Optimization of the compaction of hard-metal powder for the production of cutting tool inserts

by K. Blaski* and S. Luyckx*†

Synopsis

This paper reports an investigation aimed at optimizing the compaction of granulated hard-metal powder for the production of cutting tool inserts. The optimal compaction is that which yields optimal shrinkage during sintering, i.e. minimum porosity in the sintered part. Extensive compaction tests on 23 different hard-metal powders have been carried out and have shown that the ideal 'green density' of a hard-metal compact, i.e. the density after compaction, increases linearly with the apparent density of the powder. On the basis of this result, an equation has been derived, which allows one to predict the optimal shrinkage that a hard-metal compact undergoes during sintering once the following data are known: the required sintered density, the volatile content of the powder and the apparent density of the powder. Since these data are available to the tooling designer, this equation allows one to design tooling for the compaction of hard-metal, which leads to optimal shrinkage

Introduction

Hard metals are among the most widely used materials in the manufacture of cutting tool inserts. They consist of WC and Co (WC-Co) or WC, 'mixed carbides' and Co (WC-TiC/TaC/NbC-Co).

The production process of hard-metal cutting tool inserts includes the following stages[1]:

- mixing and milling of the WC, other carbides and Co powders
- addition of a lubricant to the powder
- granulation of the powder by spray-drying
- compaction of the granulated powder to the shape and size required
- sintering of the compacted (or 'green') part.

Every stage of the process must be optimized if the quality of the final product is to be within specifications.

This paper reports work done to optimize the compaction of the granulated powder, i.e. stage 4. Cutting tool inserts are typically compacted by uniaxial pressing using WC-Co tooling, i.e. WC-Co dies and pistons. The density of the compacted part ('green density') is critical to achieve a sintered component with optimal density ('sintered density', which is 'optimal' when the porosity in the sintered part is minimal) and correct shape and dimensions, because the green compact shrinks during sintering and the amount of shrinkage is the larger the lower the green density[2]. A manufacturer must be able to predict the shrinkage in order to design dies of the correct dimensions and to produce green compacts of optimal and consistent density. This is a general problem of the powder metallurgy industry, but it is particularly important for hard metal because the shrinkage of this material occurring during sintering is large (typically above 20%), and the presence of even minor porosity in the final product seriously compromises the product's performance, on account of the brittleness of the material.

Method

The investigation consisted of determining experimentally the optimal compaction conditions for batches of 23 different hard-metal powder grades and of deriving a relationship between individual powder properties and compaction conditions that would lead to optimal shrinkage, i.e. the shrinkage that would yield an optimal sintered product or a product with minimal porosity.

Table I lists the powders used for the investigation and their characteristics, i.e. the mean size of the WC grains, the cobalt content and whether they contain 'mixed carbides'. As mentioned above, all the powders in Table I had been granulated by spray-drying. For each

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* *School of Chemical and Metallurgical Engineering, University of the Witwatersrand.*

† *DST/NRF Center of Excellence in Strong Materials, Johannesburg, South Africa.*

SA ISSN 0038–223X/3.00 + 0.00. Paper received Apr. 2007; revised paper received Sep. 2007.

Table I

List of the powders used in this investigation, with their ideal sintered density (SG, which, in the present case stands for 'density' and not 'specific gravity'), their Co content (wt%) and the average size of the WC grains. The fifth column indicates if the powders contain mixed carbides (TiC/TaC/NbC) or not: Y stands for Yes and N for Not

Powder grade name	Average S.G. (g/cm^3)	Co (%)	Average grain size (μm)	Mixed crystals
230	14.55	9.7	2–6	N
AP20	14.40	10.5	2–3	N
CN10	14.35	6.7	<1	Y
CR10	14.30	9.5	<1	N
H1P	12.93	6.0	1	Y
H6	14.95	5.7	1–1.5	Y-very little
K15M	12.75	7.3	1–2	Y
MT16	13.90	16.0	2–3	N
MZ15	14.00	15.2	2–4	N
N6/194	14.90	6.0	1–3	N
P25M	12.55	9.5	1–2	Y
P30M	12.40	10.0	2–3	Y
P40M	13.20	10.0	2–3	Y
P511	14.40	11.7	3–6	Y
P7	14.80	7.5	3–4	N
PBF	14.95	5.9	2–3	N
PBT	14.93	6.0	2–4	N
PC-20	14.60	6.0	1–3	Y
PI-15	14.08	6.0	2–3	Y
PI-25	14.08	6.6	2–3	Y
PI-40	13.80	8.5	2–4	Y
Q3	13.25	23.0	3–6	N
S9	12.30	10.0	2–3	Y

