Functionalisation of PM Components by Integration of Inherent Data Carriers and Sensory Elements

B.-A. Behrens, N. Vahed[1]* and M. Kammler[2]*

Institute of Forming Technology and Machines (IFUM), Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany
*E-Mail: vahed@ifum.uni-hannover.de[1], kammler@ifum.uni-hannover.de[2]

Summary: Apart from a great variety of shaping possibilities powder metallurgical techniques offer the integration of foreign elements for static and variable data storage or to embed elements with sensory features in structural parts. The integration of foreign elements as single parts arranged in matrices or traces of foreign powders allows for storing information like brand, serial numbers or other codable data. Integrated sensor elements can be utilised for monitoring loading conditions like strains and stresses or temperatures during the life-cycle of technical parts.

In this work foreign elements were embedded in the powder prior to consolidation. The powder was compacted to a green body and sintered afterwards. During compaction the foreign elements interact with the base material and change their position according to the deformation of the surrounding powder. Finite element analyses were carried out in order to detect a suitable initial arrangement of foreign elements and to ensure their correct position at the end of compaction.

Furthermore, the interface conditions between the base powder and the foreign elements are of interest. Therefore experimental investigations were carried out using magneto elastic sensors consisting of NiFe-layers on different substrates as aluminium, silicium and aluminium oxide with aluminium and steel powder. The bonding quality was analysed by metallographic investigations. By means of X-ray and Computed Tomography (CT) the position of the foreign elements within the parts is controlled, which is of a high importance for a correct determination of loading conditions and to read out stored information.

Keywords: PM Components, Data Storage, Sensor, Finite Element Method (FEM)

1. General

1.1. Powder metallurgy

Powder metallurgy is a process designed to convert powder material into engineering components. It allows the production of parts with predefined shape which are mainly applied without further processing. The initial materials are usually solid metal alloys or ceramics in the form of a mass of dry particles with a maximum average diameter of 150 μm [1]. The main steps in conventional powder metallurgy processes are compaction and sintering. During compaction the bulk powder is transformed into a preform (green compact) which can be handled without disruption. At this stage the powder particles undergo elastic and plastic deformations which flatten the contact between the particles. This increases the frictional forces between the particles and results in material hardening. However, the pores between the particles do not vanish completely. The relative density of the green compact correlates with the applied pressure and is influenced by the particle geometry as well as chemical and physical properties of the powder material [2]. Higher density of the green compact results in higher strength of the part and lower dimensional inaccuracy after the subsequent sintering process.

The powder compaction is subcategorized into cold and warm compaction. It is also distinguished between axial (die) pressing and isostatic pressing. The axial pressing is classified into single-action and double-action pressing. This classification describes whether the bulk powder is compacted by force effect in one direction or by two bilateral forces. Compared to the single-action pressing, the homogeneity of green compact is improved by double action pressing due to the transcended die friction. The most common compaction method, however, is cold axial pressing which is also applied in the presented work for producing the samples.

A green compact reaches its highest strength by undergoing a sintering process. Sintering involves heating the preform to a temperature below the melting point of the major constituent [1]. During sintering the thermally activated inter-diffusion processes between the powder particles take place and the cohesion bondings of the particles grow. In many cases the formation of a liquid phase is also involved which contributes to a higher density of the sintered part. The mechanism of sintering can be explained by the surface energy associated with powder. The surface energy depends on the inverse of diameter. Thus, the smaller the particle, the higher is the energy. The particles tend to grow to larger particles with lower surface energy and so the smaller particles sinter faster. As the grain size grows, the porosity decreases evident with the increase in temperature. A pore on the particle boundary can experience different kinds of evolution: It can change its shape or be dragged as the particle grows. Also the particle boundary can break away and leave an isolated pore [3]. In addition to sintering temperature, the sintering time and atmosphere also influence the sintering results and are determined according to the powder ingredients. The sintering atmosphere (for example Ar, N) provides removal of lubricants or additives from the powder. In some cases the sintering is carried out under vacuum. The temperature-time pathway and the atmosphere are controlled by a sintering furnace. A controlled cooling rate avoids an excessive hardening of the sintered part.

