NUMERICAL INVESTIGATION OF A HOT FORGING PROCESS FOR PARTIALLY PARTICLE-REINFORCED SINTERED COMPONENTS

Bernd-Arno BEHRENS, Martin BONHAGE, Alexander CHUGREEV, Ingo ROSS,
Irfan Yousaf MALIK

*Leibniz Universität Hannover, Institute of Forming Technology and Machines, An der Universität 2,
30823 Garbsen, Germany, EU, malik@ifum.uni-hannover.de*

Abstract

The expanding range of applications for parts made of light metals (magnesium, aluminium or titanium) could lead to a replacement of parts made of steel by the ones manufactured from light metal parts. However, magnesium and aluminium parts in particular reach their technical limits when exposed to high tribological, mechanical or thermal stress. For this reason, often the so called metal-matrix-composites (MMC), which possess the advantages of light metal (low weight and high ductility) as well as of the reinforcing phase (high hardness, high strength and good wear resistance), are used.

This paper provides the initial findings of a fundamental investigation of the specific forming behaviour and the mechanical material properties for production of partially particle-reinforced powder metal parts. Cylindrical raw parts consisting of aluminium powder and a ceramic powder are produced by powder pressing and further compacted in a subsequent sintering process. The produced raw parts form the basis for an examination for a reduction of the existing residual porosities by subsequent upsetting and extrusion processes. The effects of the different process parameters (pressing force and forming temperature) on the material flow of the partially particle-reinforced material system and the structural strength of the formed parts are investigated. Numerical simulations are performed to analyse the density development during the above mentioned forming processes in order to determine the influence of porosity on the deformation behaviour of the considered material. The findings will help to evaluate the dependence of the residual porosity for sinter-forged parts on the prevailing forming mechanisms.

Keywords: Powder metallurgy, aluminium, metal-matrix-composites, FEM

1. INTRODUCTION

The optimisation of manufacturing processes in order to increase the efficiency and quality of products plays an increasingly important role in the times of rising energy and material costs. Due to these constantly increasing expenditures in the global market, manufacturing companies are trying to take design measures or use alternative manufacturing processes such as powder metallurgy (PM).

1.1. Powder Metallurgy

The PM process is one of the most efficient methods for mass production of small structural components. Due to their properties, PM components are ideal for a wide range of different industrial applications. One of the biggest consumers of PM components is the automotive industry. Moreover, they are utilized in fields of aerospace, medical technology, household utensils as well as sports [1,2]. In contrary to conventional production processes, PM in particular offers various advantages in terms of energy saving as well as material utilization. Furthermore, it enables the use of a wide variety of composite and alloyed powder materials for component production [1]. By adding alloy elements, material properties, such as hardness or strength, as well as application can be adapted in the respective areas of utilization [3]. However, depending on the used process parameters during pressing and sintering, a residual porosity in the structure remains which can lead to reduced mechanical properties as compared to components made of solid material. For this reason, special methods of re-densification are used in certain areas of application [4].

The most commonly used production process of powder parts is the conventional pressing and sintering [5]. Other methods are warm pressing, hot isostatic pressing, sinter forging or additive manufacturing [2]. These methods allow for various complex geometries and density values. Within this work, the compression process by sinter forging to reduce the porosity will be examined more closely.

1.2. Sinter Forging

A material density up to 92 % of the theoretical density of a solid material can be achieved in a conventional PM production process. This depends on the size of the component, the properties of the powder and the applied compacting pressure. The tensile strength of the sintered material is proportional to its relative density. A repeated pressing and sintering process can result in densities of up to 96 %. Further densification of the components can be accomplished by sinter forging at elevated temperatures. With sinter forging, density values up to 100 % are theoretically possible [1]. In general, two different process variants of sinter forging exist, namely sinter forging without material flow and sinter forging with a material flow. Sinter forging without material flow leads to a reduction of the pore height whereby the width remains unchanged. Whereas, the axial compressive stress in sinter forging with high material flow leads to a lateral flow of the material. This can cause a dissipation of large pores in to smaller pores. With increasing material flow, the dissipation process of the pores continues and results in a significant reduction of the material porosity. In this work, two sinter forging processes with material flow are considered.