powder 'historical' properties, such as the apparent density and the mean size and distribution of the granules, were available from the producer; however, the properties were re-measured for each batch

After measuring the apparent density and the granules' size distribution, each powder was compacted under conditions that would lead to a range of at least 8 different green densities. The equipment used for the measurements and the compaction was the following:

- the apparent density was measured using a Hall flow meter
- the granules' mean size and size distribution was measured by means of standard stackable sieves of 300, 212, 125, 90 and 63 μm aperture size
- the compaction was carried out in a fully programmable CNC hydraulic Dorst press model TPAI5HS. The compact height accuracy was to within ± 2 μm and the weight within ± 0.01 g.

The different green densities were achieved as follows:

- a range of green densities was selected for each powder (above and below the expected acceptable green densities)
- the mass of powder was varied within a range that would correspond to the selected range of green densities at a selected constant volume
- the constant volume was obtained by using the same die for all compactions and all powders, and programming the height of the piston to be constant (so that the pressure varied when varying the mass).

The shape and size of the cutting tool inserts produced during the investigation is shown in Figure 1. Inserts of other sizes and shapes were produced at the end of the investigation to validate the results obtained.

The green compacts produced were examined under a stereomicroscope to select those that appeared to have the best green density. The 'best green density' (i.e. the green density obtained at the most correct pressure) was identified

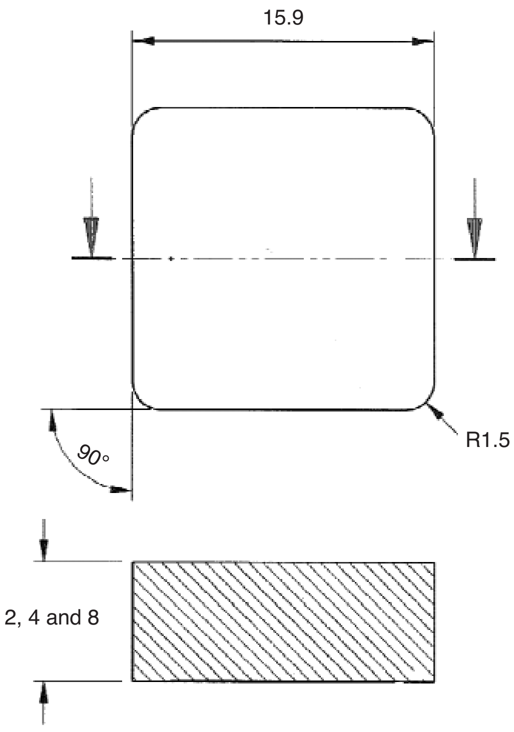

Figure 1—Shape and dimensions (in cm) of the hard-metal cutting tools inserts compacted and sintered during this investigation. The thickness of the inserts was either 2 or 4 or 8 cm, as indicated in the text

on the following basis: in the parts that were underpressed the compressed powder granules were still partly distinguishable from each other, while in the parts that were overpressed fine cracks and/or delaminations were visible. The selection of the 'best green density' involved the assistance of a member of the sponsors' (Powder Industries (Pty) Ltd) technical staff who had vast experience in assessing the quality of compacted parts by this method. Within the range of compacts produced, two or three compacts usually appeared to show 'good' compaction. The green density of all the parts was determined by dividing the known mass by the constant green volume, which was remeasured by means of a Mitutoyo digital vernier with 0.01 resolution.

The relationship between optimal shrinkage and powder properties that was obtained was validated by sintering the green compacts and verifying that those whose green density satisfied the derived relationship exhibited least porosity.

