hardmetals ~550 GPa versus steel 200 GPa), hardmetal tooling exhibits less springback during part ejection.

The principles of the composite steel/hardmetal design are that:

- the insert remains in compression at all times
- the interference fit between the insert and the die is sufficiently strong to withstand ejection of the pressed part
- the thermal processes used in fitting have no adverse metallurgical effects
- the pre-stressing is within the strength limits of the materials.

Such calculations require accurate knowledge of radial stresses during both compaction and ejection, and must take into account pressed-part height [9].

2.2.3.2 Powder Fill and Powder Transfer

Sensitivity studies using CM are powerful tools for showing the potential effect of powder fill distribution on pressed-part integrity. One study [10] compared the effect of nonuniform powder fill on pressed density distributions on 2 different shapes (see also Chapter 9). The results showed that on a plain cylinder nonuniform fill density had little effect, whereas on a more complex geometry nonuniform fill resulted both in nonuniform pressed density distributions and large inaccuracies in predicting tool forces. From the production standpoint this implies that poor flow blends and high press speeds (underfilled tooling) may be tolerated on simple parts, but to obtain high-quality pressings on complex shapes every effort must be made to obtain uniform die fill by optimising powder-fill characteristics and press kinematics.

In the case of pharmaceuticals a further requirement can be for accurate control of part weight using multitooled rotary presses (See Chapter 14).

Before pressure is applied, powders may be moved freely within the die cavity; the ideal tool design will ensure that powder particles are transferred to their final relative positions before pressure is applied [11]. Where this is not practicable (many presses will lack this capability; some geometrical features can only be imparted by compaction) it is important that powder transfer takes place below a certain threshold density (typically 4.0 - 4.5 g/cm^3 on a ferrous part); shear cracks can otherwise form. CM has considerable potential for optimising these early stages of compaction, including the ability to choose press kinematics to correspond to the powder fill characteristics and to minimise powder transfer above the advisable threshold densities.

For a given final component shape there are usually several different ways to design the compaction tooling. While the final pressed shape is determined by the finished component design, the starting cavity is determined by a combination of powder fill density, the ability of the powder to transfer laterally, the capabilities of the compaction press and the economics of the tooling. Thus, large-batch production on a high added value component can usually justify using a complex tool on a complex press (which often operates at lower speeds). In contrast, it may be difficult to justify an expensive tool for small batch production on a low added value component; such parts may have to be compacted on simple presses. Such presses may not have the capability to provide the best fill profile of the part, and may relay on significant powder transfer during the early part of the compaction stroke. CM is a tool for the parts producer to decide the level of complexity that can be imparted to the sintered component without introducing defects that cannot be machined out; additionally it enables him to optimise press selection.

CM therefore offers the possibilities of designing tooling to:

- enable simple presses to produce high-integrity complex parts
- design sintered components requiring minimal machining
- enable complex presses to produce high-integrity complex parts incorporating geometrical features that would otherwise lead to internal shear cracks.

2.2.3.3 Friction

It is known that friction between powder and die walls is one of the main contributors to density gradients in powder compacts [12].

Early simulations assumed that the powder:die-wall friction coefficient μ remained constant as pressed density increased. While this may indeed be a reasonable approximation for spherical powders, it is clear that irregular powders in ductile materials (such as atomised iron powders) will exhibit fast reducing μ in the early stages of compaction, as particles are forced under pressure to conform to the die wall ([12] Fig. 17).

Factors to be considered include:

- die finish including grinding direction
- relative hardnesses of die and powders
- the role of admixed lubricant (quantity and type).

Depending upon these factors, on irregular powders in ductile materials at the end of the compaction stroke μ may reduce to 75 or even 50% of its value at the start of the stroke. Sensitivity studies using CM may be used in the selection of the best die material and finish; it will be advisable to characterise μ by a linear or algebraic expression to reflect its variation during the compaction stroke.

