An Improved Design Method for Net-shape Manufacturing in Powder Metallurgy

Abstract. The effectiveness of powder metallurgy as net-shape/near net-shape manufacturing technology is determined by the possibility of obtaining complex parts matching the required narrow tolerances. Sintering process determines change in volume of the green, and the related dimensional changes are significantly anisotropic. Anisotropy is affected by several variables, such as material, compaction and sintering parameters, geometry, whose influence is difficult to be distinguished and determined. Anisotropic dimensional change on sintering has been investigated in depth using an experimental approach, relating measurements results to the mechanisms responsible for the phenomenon. Main results concerning the influence of different variables are briefly presented in this work. Such results served as the basis for the development and further improvement of a design method, aimed at predicting anisotropic dimensional change. Main steps of the design method are presented and an example of application to a real part is described. Strong agreement between predicted and real dimensional changes has been observed, and compared to the attainable dimensional tolerances.

Keywords: design for powder metallurgy, precision engineering, product development, dimensional tolerances.

1 Introduction

Net-shape technologies are significantly growing in importance as "green technologies", thanks to the possibility of avoiding (or strongly limiting) machining operations, which determine large amount of scrap, increased energy consumption and consequently higher cost of components [1]. Powder metallurgy (PM) is the most widespread net-shape/near net-shape technology, finding application in many different sectors, such as automotive, medical, consumer goods, construction etc.
Figure 1 compares powder metallurgy to traditional technologies, in terms of raw material utilization and energy consumption [2].

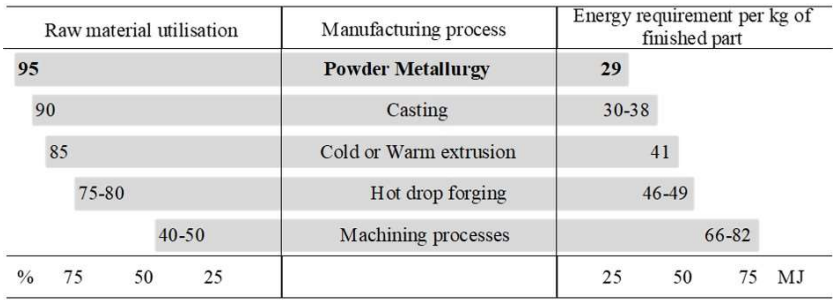

Fig. 1. Raw material utilization and energy consumption for different manufacturing processes.

Depending on batch size, geometrical complexity, mechanical properties, dimensional and geometrical precision, and cost limitations, different alternatives can be considered, from press and sinter to metal injection molding to additive manufacturing. Among them, when large batches are needed, press and sinter is almost the unreplaceable technology. In the standard process, metal powders, added with a small amount of lubricant, are compacted in a die producing the so called "green part", having sufficient cohesion to be handled safely. Uniaxial cold compaction is commonly used. The green part is then heat treated in a protective atmosphere (sintering), so that particles weld together and confer sufficient strength to the material for the intended use [3].

Aiming at avoiding secondary operations, dimensional and geometrical precision is a crucial issue, which is strongly related to the change in volume (shrinkage or swelling) occurring on sintering [4].

In the design of PM parts, the change in volume has to be carefully considered, mostly in terms of linear dimensional changes. In fact, dimensional changes are the starting point of a design method aimed at obtaining net-shape/near net-shape parts, which only can be obtained from properly dimensioned green parts. Unfortunately, dimensional change on sintering is anisotropic, and it is differently affected by a large number of variables, related to the material, the process, and the geometry, whose influence is difficult to predict [5]. As a consequence, modeling is rarely used, mainly due to the large influence of geometry and to the lack of constitutive models for powder mixes. In most of the cases dimensional changes are quite small, but the required tolerances are very narrow, what is also limiting the reliability of modeling response, so that in the companies the approach is often "trial and error", until the required characteristics are obtained.

