Microstructure and compression strength of novel TRIP-steel/Mg-PSZ composites

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Abstract. A novel steel-based composite material, composed of metastable austenitic stainless steel as matrix and up to 15 % zirconia as reinforcement, is processed by two powder metallurgy routes. The matrix exhibits the so-called TRIP-effect (TRIP: Transformation-Induced Plasticity) and shows a deformation-induced formation of martensite. Compression tests of rod samples processed by cold isostatic pressing show increased strength compared to the non-reinforced steel matrix up to 20 % strain. Three-point bending tests show, however, reduced ductility for high zirconia contents. Filigree honeycomb structures were produced by a novel extrusion technique with extraordinary high values of specific energy absorption.

1. Introduction

Most Metal-Matrix-Composites (MMCs) have a light-metal matrix such as aluminum or magnesium. MMCs with a steel matrix, however, have not been examined very much up to now, although they may be possible candidates for use as high strength and wear resistant materials [1,2].

The combination of a steel matrix which shows the TRIP effect (TRIP: Transformation-Induced Plasticity) with a metastable ZrO₂-reinforcement also exhibiting a martensitic phase transformation was until now only investigated by the group of Guo et al. with regard to the mechanical properties. The studied composite was produced by the conventional powder metallurgical route and hot pressing [3-5]. Guo et al. thus created TRIP-steel matrix composites with reinforcements made of yttria-partially stabilized zirconia-particles (2Y-PSZ) and obtained an extraordinary high strength in high deformation rate compression experiments.

In the present work results of a new collaborative research center with the title “TRIP-Matrix-Composites – design of tough, transformation reinforced composite materials and structures on Fe-ZrO₂-basis” are presented. Samples of the steel-matrix composite materials were produced by cold-isostatic pressing and a novel extrusion technique which is used conventionally in ceramic technology. First results of a variant of the family of composite materials to be developed were already presented in very recent papers [6-8].
2. Materials and Experimental Details
The composite materials were made of AISI 304 stainless steel powder and zirconia with 3.5 wt.% MgO with particle sizes of 45 µm and 2 µm, respectively. Cylindrical rods without zirconia and with zirconia contents of 5 % and 15 % were prepared by cold isostatic pressing (CIP), square honeycomb structures without zirconia and with zirconia contents of 5 % and 10 % and a dimension of 25.5 mm x 25.5 mm with 196 channels (200 cpsi—channels per square inch) and a wall thickness of 250 µm have been extruded, cf. [6]. The green bodies were dried, debinded and finally sintered at 1350°C for 2 h. The CIPed samples had relative densities of 90 to 93 %. The microstructure of the CIPed material with 15 % zirconia is shown in Figure 1a by an optical micrograph after etching with Beraha II. The fine zirconia grains are clustered due to an insufficient mixing procedure which has to be improved in future. Because of the sintering temperature of 1350°C, the separate zirconia particles are unsintered in these clusters. However, the steel powder particles are sintered to each other and exhibit some binding to the zirconia grains. Figure 1b shows a square honeycomb sample with the filigree macrostructure.

From the rods, cylindrical samples for compression experiments of 6 mm diameter and 9 mm height as well as samples of dimension 4 mm x 6 mm x 40 mm for 3-point bending tests were machined. The CIPed samples as well as the honeycomb samples were tested in a servohydraulic 500 kN testing machine at a displacement rate of 0.016 mm/s (2x10⁻⁴ s⁻¹).

3. Results and Discussion
The results of compression and bending experiments, respectively, of the CIPed materials are shown in Figure 2. In compression, the non-reinforced sintered steel samples behave comparable to wrought steel of equivalent composition. The composites with 5 % and 15 % zirconia show an increased flow stress. The subsequent stress-strain curves of the two composites, however, differ significantly. The 5 % zirconia composite sample exhibits a comparable strain hardening as the non-reinforced material, however at higher strength. In contrast, the stress-strain curve of the 15 % zirconia composite deviates already at a strain of 8 % due to limited ductility, see the inserted micrographs of the samples after compression to 50 % true compressive strain. Additional investigations showed the deformation-induced formation of α’-martensite in the steel matrix by optical microscopy and EBSD [8].

In bending, the 5 % zirconia sample shows again a higher strength compared to the non-reinforced sample. However, the 15 % zirconia sample fails at small bending stresses in a nearly brittle mode. The fracture surfaces show that the crack path follows the unsintered zirconia clusters [8].

The compressive stress-strain curve of a honeycomb sample is given in Figure 3 together with some micrographs taken at different strains. It shows a large regime of strain hardening, followed by a plateau-like behavior with a flow stress of about 270 MPa at approximately 25 % compressive strain and a subsequent stress decrease. The micrographs show the failure of some walls of the honeycomb structure by bending and first cracks on the surface of the sample.
Figure 2: Compressive (a) and bending (b) behavior of CIPed TRIP-matrix composite samples compared to zirconia-free AISI 304 steel.

In addition to the macroscopic failure observed on the surface of the honeycomb samples, SEM investigations have been carried out. Figure 4a shows an overview from the top side of a honeycomb sample containing 10 % zirconia deformed to 50 % compressive strain. The separate walls deform plastically by bending and buckling, respectively. In some cases, rupture of the walls can be found, in accordance to the macroscopic shear band visible in Figure 3, starting at 25 % compressive strain. The deformation and failure modes are in accordance to the model of Gibson and Ashby for cellular materials [10]. The mass and volume specific energy absorption, respectively, observed during compression of the honeycomb samples shows extraordinary high values, cf. [6-8].

A metallographic longitudinal section of the deformed honeycomb sample studied by optical microscopy is shown in Figure 4b. The zirconia particle clusters are deformed because the single zirconia particles remain unsintered. In the steel matrix, a high density of glide bands is visible in the presented micrograph. However, due to the inhomogeneous deformation of the honeycomb samples, other positions of the section showed nearly no traces of deformation (not shown here). A closer view on the deformation bands showed beginning martensitic transformation of the metastable austenitic steel to the α’-martensite, cf. Figure 4b.

Figure 3: Compressive stress-strain curve of a honeycomb composite sample together with optical photographs of the sample at different deformation states.
a) [Image]  

Figure 4: SEM micrograph of a top view [6] (a) and optical micrograph (stress axis vertical, etchant Beraha II) [8] (b) of a honeycomb sample with 10% zirconia deformed to 60% compressive strain.

4. Conclusions
In the present paper new composite materials based on austenitic stainless TRIP-steel reinforced with zirconia are presented. In further studies the mixing process of the raw materials has to be improved within the framework of the ongoing research on TRIP-Matrix Composites to avoid the clustering of the zirconia particles. Both composites produced by CIP and by the novel extrusion technique of a plastic feed stock material show a reinforcement effect compared to the reference samples of non-reinforced austenitic steel. In the steel matrix, the deformation-induced formation of $\alpha'$-martensite was observed (TRIP-effect). It has to be pointed out that in the present investigation the zirconia particles exhibited a low fraction of metastable phases and therefore showed no martensitic transformation.

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