2.2.3.4 Tooling Stresses and Deflection

Early CM studies validated tool-load predictions against measurements on production presses. It soon became clear, however, that data produced experimentally needed to take into account the elasticity not only of the punches but also of the entire press frame, especially where higher compaction pressures were used; where split punches were used, interpunch friction was by no means negligible; load data calculated from hydraulic pressures was often quite inaccurate and was affected by such factors as the compressibility of the hydraulic fluid at higher pressures. It was important therefore to generate “spring constant” data by compacting solid metal blocks before introducing powders for validation trials. Such effects were more important when modelling ferrous parts (compaction pressures up to 900 MPa) than ceramics or hardmetal (pressures of 90 and 200 MPa, respectively).

2.2.3.5 Other

In addition to compaction, tooling design must consider part ejection. This has two aspects:

- the ability of the pressed compact to hold together during ejection
- the design of the tool.

The Pressed Compact

The mechanical properties underlying pressed part integrity are usually measured at final pressed part density:

- shear strength

usually measured either by uniaxial compression on shallow cylindrical specimens (height: diameter < 1.0, aspect ratio H/D ≈ 2) or by diametral compression of thin circular discs (thickness less than 25% of diameter; often termed Brazilian Disc). See also Section 2.2.3.

- tensile strength

usually measured using a simple tensile test.

The above tests are reviewed in [13]. All are readily carried out in-house using standard laboratory equipment. In both cases powder blends with higher values will produce higher-quality compacts than those with lower values.

Tooling Design for Ejection

Apart from using low-friction die materials, simple geometrical features that aid ejection can be incorporated in the tooling. These measures allow gradual relaxation of pressed part stresses during the ejection process. These can include:

- providing a gradual expansion or "draft" in the top region of the die cavity
- radiusing the transition between the die cavity top and die table.

Ejection cracks can also be reduced by withdrawing the die while maintaining moderate punch axial pressure (sometimes termed "top punch hold-down").

2.2.4 Press Selection

In its finally developed form CM will help the parts maker to make the best use of the compaction press, whether mechanically or hydraulically driven. At the initial enquiry stage CM will enable him to make a preliminary selection of press type and to include press output and operating cost in his price quotation. In general, the mechanical press will be used for high-volume simple shapes and the hydraulically driven press for lower-volume, more complex shapes. Hydraulic presses are usually used above 100 tonne punch loads, and can incorporate complex tooling kinematics within a single press cycle including rapid advance (closing of the die cavity), medium speed (initial compaction) and slow speed (final compaction).

CM will further enable the parts producer to evaluate different routes to the finished component: a simple low-cost sintered component machined to final shape may be more attractive to the customer (cheaper tooling, shorter lead time to first production part) than a more complex alternative. CM can also potentially evaluate the viability of producing complex shapes from simple presses, *e.g.* the degree to which powder transfer will take place on a 2-level part without resorting to 2-piece tooling.

2.2.5 Production and Quality Control

Setting up a new press tool can be an important cost as this involves skilled operators, uses press time unproductively and is a common cause of tool damage. CM integrated with press-actuating software potentially reduces this time significantly.

Where die cavities are deep and narrow, and powder blends have poor fill characteristics, special care must be taken to obtain the most uniform die fill possible (filling-shoe vibration, bottom punch withdrawal for suction fill, slower filling rates for air evolution, *etc*.)

On complex shapes involving significant powder transfer it will be important to ensure that this occurs below the pressed density at which shear cracks can form; quite small inaccuracies in punch motion can be the difference between cracked and crack-free parts.

Quality control is most effective online early in the production sequence. Sensitivity analyses using CM may be used to calculate which powder and compaction process variables are likely to have the greatest effect on the quality of the final component. These data can then be used to set the allowable variations for these critical in process variables.

2.2.6 Sintering and Infiltration

The purpose of this book is to examine die-compaction modelling; clearly models capable of calculating sintering shrinkage, warpage and even metallurgical structures are also of great importance [14].

2.2.6.1 Supersolidus Sintering

Phenomenological sinter models can be used to calculate the required uniformity of pressed density to avoid corrective machining of the sintered part. In this case constitutive data is generated using dilatometers; other characteristics can be predicted using differential scanning calorimeters and differential thermal analysers.