Results and discussion

Results of the experiments

Figure 2 shows that the green density of the compacts, which had been judged to have undergone the best compaction (the 'best' or 'ideal' green density) tends to increase with increasing the apparent density of the powder, as could be expected.

The increase, however, is not monotonic and the three following hypotheses were put forward to explain the non-monotonic increase (the third hypothesis proved to be correct):

- The 'best' compaction conditions may not have been identified correctly, since in some cases it was difficult to decide which out of two or three compacts was the 'best'. However, the difference in green density among the two or three compacts was generally only of the order of 1% so it would not affect significantly the graph in Figure 2
- The data from powders that contained other carbides (TiC, TaC, NbC) may not lie on the same line as the data from pure WC-Co powders. However, a simple check revealed that some of the data deviating substantially from the generally increasing trend in Figure 2 belonged to WC-Co powders and some to powders with mixed carbides, and so the composition of the powders was not the reason for the non-monotonic increase
- The granules' mean size and size distribution (which strongly affects the apparent density[2]) may not have been the same for all powders. This, in fact, was found to be the case and to be the main cause of deviations from the generally increasing trend.

Once the main cause from deviations from a monotonic increase was discovered, the granules' size and size distribution obtained for each batch of powder was compared to the historical size and size distribution of the same powder, i.e. the size and size distribution that had been obtained in the past, according to the producer's records. In most cases it was found that the size and size distribution of the granules in the batches used for the present experiments were the same as the historical ones (which were similar to the distribution in Figure 3 for all powders tested), but in some cases they were substantially different. The latter cases were most of the cases deviating from the generally increasing trend. The data from these cases were removed from the graph in Figure 2 because they were considered not representative of the corresponding powders, and a new graph was obtained (Figure 4) which, by regression analysis, was found to approximate a straight line (regression coefficient $R^2 = 0.965$).

The equation of the straight line in Figure 4 is

$$Dg = 1.6\,Da + 2.51 \qquad [1]$$

where Dg = green density in g/cm^3
Da = apparent density in g/cm^3.

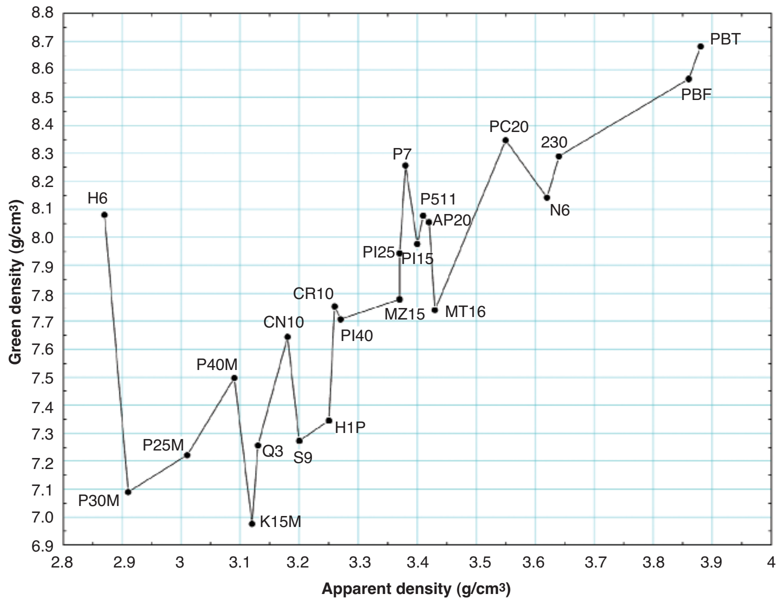

Figure 2—Plot of the ideal green density of the compacts produced versus the apparent density of the corresponding powders. It shows a general increase of the green density with increasing apparent density, but the increase is not monotonic