The anisotropy of dimensional change on sintering has been extensively studied by the authors, aiming at defining a design method to predict anisotropic dimensional change on sintering. The relationships used in the method are defined on the basis of a deep investigation of the mechanisms involved, starting from experimental data. Dimensions have been measured in the green and sintered state and dimensional changes have been derived for different parts, analyzing the influence of geometry, material, process parameters (such as compaction strategy, and sintering temperature and atmosphere). Main results are briefly recalled in the following paragraphs. An anisotropy parameter, aimed at quantifying the anisotropy extent, has been defined and used to develop the design method, which is described in the following and validated on a real part.

2 Dimensional change on sintering

Dimensional change has been derived measuring the same parts in the green and sintered state by a CMM machine. The parts were measured by scanning mode and the data were processed by Matlab to calculate the features, from which dimensions were derived (diameters from cylindrical surfaces, distances from couples of parallel planes etc. The procedure for data processing is explained in depth in [6]. In the last years, the attention was mainly focused on axi-symmetric, ring-shaped parts, which represent the

most largely implemented geometry in press and sinter. Consequently, dimensional changes refer to entities, which can always be considered as external diameters (D_{ext}), internal diameters (D_{int}), and heights (h), as defined by equations (1) to (3), where subscript g and subscript s refer to green and sintered state, respectively.

$$\varepsilon_{D_{ext}} = \frac{D_{ext_s} - D_{ext_g}}{D_{ext_g}} \tag{1}$$

$$\varepsilon_{D_{int}} = \frac{D_{int_s} - D_{int_g}}{D_{int_g}} \tag{2}$$

$$\varepsilon_{h} = \frac{h_s - h_g}{h_g} \tag{3}$$

Anisotropy is mainly related to the different dimensional change along the axis (ε_h) and in the plane orthogonal to the axis ($\varepsilon_{D\ ext}$, $\varepsilon_{D\ int}$), however dimensional change of external diameter may differ from dimensional change of the internal diameter too, as demonstrated in [7]. Dimensional changes and their anisotropy are strongly, and sometimes unexpectedly, affected by many different variables, whose influence has been investigated in depth in previous work. Main results are following briefly summarized. The aim is here highlighting the variety and complexity of variables involved, referring to the specific papers for explanation in depth.

2.1 Influence of material

Metal powders used in press and sinter may differ for chemical composition, particle size and particle size distribution, and powder mix can be obtained by pre-alloyed or diffusion bonded powders. All of these parameters have a strong influence on dimensional change, starting from change in volume. Either swelling (increase in volume after sintering) or shrinking (decrease in volume after sintering) may occur, mainly depending on the chemical composition, as shown in figure 2. The considered materials are used for about 75% of press and sinter production.

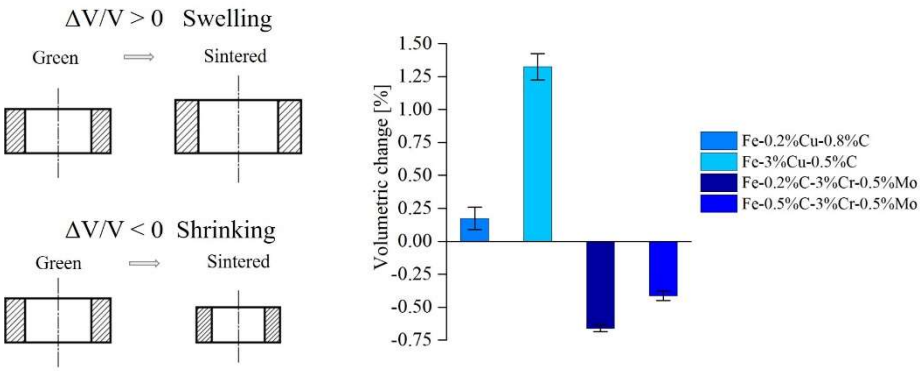

Fig. 2. Influence of chemical composition on the change in volume.

Swelling is mainly related to the presence of copper, which determines liquid phase sintering due to its melting temperature, lower than sintering temperature. The larger the copper content, the higher the swelling amount [8]. In the shrinking powder mix, the increase in carbon content determines a lower shrinkage [9].