Discrete element sinter models offer the potential to predict the sintering of a press part from fundamental principles.

2.2.6.2 Subsolidus Sintering

Subsolidus sintering of ferrous parts is a compromise between the need to form strong interparticle bonds and the need to control dimensions. Although an undesirable practice metallurgically, admixed elemental compositions can be adjusted to control size change through sintering, increased admixed nickel causing increased shrinkage, admixed copper causing growth [15].

2.2.6.3 Infiltration

In this process the pressed part is placed in contact with a low melting point material the volume of which is equivalent to the volume of interconnected porosity in the pressed part. During sintering the low melting point material fills the pores by capillary action. For infiltration to be successful all part porosity must be interconnected. CM may be used to predict the distribution of density within the pressed component to ensure that density levels are statistically unlikely to give rise to closed-off pores (typically below 85% of full theoretical density).

2.3 Requirements for Compaction Modelling

2.3.1 Input-Data Generation

CM requires reliable accurate input data on powder properties, interaction between powder and tooling, press kinematics and green-part properties. Table 2.2 below lists the key data and how generated (see also Table 8.1 and Chapter 14 for discussion of pharmaceuticals).

Powder properties: Fill/Flow: while a die-filling rig such as that described in [16] is relatively inexpensive, for industry purposes it will be sufficient to characterise powders on an experimental press using tooling geometrically similar to that being studied.

Instrumented die: it is seen that much data can be generated using this lower cost method.

Low-pressure compaction and powder transfer: there are currently no simpler alternative methods to the laboratory techniques

Press-frame stiffness or spring constant is measured by pressing solid metal blocks (Section 2.3.4) but results have to be corrected for punch elasticity. This aspect is discussed more fully in Chapter 11.

Table 2.2. Key input data and how generated

NA = not available

		Research	Industry	Key Ref	Chapter
Powder properties	Plastic deformation	Triaxial stress rig	Instrumented die	[7]	6
	Fill/flow	Die-filling rig (critical shoe velocity)	Experimental press with generic tooling	[4], *[5], [6],* [16]	9
	Fill density distribution	Die/shoe-filling rig + X-ray CT	Die/shoe filling rig + metallography	[17], [18], [10], *[16]*	9, 11, 12
	Low-pressure compaction	Low-pressure triaxial stress rig	NA	[7]	6
	Powder transfer	Powder-transfer rig	NA	[19,] [20], [4], [21]	9
Powder/tooling interface	Friction	Shear plate	Shear plate	[22]	8
		Instrumented die	Instrumented die		8
Green-part properties	Poisson's ratio	Axial compression		[23]	5
	Young's modulus	Uniaxial compression or ultrasonics	Uniaxial compression	[23]	5
	Shear failure line	Diametral or axial compression	Uniaxial compression	[24], [13], [21]	7
	Tensile strength	Uniaxial compression	Uniaxial compression	[24], [13], [21]	6
Press operation	Punch and die kinematics	Control signal driving press	Control signal driving press	[25], [26]	11
	Load	Load cell	Hydraulic pressure	[27]	11
	Press deflection		"Spring constant" tests	[25]	11

2.3.2 Modelling and Part Manufacture: Requirements of the Hardmetal Industry ("HM")

What is a successful model from the viewpoint of industry? The answer is productivity. Thus there is a long distance to travel starting from the mathematical formula and arriving at the net-shape or crack-free pressed and eventually sintered part. In this respect some requirements from the hardmetal (HM) industry are put forward below. Although this discussion is intended to be as general as possible, differences exist between companies depending upon the level of internal expertise as a matter of course.

2.3.2.1 Reliability and Robustness

The first of these requirements is of course reliable and robust modelling – by modelling is meant in this case the mathematical model and its implementation in the numerical code. This is not the case for all industries. For HM, dimensional control of the net-shape sintered parts is the main priority and this is currently satisfactorily described and predicted by compaction (and sintering) modelling (CM). However, the tolerances required by the market are very tight and can sometimes be less than 1 % of the actual dimension. This is a difficult challenge for modelling that is used more to give *accurate trends* rather than definitive results. Nevertheless, accurate trends can also be very useful in the optimisation process.