1.3. Modelling of Material Porosity

PM produced components have a porous material structure which is defined by its relative density and depends on the process of shaping and subsequent heat treatment. Due to this, during plastic deformation porous materials behave differently than solid materials. For the evaluation of the flow behaviour of such materials, the Gurson-Tvergaard-Needleman model (GTN model) was established by Gurson and later on was further modified by Tvergaard and Needleman as provided in equation (1) [6,7]:

$$\Phi = \left(\frac{q}{\sigma_y}\right)^2 + 2q_1 f \cosh\left(-\frac{3}{2}\frac{q_2 p}{k\sigma_y}\right) - \left(1 + q_3 f^2\right) \tag{1}$$

Here, the parameter p and q are the hydrostatic (i.e. mean stress) and deviatoric components (i.e. equivalent v. Mises stress) of the Cauchy stress tensor, respectively. q_1, q_2 and q_3 are material-specific constants introduced by Tvergaard and are known as fitting parameters where $q_3 = (q_1)^2$, σ_y represents the yield or flow stress of the matrix material (MPa) and f is the void volume fraction or the degree of porosity of the material based on the modifications of Tvergaard and Needleman.

In the scope of this work, an insight into the production of partially particle reinforced powder metal parts is presented. The main goal is to investigate the influence of the reinforcement powder content on porosity and hence on the quality as well as strength of produced components. It is aimed to perform a numerical modelling of two different sinter forging processes (with material flow) in order to evaluate the porosity distribution in the produced components. The above mentioned GTN model is applied for this purpose.

2. PRODUCTION AND FORGING OF THE SEMI-FINISHED WORKPIECES

For the experimental investigation, Alumix 123 (aluminum powder with 4.8 % copper, 0.7 % silicium and 0.6 % magnesium) was used. The powder has a spherical grain shape. Titanium carbide (TiC) was used as ceramic powder. An SEM analysis was performed to find out its size distribution. An asymmetric, spattered grain shape was observed with most particles smaller than 20 µm.

For the powder compaction, a two-sided uniaxial pressing tool system was used. The tool system consists of an upper and a lower stamp (each Ø = 36 mm) as well as a die which is mechanically reinforced by a die carrier. The pressing of the powder compacts was carried out on a multi-axis hydraulic press (manufacturer: SMS Meer). The powder was filled into the die and compacted by the movement of the upper and lower stamp. Three different material mixtures were prepared comprising of Alumix 123 with 0 %, 5 % and 20 % TiC reinforcement respectively. For this investigation, different powder compacts were produced by application of 400, 500 and 600 MPa pressure. Subsequently, the compacts were sintered for 20 minutes at a temperature of 590 °C under vacuum conditions. The heights, weights as well as densities of the semi-finished workpieces were measured to determine their relative density by Archimedes' principle (see **Figure 1**). In order to observe the distribution of aluminium, TiC and pores in the semi-finished workpieces, metallographic investigation was performed. In **Figure 1** micrographs of the sintered components with a pre-compression of 400 MPa are exemplarily shown. The metallographic images display the area in the middle of the components with different TiC-particle reinforcements. It can be seen that higher particle reinforcement results in an increased porosity in the component which leads to a reduction in the relative density.