1.2. Research Introduction

Powder metallurgical techniques offer the potential to extend the functionality of structural parts by the integration of inherent data carriers to sensory elements. These foreign elements are embedded in the powder in predefined positions prior to compaction. Fig. 1 demonstrates the principle of integrating a foreign element in a green compact which is applied in this work. The die consists of two matching pieces: the lower die and the upper die. This specific tool design facilitates the insertion of foreign elements into a defined depth of the powder body. At the beginning, the lower die is filled with a defined amount of base powder. The powder surface is leveled and subsequently the foreign element is placed on the bulk powder. Then the upper die is placed on the lower die which creates space for the remaining powder to be filled into the die. Finally, powder and foreign elements are pressed and form the so-called green compact. In order to eject the sample, the bottom plate must be removed.

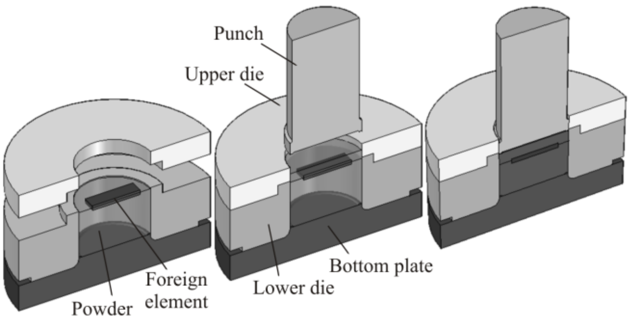

Figure 1. Integration of a foreign element into a green compact (axial die pressing).

As data carriers single parts arranged in coding patterns or - in order to increase the storage density - free definable traces of foreign powders can be used. The read-out of the stored data is based on the physical difference between the base powder and the foreign material (e.g. X-ray or Computed Tomography). If necessary, the data can be decoded through an image processing.

It is also possible to embed elements with sensory features, which allow for the analysis of representative strains, stresses or temperatures. In this case an external reader is required for analysing and monitoring the measurement data. For such applications a high bonding quality is essential to avoid elastic slip between the base material and the embedded elements or the occurrence of internal notches.

2. Static data storage

Researches concerning the storage of static data in a sintered part were carried out using aluminium powder Alumix 13 (Ecka Granules®) as basic powder. This powder is fine-grained, with an average grain size of $d_{50} = 80$ µm. As data carrier polished spheres of heat-treatable steel (1.3505) with a diameter of 0.5 to 1.0 mm were applied. By placing the spheres in a defined arrangement, for example a binary matrix, within the part body a number or code can be stored. The substitution of the spheres by a foreign powder allows the storage of a larger amount of data with more flexibility in producing the patterns. For example logos, coded symbols or direct indications in letters and numbers can be depicted. The foreign powder used for this purpose was the steel powder ATOMET 1001, (QMP Co.) with an average grain size of $d_{50} = 88$ µm.

A major focus of the tests lay on the compaction properties of the compound powder. The chosen foreign particles or powder should have an appropriate cohesion to the basic powder. Additionally, the particle size or the geometry of the patterns should fulfil the requirements concerning the positioning and read-out processes. In order to create exact and reproducible markings in the component, the foreign particles or powder were positioned on the level surface of bulk powder at the marking section (Figure 2) with the aid of an automatic positioning device.

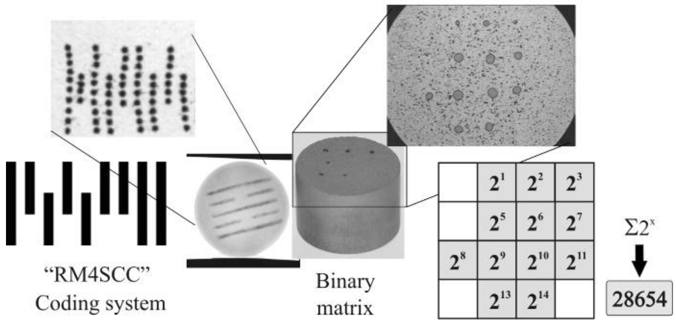

Figure 2. Data storage by means of foreign powder (left) and foreign particles (right).