2.3.2.2 Other Requirements

Once the reliability and robustness requirements are fulfilled, some other issues still remain for a real industrial use of CM. The requirements are less rigorous if the use of CM is confined to the company R&D department rather than the design office or the production department. By R&D, design office and production we mean the following typical qualifications:

- *R&D*: People with a degree in science, with basic to very good knowledge of finite element codes, basic or no CAD software knowledge and basic to good knowledge of production.
- *Design*: People with a technical degree, with very good knowledge of CAD software, good knowledge of production conditions and no or basic knowledge of finite element code.
- *Production*: People with no or basic CAD knowledge but with very good knowledge of production.

Whether R&D and design exist as separate departments depends mainly on the size of the company. In HM the majority of manufacturing companies are large enough to have separate R&D and design offices. In the HM industry CM projects with the goal of optimising productivity are run by the R&D department in direct cooperation with production, the design office being partly involved. This may not be the case in other industry sectors where the design office often replaces R&D.

The following summarises the HM industry requirements for implementation:

- user friendliness
- computing power
- interface with CAD
- interface with press software
- selection of finite elements (codes)
- importing input data
- optimisation tools.

User friendliness enables CM to perform complex tasks more rapidly, with less manual work and possibly with less expertise than initially required. The degree of user friendliness may have to be developed differently depending on the current expertise in CM of the R&D and design department. It is also related to the optimisation tools since user friendliness eases the use of such tools. Regarding production, the whole process should be a "ready to use black box" for the optimisation of pressing schedules.

Computing power is currently sufficient to carry out the calculation of a complex 3D model in a few hours to a few days. This is fast enough for development projects in R&D and design office but major improvements are needed if it is to be used in production.

CAD is the main working tool of the design office, therefore *Interface with CAD* is a key issue. The main FE codes already allow R&D to import CAD files for numerical simulation. However, few CAD software packages in the design office are provided with FE interfaces with CM package.

Interface with press software should be the final link in the chain of implementation of CM from research to production. Such an interface would allow, within a few minutes, the optimisation of the pressing schedule according to the final geometry, powder type. However, in the HM industry the optimisation of the pressing schedule is not as important as optimisation of the sintering cycle.

Finite-element codes are nowadays mainly used by R&D. One can find even in commercial codes simple CM packages that can be updated. The design office should be able to use, through a suitable CAD interface, a simplified version of FE code committed to the prediction of powder pressing.

Input Data for CM are well defined for R&D purpose with standard tests. Improved user friendliness could be, in this field, an advantage for implementation in design office.

Optimisation tools combined with existing FE code should help the R&D department to provide fast and reliable solutions to design office and production problems. These could include integration possibilities (of different modules, *e.g.* pressing + sintering for HM), automation (of numerical prediction assessments, choice of alternative solutions and rerun of simulation) and user-friendly interfaces.

These requirements are summarised in the following table with the legend:

"Is currently sufficient": ☺ (fairly) to ☺☺☺ (completely)
"Must be improved": X[1,2…] (slightly) to XXX[1,2…] (drastically) and depends on requirements No. 1,2…
In **Bold**: Main requirements to be developed
Underlined: Main CM tool for the department (current or to-be)
Superscripts denote requirement numbers (*e.g.* ☺☺X[5] - refers to: finite elements (codes)

Table 2.3. Requirements for the use of CM in HM industry

No.	Requirement	R&D	Design	Production
1	user friendliness	☺☺X[5] to **XXX**[5]	☺**XX**[5] **to** **XXX**[5]	**XXX**
2	computing power	☺XX	☺XX	**XXX**
3	interface with CAD	☺☺X[5]	**XXX**[1,5]	☺**XX**
4	interface with press software	-	-	**XXX**[1,2,3,5,7]
5	finite-element codes	☺☺X	XXX[1,3,7]	**XXX**
6	importing input data	☺☺X[1]	☺XX[1]	-
7	optimisation tools	**XXX**[1,5]	**XXX**[1]	**XXX**

2.3.2.3 Discussion of Requirements

In the table above the number of main requirements, **X**, can be totalled arithmetically as follows: R&D 3 to 6, design office 8 to 9, production 17. If we convert each mark by its equivalent in time and money, the first step of the implementation should be the R&D department.