Figure 3 shows the influence of the type of powder mix and the particle size on the anisotropy of dimensional changes, left and right respectively.

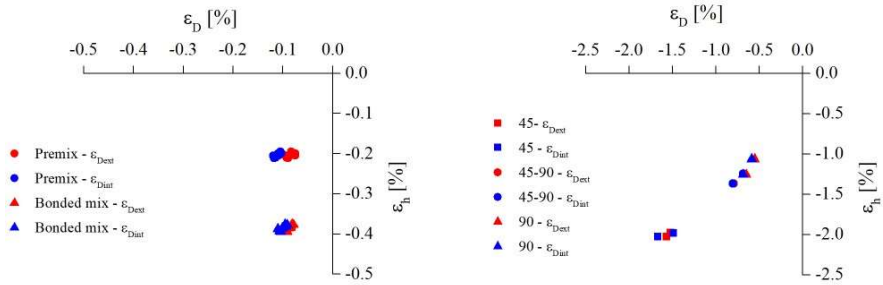

Fig. 3. Influence of alloying system (left) and particle size (right) on dimensional changes of height and diameters.

Anisotropy of dimensional changes is larger in bonded mix, dimensional change in height is about four time the dimensional change of diameters, while in premix it is about twice. However, a larger difference in the dimensional changes of external and internal diameters is shown in premix [9]. About the influence of particle size, a significant anisotropy is observed for finer particle size (45, meaning lower than 45 μm), while the coarser ones (90, meaning larger than 90 μm) show a tendency to a less anisotropic dimensional change [10].

2.2 Influence of process parameters

Uniaxial cold compaction determines green density and green density distribution, which in turn affect the density and density distribution of final part after sintering. Figure 4 shows the influence of green density and sintering temperature on dimensional changes.

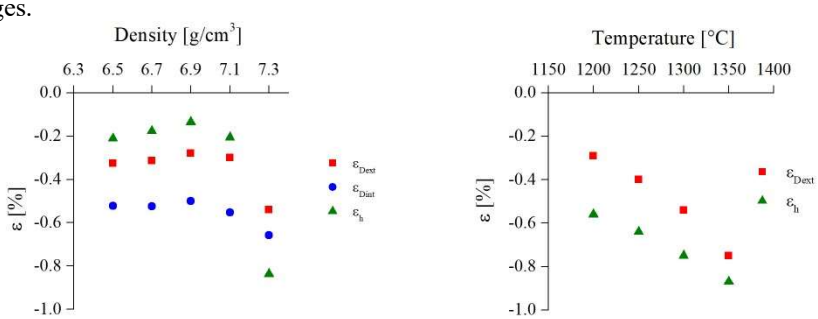

Fig. 4. Influence of green density (left) and sintering temperature (right) on dimensional changes of height and diameters.

Figure 4 shows that dimensional changes are significantly anisotropic for any green density, but for green density up to 7.1 g/cm^3 dimensional changes of diameters are larger than dimensional change of height, while the opposite is observed for the highest green density. In all the cases a noticeable difference is also observed between dimensional change of internal and external diameters [11]. Concerning the influence of sintering temperature, it has to be pointed out that sintering at very high temperature determines an increase of dimensional changes, as expectable, but a tendency versus a less anisotropic behaviour, what might help the designers [12]. Work is in progress to highlight the influence of high sintering temperature on the stability of geometrical characteristics.

2.3 Influence of geometry

Designing anisotropic dimensional change of PM parts is further complicated by the influence of geometry [13-14]. In fact, the influence of materials and process parameters above briefly described, also depends on geometry. Figure 5 shows the dimensional change of internal and external diameters along the axis, and the dimensional change of the height along the diameter.