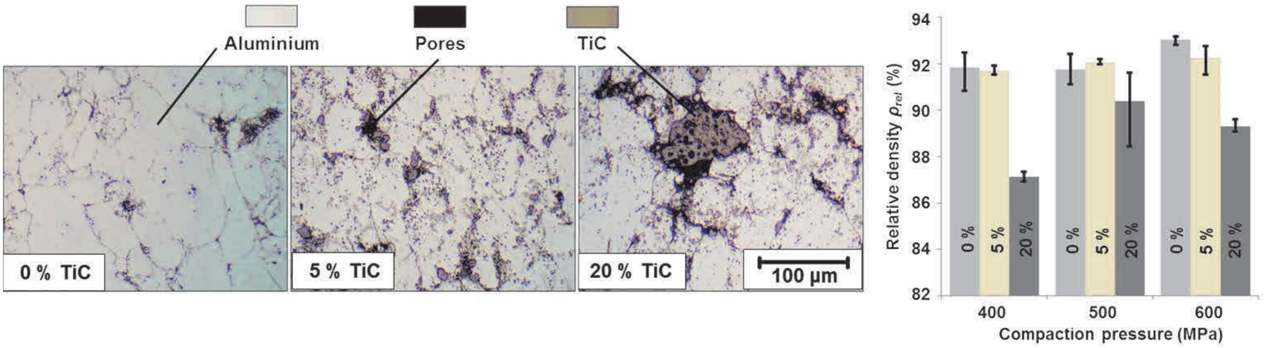

Figure 1 Micrographs of sintered components with a pre-compression of 600 MPa (left); relative density of powder compacts with different pre-compression pressures (right)

The sintered cylindrical semi-finished workpieces were forged with a material flow by means of an upsetting and a forward extrusion process. For both of the forging processes, a modular tool system was manufactured as depicted in **Figure 2.** The experiments were performed on a screw press (Weingarten PSR 160) which has a nominal capacity of 2500 kN. The forming tests were carried out at temperatures of 25 °C, 300 °C and 400 °C.

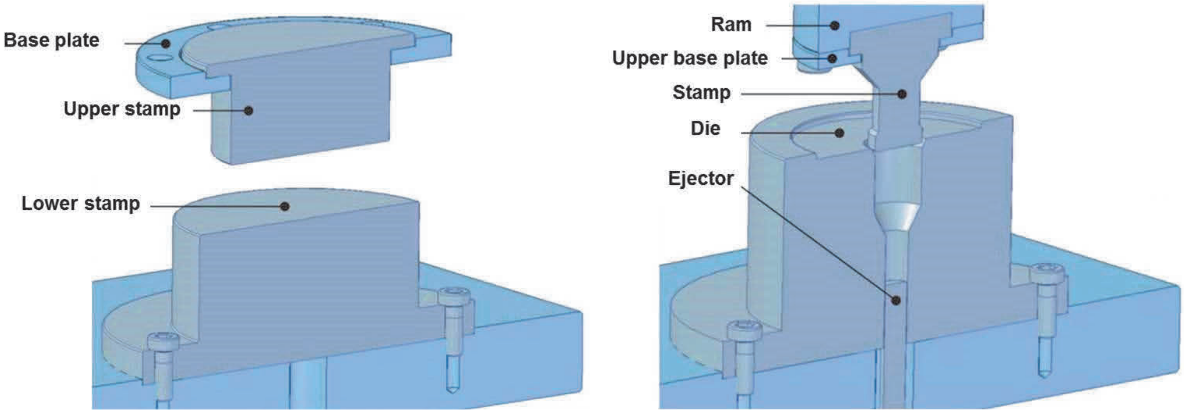

Figure 2 Modular tool system for sinter forging: upsetting (left) and forward extrusion (right)

3. CHARACTERISATION OF THE SEMI-FINISHED (SINTERED) WORKPIECES

Tensile tests have been carried out to characterise the material properties of the considered material mixtures at three different temperatures (25 °C, 300 °C and 400 °C) by means of deformation dilatometer (manufacturer: TA Instruments). Since the cylindrical semi-finished products were produced using the two-sided compaction process, it can be assumed that a comparatively lower relative density exists in the center of the sample as compared to the upper or lower zones. For this reason, the tensile specimens taken from the middle of the cylindrical semi-finished workpieces were considered for the subsequent investigations. Based on these experiments, force displacement curves were recorded and parameterised to obtain the flow curves of different semi-finished components. Subsequently, these flow curves were used to evaluate the plastic strain and stress data (see **Figure 3**) to be used for the numerical investigations.