The main requirement is then the optimisation tools. Assuming that a FE code with CM and sintering package and CAD interface is available, numerical simulation of compaction and sintering of complex 3D geometries can be performed. The expertise required depends upon the level of user friendliness available. This is currently the most advanced status of CM in the HM industry. Manual optimisation tasks are then performed using parametric studies. Optimisation tools would decrease drastically development times and enable some difficult projects to be solved.

Implementing CM directly in a design office requires additional improvements mostly in terms of user friendliness, interface with CAD software and optimisation tools. Since design engineers are not necessarily CM specialists, the principle of the black box must be more generalised in terms of model generation, importing input data, interface to FE code and optimisation.

Direct use of CM in production in HM industry is not conceivable for the moment, not least because the cost outweighs the benefits. Besides, onsite experience and improved press designs compete with CM implementation in optimising pressing schedules

2.3.2.4 Conclusion

Once CM achieves a satisfactory level of reliability and robustness – which is not the case for all the PM sectors – additional requirements must also be fullfilled.

CM could be successfully implemented as a first step in R&D with some improvements described above. It is after all one of the functions of the R&D department to introduce into the company innovative solutions coming from research.

Implementation of CM in the design office could be of interest to SMEs but requires up to three times greater investments than for R&D.

Production cannot currently use CM directly, as high productivity conditions require ready-to-use solutions that are not the case for CM at this level.

Training should also be mentioned. CM training courses – at best directly in the company – could help to reduce the level of the requirements in R&D and furthermore in the design office for the implementation of CM in their working tool environment.

2.3.3 Modelling and Parts Manufacture: Requirements of Ferrous Structural (FS) Parts Industry

As computer simulation techniques continue to improve, the question is repeatedly asked whether the time has come to implement these industrially. In the production of ferrous structural powder metal components, powder compaction is one of the core steps in the process. For modelling to be implemented requires that specific production problems can be solved efficiently.

Along with sintering, axial die compaction is a major production step in ferrous-part production. Components are pressed near net shape to increasingly more complex geometries. Associated with this, press and press-tool design become more sophisticated. Controlling the pressing kinematics of a multilevel part using tooling incorporating several upper and lower punches and core rods needs skilled operators. Increasingly these are assisted by software tools. Small deviations from ideal pressing kinematics can easily cause defects in the pressed component. Determining the cause of such defects can be very difficult.

Typical defects include:

- inhomogeneous density distribution
- shear cracks resulting from unfavourable transfers of powder in the die cavity
- brittle cracks resulting from unloading and springback of the pressing tool
- failure of the press tool itself owing to overloading.

For the above reasons simulation software needs to predict both density distribution and crack formation. In ferrous-part production, size changes in sintering are relatively small and therefore part distortion through sintering is not important.

2.3.3.1 The Process Chain

The process chain from part design to compaction usually starts with a 3D design model of the component. This is then used to design the compaction tooling. In turn this is then used to generate the press kinematics. Tool deflections can be predicted using loading data generated from compaction experiments. As far as possible proportional compaction is used in processing the powder from fill to final pressed density. The press setter approaches the final press kinematics carefully from the safe side, taking into account press-frame elasticity and filling effects.

2.3.3.2 Time Considerations

Experience from structural mechanical FE analysis shows that it is not always possible to carry out a fully detailed 3D simulation in an acceptable time, even using powerful PCs. Small geometrical variations can increase the size of the FE model quickly up to one million degrees of freedom. For computing purposes, therefore, it is often necessary to simplify part geometry and to take out non-essential details. Considerable simplifications can be achieved by considering tooling to be stiff, and taking advantage of part symmetries. It may, for example, be sufficient to solve a smaller segment of part volume or even reduce the part from 3D to 2D especially in the case of axi symmetric parts. Such assumptions and simplifications can be successful but require good knowledge of FE, CAD and the interface between simulation and CAD software. For these reasons the wider application of simulation software is hindered by the shortage of FEM-experienced staff. Such skilled operators do not need well-developed user interfaces, a stable operating material routine implemented in a commercial FE code is sufficient. In contrast, the use of simulation as a "black box" by a typical designer or even on the shop floor would have to process nonsimplified FE models requiring comprehensive material database, robust computing and especially powerful computers.