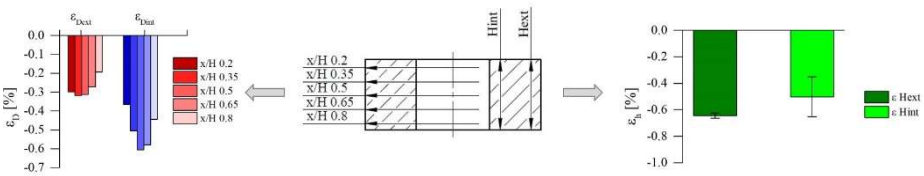

Fig. 5. Dimensional changes of diameters along the axis (left) and dimensional change of height in different positions (right).

Figure 5 highlights that dimensional change of internal and external diameters not only differ as mean values, but also as their trend along the axis. Moreover, dimensional change of the height may also differ, when measured in different positions along the diameter. This is mainly due to the density distribution and to the influence of compaction strategy [15].

3 Design method to predict anisotropic dimensional changes

As briefly highlighted above, a wide experimental knowledge base is needed to improve the reliability of a model describing dimensional change on sintering. Starting from the main effect, dimensional changes can be related to the change in volume V, and under the hypothesis of isotropic dimensional change ε_{iso} the relationship is given by eq. 4

$$1 + \frac{V_s - V_g}{V_g} = (1 + \varepsilon_{iso})^3 \quad (4)$$

As underlined above, dimensional change is actually anisotropic, so that the relationship between change in volume and dimensional changes turns from equation (4) to equation (5)

$$1 + \frac{V_s - V_g}{V_g} = (1 + \varepsilon_h) \cdot \frac{\left(1 + \varepsilon_{D_{ext}}\right)^2 - R^2\left(1 + \varepsilon_{D_{int}}\right)^2}{1 - R^2} \quad (5)$$

Where $R = \frac{D_{int_g}}{D_{ext_g}}$. The relationship between isotropic and anisotropic dimensional changes has been defined through the change in volume, combining equation (4) and equation (5), obtaining equation (6)

$$(1 + \varepsilon_{iso})^3 = (1 + \varepsilon_h) \cdot \frac{\left(1 + \varepsilon_{D_{ext}}\right)^2 - R^2\left(1 + \varepsilon_{D_{int}}\right)^2}{1 - R^2} \quad (6)$$

A relationship between dimensional change of external and internal diameter, expressed by equation (7), has been experimentally derived, considering a huge sampling differing for dimensions, materials and sintering conditions, which determine parameter α [9]

$$\frac{1 + \varepsilon_{D_{int}}}{1 + \varepsilon_{D_{ext}}} = \alpha = f(\varepsilon_{is}\ , geometry) \quad (7)$$

Exploiting the equations above, anisotropic and isotropic dimensional changes have been represented as points on a graph, and an anisotropy parameter K has been defined as the distance between such points, according to equation (8), where γ is a geometrical parameter incorporating α [14].

$$K = \frac{\left(1 + \varepsilon_{D_{ext}}\right)\gamma - (1 + \varepsilon_{iso})}{\varepsilon_{iso}} \quad (8)$$

A large experimental investigation allowed determining a database to be used in the design method, collecting the geometrical parameter γ, and the anisotropy parameter K, both of them defined as function of geometry and ε_{iso} [16]. The isotropic dimensional change ε_{iso}, in turn, depends on materials and process parameters. Work is in progress to enlarge and strengthen the existing database, in cooperation with the major European PM parts producers.

Using the above parameters and relationships, a design method aimed at predicting the anisotropic dimensional change on sintering has been developed, whose main steps are summarized in figure 6.

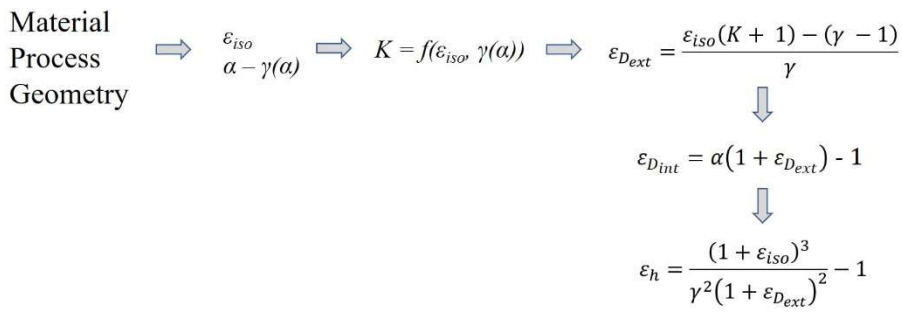

Fig. 6. Schematic representation of the design method predicting anisotropic dimensional change on sintering.