3. Integration of functional elements

As functional elements magneto elastic nickel-iron-layers with a thickness of 500 nm on different substrate materials were embedded in sintered parts. The magneto elastic NiFe-layers on substrates like aluminium, silicium or aluminium oxide are especially appropriate for an online-measurement of strains and resulting stresses within a part using an external eddy current sensor-system. The variation of the permeability in NiFe-layer in response to modification of the magnetic field due to an elastic deformation can be correlated with the causing stress. The main point in integrating such elements is to achieve a high binding quality between the substrate material and the basic powder. For this means the substrate material should be properly paired with the basic material.

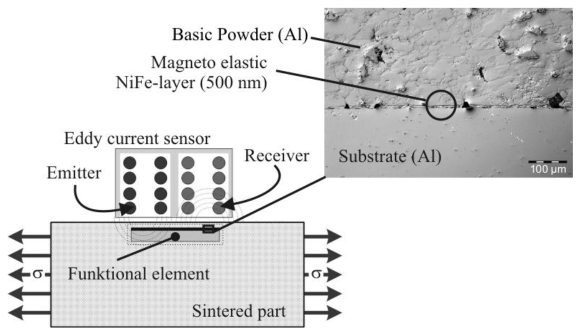

Figure 2. A magneto elastic NiFe-Element in a sintered part.

The experiments show that the best result concerning the bonding quality is achieved by integrating a NiFe-layer on an Aluminium substrate into an Aluminium part. The substrates made of silicium or aluminium oxide are not appropriate due to insufficient ductility, so that the strains in the part can not be fully transferred to the magneto elastic layer. Concerning the signal strength, the basic powder should consist of a paramagnetic material, for example Aluminium. Ferromagnetic material would interfere with the magnetic field of the eddy current sensor and result in inaccurate signals. Figure 2 shows the principle of the loading measurement using an integrated magneto elastic element and also a metallographic image of the bonding zone between the Al-subtrate and Al-basic powder. The depicted sample is a sintered part made of Alumix13 powder, pressed at 53 MPa and sintered at 560°C for 30 min.

4. Numerical Simulation

In this project the Drucker Prager Cap Model [4] was chosen to describe the compaction behaviour of the used powder materials. This model, which has originally been established for the simulation of the constitutive behaviour of geological materials, has been used successfully for the modelling of powder-technological processes for a long time [4, 5, 6, 7, 8]. In the plane of the hydrostatic pressure and of the equivalent von Mises stress the yield locus is composed by the elliptical compaction cap F_C and the failure line F_S (1).

$$\begin{aligned} F_c &= \sqrt{[(p-p_a)^2 + (R\cdot q)^2]} - R\left(d + p_a \cdot \tan\beta\right) = 0 \\ F_s &= q - p\cdot\tan\beta - d = 0 \end{aligned} \tag{1}$$

The parameter R represents the eccentricity of the compaction cap, d the shear strength, β the angle of the inner friction and p_a the pressure which is necessary for the compaction cap to pass into the failure line, fig. 3.

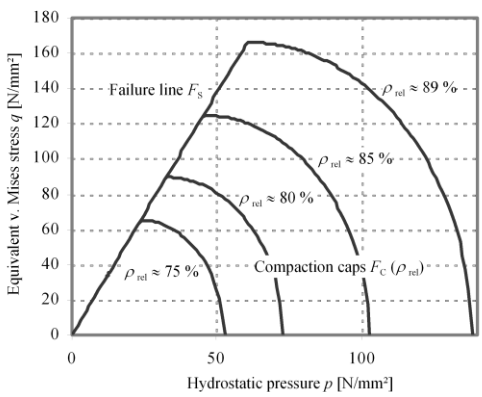

Figure 4. Yield loci of the Drucker Prager Cap Model for aluminium powder [9].