Preparing a detailed CAD model and carrying out the simulation can easily take one or two weeks. This is much too long a response time for solving typical production problems, which can be solved much faster by an experienced operator using trial and error methods. However, some problems are more difficult, and need to be solved without risking costly tool-design changes. In these cases simulation can be advantageous, providing the effective punch movements are known. The best numerically controlled presses provide accurate data on punch movements. In contrast, the wider use of simulation on older presses will be limited. Compaction simulation is also useful for basic feasibility studies and for the development of new tool-design concepts.

2.3.3.3 Cost Considerations
The introduction of compaction simulation into a company can finally only be justified by a positive cost:benefit ratio. This includes the *costs* of hardware and software, operator training and modifications to presses to improve data logging. The *benefits* of using simulation are more difficult to quantify, since these only result from practical experience in solving some tough problems.

2.3.3.4 Conclusions
It can be concluded that the first requirement for implementation of simulation is to satisfy the needs to predict density distribution, crack formation and tool loading. It is not currently clear whether the prediction of cracking using material models should best be carried out using continuum mechanics or using particle methods. On materials involving significant shrinkage and distortion through sintering the simulation of density distribution is an obvious advantage. In ferrous Powder Metall this is not so important. Simulation packages require good interfaces to CAD and press-control systems. The user interface is not very important currently, since uses of modelling are limited to FEM-experienced staff. The steady and fast development of both simulation techniques and computing power could ultimately lead to powder presses being controlled like modern CAM machining centres: after import of CAD data and powder information the pressing kinematics would be generated automatically. Until then considerable advances can be achieved by systematic guidelines and well-educated machine operators.

2.3.4 Validation

Parts makers need to be able to validate CM predictions. Industry views on the validation techniques listed in Table 2.4 are given below (see also further detail on some of these techniques in Chapter 12).

2.3.4.1 Validation of Green-part-density Predictions
Important decisions on part feasibility, tooling design and press settings will be taken in the light of green-part-density predictions. At the design stage the computer predictions will be compared with past experience on similar shapes; at the prototype stage techniques such as those listed in Chapter 12 will be used, with the emphasis on the simpler quicker methods. Where parts are to be sintered to full density evaluation of sintered dimension provides a simple additional check.

2.3.4.2 Validation of Internal-crack Predictions
In the case of ferrous structural parts, internal porosity will be similar in size to the primary powder particles - typically up to 150 μm. For the purposes of defect detection, therefore, it will be necessary only to detect internal defects significantly larger than this figure - *e.g.* 0.3 mm and above.

Where parts are to be sintered to full density, smaller defects may “heal”. However, in general this is not reliable, and similar efforts should be made to produce crack-free green parts as are made on ferrous components.

Techniques for crack detection such as acoustic resonance are well proven for use on sintered parts; however, industry has a continuing high-priority requirement for online techniques for crack detection on green parts.

Table 2.4. Validation: research and industry techniques

	Ref	**Research**	**Industry tests**	
			Nondestructive	**Destructive**
Green-part density	[28, 17, 18]	XRT (see Section 11.5)	surface hardness	slice, weight and measurement
		SEM-EDS (see Section 11.4)	bulk density by measurement and weight	quantitative metallography
				sintered dimension (lps only)
Internal shear cracks	[28]		acoustic resonance tests on sintered parts	microstructural
			X-ray	X-ray (large section thicknesses)
			ultrasound	
Tensile cracks	[28]		visual, magnetic	etch
			punch loads	
			X-ray	
			ultrasound	
			eddy current	

lps = materials subject to liquid phase sintering (*e.g.* Hardmetals)

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