4. NUMERICAL SIMULATION OF THE SINTERFORGING PROCESS

Behrens et al. have presented their work related to application of FEM for powder pressing as well as sintering process in [8]. This paper builds on those findings and provides an insight into the numerical investigation of the sinter forging process described above by means of FE program Abaqus. For this purpose, the model implemented in Abaqus according to Gurson-Tvergaard-Needleman (GTN), as mentioned in section 1.3, is applied. The accuracy of this model depends on the selection or evaluation of the considered parameters. This requires determination of the seven parameters namely the so called Tvergaard fitting parameters q_1 and q_2, void nucleation parameters f_n (volume fraction of the nucleation voids), ϵ_n (normal distribution of the mean nucleation strain) and s_n (standard distribution of ϵ_n) as well as the porous failure parameters f_c (critical void volume fraction) and f_f (total void volume fraction at total failure). Investigations by Faleskog have shown that the Tvergaard fitting parameters are closely related to the strain hardening exponent N and the material strength σ_0/E [9]. Research work of Tvergaard showed that a large number of materials can be approximated with a moderate strain hardening exponent by using values of 1.5 and 1.0 for q_1 and q_2, respectively [7]. The void nucleation parameters as well as the porous failure parameters can be determined by tensile tests in experimental as well as numerical form and metallographic investigations. However, these procedures are very complex and time-consuming, which is why the values proposed by Richelsen and Tvergaard ($f_n = 0.04$, $\epsilon_n = 0.3$, $s_n = 0.05$, $f_c = 0.06$ and $f_f = 0.667$) were used in this work [10]. In addition, the total densities as well as the initial relative densities for different semi-finished workpieces evaluated after experiments in the section 2 were considered for defining the initial material behaviour during our numerical investigations.

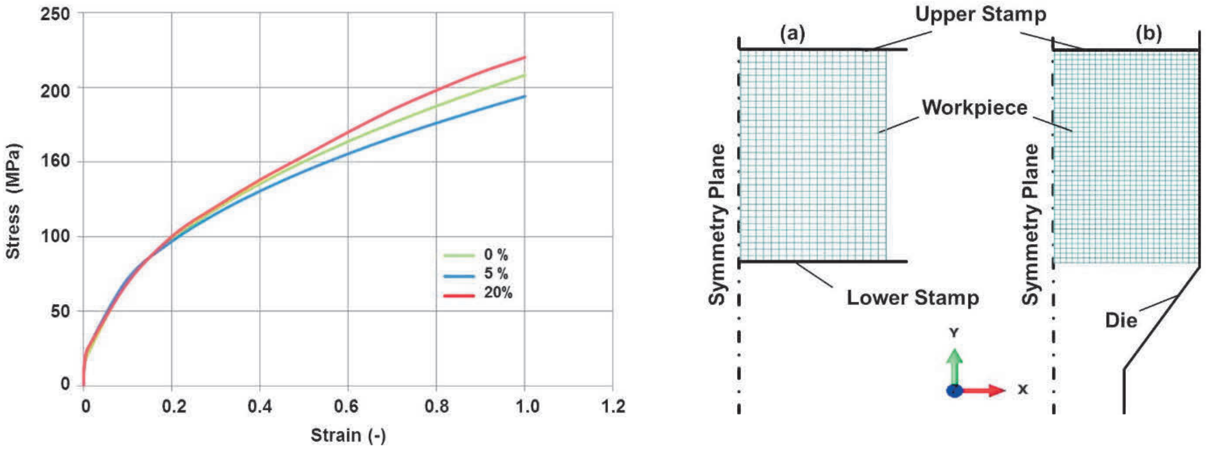

Figure 3 Stress-Strain curves for material mixtures with 600 MPa pre-compression (left); 2D axisymmetric model and mesh of the tool system: (a) upsetting process, (b) forward extrusion process (right)