Starting point is given by the isotropic dimensional change ε_{iso}, and the geometrical parameters α, γ(α), which allows determining the anisotropy parameter *K*. Consequently, dimensional changes of external diameter (equation 8), internal diameter (equation 7), and height (equation 6) can be predicted.

4 Design method applied to a real part

The design method above refers to a ring-shaped part, consequently it can be applied to real axi-symmetric parts, providing that coaxial rings can be identified. Coaxial rings can be identified as by two different approaches: "column-based approach" (the powder columns, which can be identified during uniaxial compaction) or "maximum-section based approach" (the maximum amount of shrinking/swelling material, dragging after the other rings). The dimensional changes of diameters common to different rings are set congruent [17].

The design method has been applied to the gear shown in figure 7, split according to the two approaches above. As a first approximation, the teeth profile has been neglected. According to author's experience, being the external diameter defining the envelope of the top of the teeth correctly predicted, the teeth profile and the diameter at the basis of the teeth derive accordingly.

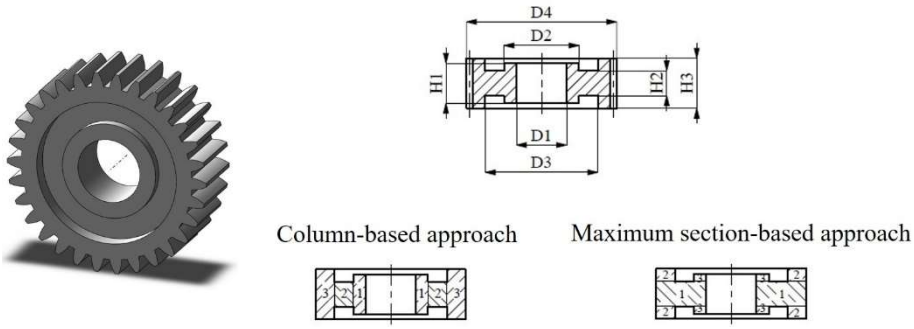

Fig. 7. Coaxial rings identified in a gear by "column-based approach" and by "maximum- section based approach".

Diameters and heights shown in figure 7 have been measured in the green and sintered parts by CMM, deriving the real dimensional changes. The design method summarized in figure 6 has been applied to the coaxial rings identified in figure 6 and predicted dimensional changes have been calculated. Predicted dimensional changes are compared to the real ones in figure 8.

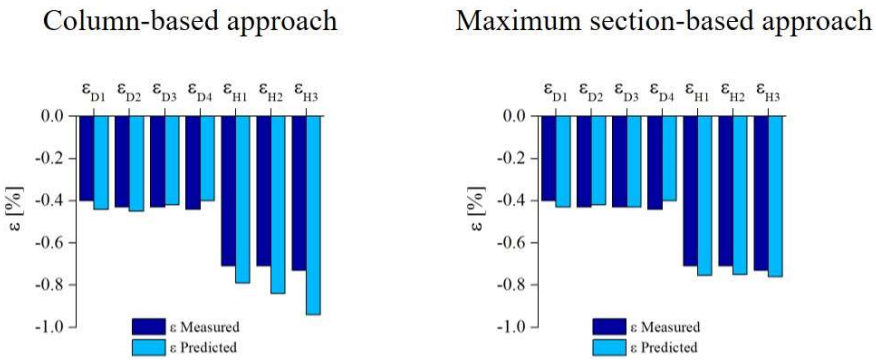

Fig. 8. Comparison between predicted and measured dimensional changes, over measured, by "column-based approach" and by "maximum section-based approach".