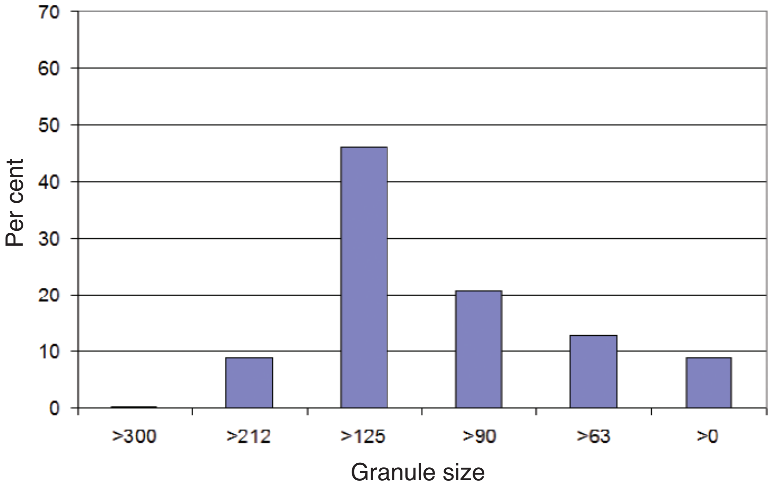

Figure 3—Historical granules' size and size distribution of the powders used in this investigation

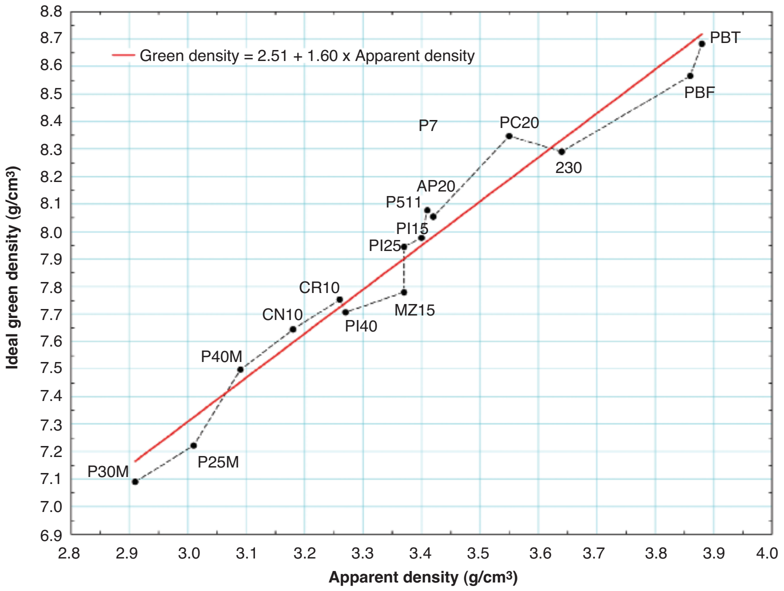

Figure 4—Plot of the ideal green density of the compacts produced from the powders having the same granules' size distribution as in Figure 3, versus the apparent density of the powders

where the unit of density used in this work (g/cm^3) is the unit used internationally in the cemented carbide industry.

Derivation of the optimum shrinkage equation

From the definition of linear shrinkage[2]:

$$LS\% = \left[\left(Vg/Vs\right)^{1/3} - 1\right] \times 100 \qquad [2]$$

where:

LS = linear shrinkage
Vg = volume of green compact
Vs = volume of sintered part.

Since

$$Vg = \frac{Mg}{Dg} \text{ and } Vs = \frac{Ms}{Ds} \qquad [3]$$

with Mg = mass of green compact
Ms = mass of sintered component
Ds = sintered density

then:

$$LS\% = \left[\left(\frac{Mg \times Ds}{Dg \times Ms}\right)^{1/3} - 1\right] \times 100 \qquad [4]$$

But:

$$Mg = Ms \times \left(1 + \text{volatile wt\%}/100\right) \qquad [5]$$

because of the lubricant added to the powder before granulation, which is volatile and is lost during sintering. It was found from the producer's records that the volatile content of the powders used in the investigation was always close to 2.4 wt%.