For the numerical investigation, the same semi-finished workpiece geometry is considered for both of the sinter forging processes. This is a cylindrical semi-finished product with a height of 33 mm and a diameter of 36 mm. A 2D axisymmetric model of the tool system was used for the numerical simulation of both the processes. The tools (stamp and die) were assigned rigid behaviour, whereas the workpiece was defined as deformable axisymmetric. A structured mesh was created for the workpiece by means of CAX4R type 4-node bilinear axisymmetric quadrilateral elements with reduced integration. Element length of 0.75 mm and 1 mm were chosen for the forward extrusion and upsetting, respectively and accordingly comprise of a total of 627 and 1100 elements (see **Figure 3**). In order to accurately capture the material flow behaviour during the forming processes, an adaptive mesh algorithm (ALE) was incorporated. Surface to surface contact is defined and friction is described by using the coulomb's model with a friction coefficient of 0.3 for the contact between tools and workpiece. The upper tool (stamp) is lowered by approximately 15.6 mm during the upsetting process and by 21 mm during the forward extrusion process.

In this paper the simulation results based on the above described models and process parameters at a workpiece temperature of 400 °C for the samples compacted with 600 MPa pre-compression are exemplarily presented. The contour plots shown in **Figure 4** describe the void volume fraction, given in %, which represents the difference between density and relative density. Both of the processes were numerically evaluated by comparison of porosity in workpieces with different TiC content at the end of respective forming process.

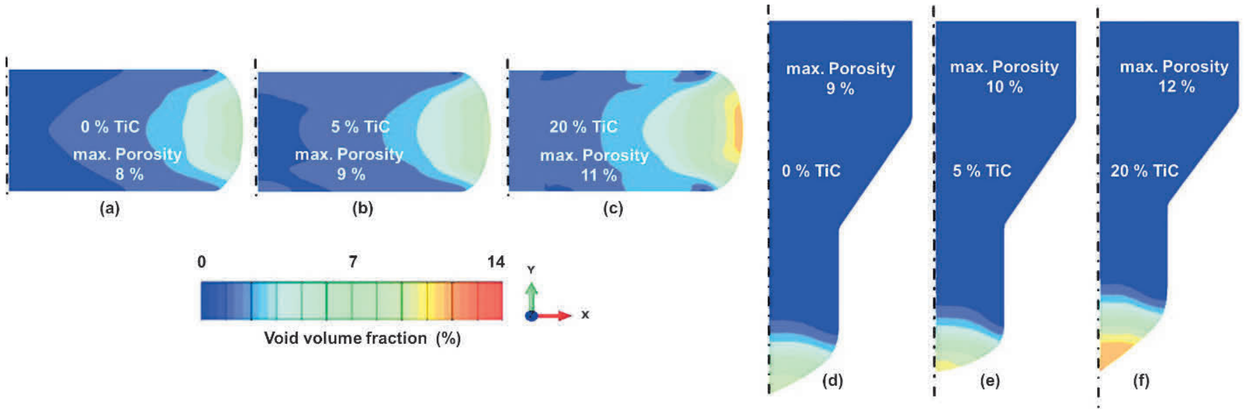

Figure 4 Contours of porosity in samples with different TiC content after upsetting (a-c) and forward extrusion process (d-f) for 600 MPa pre-compression at a process temperature of 400 °C

The samples had an initial void volume fraction of about 14 %. **Figure 4** (a-c) shows that the regions in the core as well at the upper and lower edges show complete compaction for upsetting process with all TiC mixtures. However, in the bulging area, void volume appears to be increasing with an increase in the percentage of TiC. This will result in higher tensile stresses on the bulge surface which will decrease towards the middle of the sample. Cracks are expected to appear in the bulge surface, in particular for the samples with 20 % TiC mixture. In the case of forward extrusion process, **Figure 4** (d-f) shows that all the samples undergo an almost complete compaction of the samples in most of the areas. This is due to the high compression stresses acting on the top as well as sides of the sample. A residual porosity is only present in the tip of the sample's lower area as only negligible compression takes place in this area. As in the case of upsetting, the porosity during the forward extrusion process also seems to increase with an increase in the TiC. It could be argued that addition of foreign particles (i.e. TiC in this case) has led to a brittleness of the sample and hence a content as high as 20 % needs to be avoided.