Figure 8 shows that diameters are accurately predicted by both column-based and maximum section-based approaches, while the latter is more accurate in predicting heights. From the designer point of view, the significance of the result is further highlighted considering the IT tolerance classes related to the difference between predicted and measured dimensional changes.

4.1 Tolerance classes

Figure 9 shows the ISO IT classes derived comparing the measured dimensions of the real part with the predicted ones, as derived by the two different approaches.

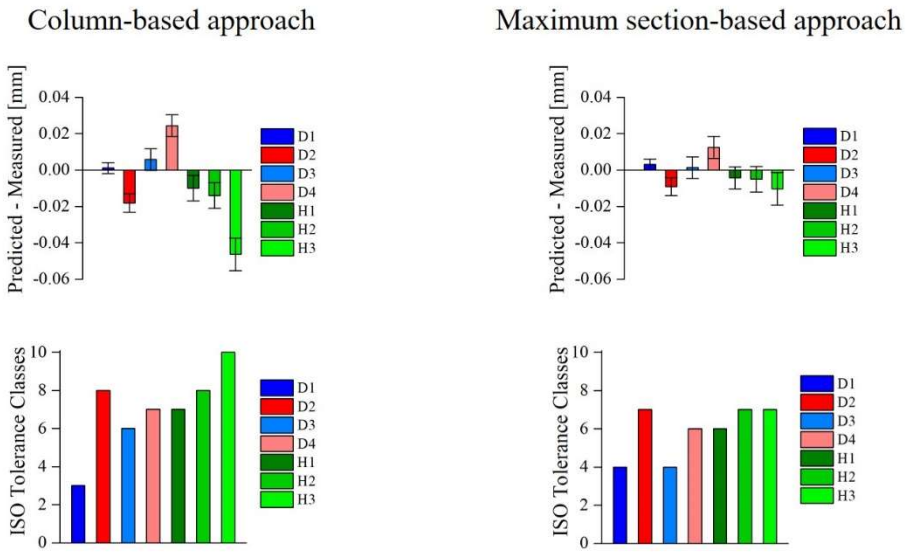

Fig. 9. ISO IT Tolerance classes derived form the difference between predicted and measured dimensions by "column-based approach" and by "maximum section-based approach".

In the standard process, dimensional tolerances attainable in the compaction plane (diameters) are generally IT8-IT9, while in the axial direction (heights) are IT9-IT11. As by figure 9, the dimensional tolerances derived from the difference between real and predicted dimensions are lower than the standard ones for both column-based and maximum section-based approaches, being exceptionally good in the latter case (never exceeding IT7).

All the dimensions predicted through the design method / maximum section-based approach are very accurate, so that the method's effectiveness is validated.

5 Conclusions

A design method aimed at improving powder metallurgy as a net-shape/near net-shape technology is presented in this work. The method is based on the possibility of accurately predicting anisotropic dimensional changes on sintering.

A large number of variables affect the anisotropy of dimensional changes, such as material (chemical composition determines either swelling or shrinking on sintering, anisotropy of dimensional changes is larger in diffusion bonded powder mix than in premix, and also in fine particle with respect to coarse particle size), process parameters (dimensional change is larger for height than for diameters for high green density; on increasing sintering temperature, dimensional changes tend to be less anisotropic), and geometry (dimensional change also depends on the position where features are measured).

Focusing on ring-shaped parts, an anisotropy parameter K and geometrical parameters α and γ have been defined on the basis of a large experimental campaign, as by the influence of the parameters above. Using K, α, and γ, a design method to predict anisotropic dimensional changes has been proposed.

The method has been applied to predict dimensional changes on a real part, using different approaches to split the part in order to apply the design method to coaxial rings. Through the approach called "maximum section-based" dimensional changes were predicted with very good accuracy. The dimensional tolerances derived from the difference between real and predicted dimensions were exceptionally good (never exceeding IT7) with respect to the standard dimensional tolerances in press and sinter (IT9-IT11).

The effectiveness of the design method has been demonstrated. Work is in progress aiming at increasing the database to be used for reference, to further enlarge the field of application.

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