Then, substituting in [4] Equations [5] and [1], one obtains:

$$LS\% = \left[\left(\frac{1.024Ds}{1.6Da + 2.51}\right)^{1/3} - 1\right] \times 100 \qquad [6]$$

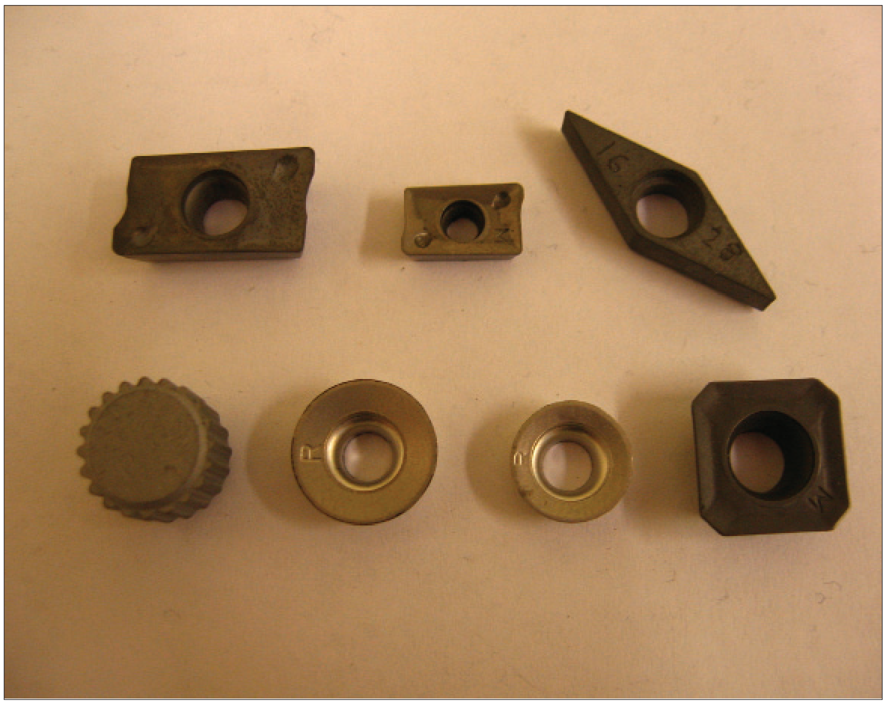

Figure 5—Examples of hard-metal components of various shape and size, which were produced successfully by applying Equations [1] and [6]

which allows one to predict the shrinkage of a green component once the apparent density of the granulated powder and the required sintered density (both in g/cm3) are known, as long as the granules' mean size and size distribution of the powder is similar to that of the powders used in this investigation. If the volatile content of the powder is higher or lower than 2.4%, the coefficient of *Ds* can be modified.

Validation of the results

The results reported above were validated by two means:

- The green compacts were sintered and it was found that the sintered parts corresponding to the green densities that satisfied Equation [1] were the most pore free[3], which indicates that the shrinkage had been optimal;
- Equations [1] and [6] were applied to the compaction of inserts different in shape and size from those in Figure 1: the optimal shrinkage was predicted from Equation [6] and the green density required to achieve that shrinkage was calculated from Equation [1]. The components (examples are given in Figure 5) were sintered successfully, i.e. they were pore free, although in the past some had been found difficult to compact.

Conclusions

This investigation has produced two important relationships: (i) a linear relationship between the apparent density of a powder and the green density of compacts produced from that powder that would yield optimal shrinkage during sintering (Equation [1]); and (ii) an equation that allows one to predict the shrinkage of a component once the apparent density of the powder, the required sintered density and the volatile content of the powder are known (Equation [6]). Since these data are available to the tool designer, Equation [6] allows the designer to calculate the dimensions of the tooling required to produce sintered components with specified dimensions.

Equations [1] and [6], however, are valid only for granulated powders of granule's mean size and size distribution similar to those in Figure 3. Substantial deviations from granule size or size distribution would lead to substantial differences in apparent density[2] and would invalidate Equation [1]. However, it must be noted that, within one company, granulated powders produced under the same spray-drying conditions are usually of consistent size and size distribution, which would make it possible to derive an expression of the type of Equation [1] valid within that specific company.

Acknowledgements

The authors wish to acknowledge the sponsorship of Powder Industries (Pty) Ltd, Denver, South Africa, and the invaluable assistance of Mr S. Volschenk, a member of Powder Industries' technical staff.

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