5. CONCLUSION AND OUTLOOK

Within this study, two different sinter forging processes were investigated by using cylindrical semi-finished workpieces which were produced by conventional powder pressing. For the semi-finished workpieces, aluminium with and without ceramic powder (TiC) content was pressed under pressures of 400 MPa, 500 MPa and 600 MPa followed by sintering in vacuum at a temperature of 590 °C for 20 minutes. A material characterization as well as a metallographic investigation was performed based on specimens obtained from the semi-finished workpieces. Subsequently, these semi-finished workpieces were forged with a material flow by upsetting and forward extrusion processes at room temperature, 300 °C as well as 400 °C. In addition, an FE-based investigation was carried out to investigate the process. The numerical investigations shows that it is possible to sinter forge reinforced cylindrical semi-finished workpieces into different geometries without macroscopic defects. However, a critical value of the maximum TiC content needs to be evaluated to avoid brittleness in the produced parts.

In the future work, a validation of the numerical results will be performed by means of comparison with the produced parts. Moreover, radial components with concentric layers of aluminium and MMC will be pressed and sintered before performing a forging process. In order to illustrate the porosity content of these sinter forged concentric components, metallographic images will be used. These metallographic images will also allow to evaluate the influence of resulting densities on the porosity reduction in the sinter forged components

ACKNOWLEDGEMENTS

The presented results are based on the framework of the research project "Hot Forging of partially particle-reinforced sintered components" under the grant number BE1691/195-1. The authors would like to thank the German Research Foundation (DFG) for the financial support.

REFERENCES

[1] SCHATT, W., WIETERS, K.-P. and KIEBACK, B. *Pulvermetallurgie: Technologien und Werkstoffe*. 2. bearbeitete und erweiterte Auflage, Berlin: Springer Verlag, 2007. p. 540.

[2] SANDER, Ch., RATZI, R., LORENZ, B. and TOBIE, T. Sintered Gears - Achievable Loaded-carrying Capacities by Conventional and New Production Methods. In *International Conference on Gears. München, Germany,* 2002.

[3] BEHRENS, B.-A., BOUGUECHA, A., VUCETIC, M., BONHAGE, M., ZAITSEV, A. and MALIK, I.Y., Compaction of a copper spiral within a cylindrical die of steel powder and investigation of their deformation behavior. In *World PM 2016 Congress and Exhibition. Hamburg, Germany,* 2016.

[4] KOETHER, R. and RAU, W. *Fertigungstechnik für Wirtschaftsingenieure*, 3. aktualisierte Auflage, München: Carl Hanser Verlag, 2008. p. 492.

[5] GASTAN, E. *Einfluss von Werkzeugschwingungen auf das Verdichtungsverhalten metallischer Pulver beim Matrizenpressen*, Dissertation, Universität Hannover, Berichte aus dem IFUM, 2012.

[6] GURSON, A. Continuum Theory of Ductile Rupture by Void Nucleation and Growth: Part I - Yield Criteria and Flow Rules for Porous Ductile Materials. *Journal of Engineering Materials and Technology*. 1977. vol. 99, no. 1, pp. 2-15.

[7] TVERGAARD, V. Influence of voids on shear band instabilities under plane strain conditions. *International Journal of Fracture Mechanics*. 1981. vol. 17, pp. 389-407.

[8] BEHRENS, B.-A. and BOUGECHA, A. Numerical and experimental investigations of aluminium powder compaction and sintering. *Material Science and Engineering Technology*. 2012. vol. 43, no. 6, pp. 511-519.

[9] FALESKOG, J., GAO, X. and SHIH, C. F. Cell model for nonlinear fracture analysis I. Micromechanics calibration. *International Journal of Fracture*. 1998. vol. 89, no. 4, pp. 355-373.

[10] RICHELSEN, A. B. and TVERGAARD, V. Dilatant plasticity or upper bound estimates for porous ductile solids. Acta Metallurgica et Materialia. 1994. vol. 42, no. 8, pp. 2561-2577.