This model allows for simulation of the powder compact as an elastoplastic, compressible continuum. Within the yield locus the material reacts elastically, stress states on the yield cap cause plastic deformation and stress states on the failure line cause the softening of the material and can lead to shear failure.

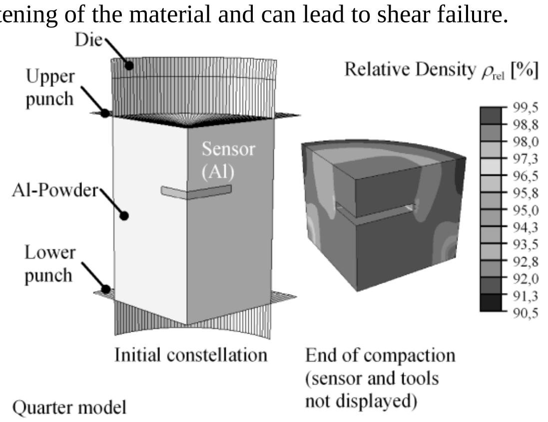

Figure 5. Simulation results for a washer embedded in a powder-pressed aluminium specimen.

For the numerical quantification of the effects of the pressing it is necessary to formulate the yield loci of the considered material depending on the relative density. Fig. 4 shows the yield loci determined for ALUMIX 13. In the plane of the hydrostatic pressure and of the equivalent von Mises stress a parallel shift or scaling of the compaction caps in dependence of the relative density occurs.

Fig. 5 shows the numerical results of the powder compaction with an embedded sensor element on aluminium substrate in Alumix 13. The influence of the sensor on the distribution of the relative density is obvious. The absolute difference of the density regarding shear failure and distortion due to sintering can be neglected in this case. But the results reveal also that in case of parts with higher complexity the numerical simulation of the pressing process is an important tool for process design.

5. Further Procedure

In future researches the application of further functional elements and sensors will be studied. The main focus of the studies will be the integration and utilization of temperature sensors in sintered parts. The preliminary tests using a temperature sensor on a ceramic substrate are already in progress. It has been successfully embedded in a steel sintered part. Also the previous tests will be continued to enhance the binding quality between the foreign material and the basic powder. The final goal of the studies is to expand the application field of the developed technology. The process parameters for different part geometries and materials are to be determined.

Acknowledgements

The results presented in this paper were obtained within the scope of the Collaborative Research Center 653 “Gentelligent Components in their Lifecycle” in the subproject “Sintering gentelligent parts from metal powder”. The authors would like to thank the German Research Foundation (DFG) for funding this project. The authors would also like to thank the Institute of Materials Science (IW), Leibniz Universitaet Hannover (LUH) for producing the X-ray images shown in this paper.

References

[1] Thümmler, F., Oberacker, R., 1993, Introduction to Powder Metallurgy, ISBN 090171626X, the Institutes of Materials, London.
[2] Schatt, W., 2007, Pulvermetallurgie: Technologien und Werkstoffe, ISBN-10 354023652-X, Springer Verlag.
[3] German, R.M., 1994, Powder Metallurgy Science, ISBN 1-878954-42-3.
[4] Drucker, D.C., Gibson, R.E., Henkel D.J., 1957, Trans. Am. Soc. Civ. Eng., 122:338–346.
[5] Coube, O., Riedel, H., 2000, Powder Metallurgy, 43/2:123-131.
[6] Kraft, T., Coube, O., Riedel, H, 2001, 3. deutschsprachiges ABAQUS Anwendertreffen, Freiburg, M. Küssner (Ed.), ABACOM Software GmbH, Aachen.
[7] Riedel H., Schweizer Maschinenmarkt, 1997, 20:54-56.
[8] Behrens B.-A., Bouguecha, A., Hanini K., 2004, UTF Science, 2:1-4.
[9] Behrens, B.-A., Seidel, H.-J., Lange, F., Kammler, M., 2011, Mat.-wiss u. Werkstofftech., 42/8:705-711.