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# BALLISTIC RESISTANCE AND IMPACT BEHAVIOUR OF $Al_2O_3$-Al CERAMIC METAL COMPOSITES

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The ballistic resistance of $Al_2O_3$-Al composites against 7.62 mm AP projectiles was determined. Three cermet materials based on different $A1_2O_3$ ceramic preforms were tested. The ceramic preforms were infiltrated with a high strength aluminum alloy by squeeze casting. The ceramic volume fraction of the materials was in the range from 70% to 84%. The ballistic limit velocities of cermet/aluminum two layer target configurations were determined. Edge-on impact tests were conducted in order to characterize the fracture behavior of the composites.

## INTRODUCTION

High strength ceramics are an essential part of most modern lightweight armor systems because of their high hardness at relative low densities. The hardness is of particular importance if the material is employed to defeat armor piercing projectiles with a high hardness steel or tungsten carbide core. However, it is well known that projectile impact causes severe fracture in ceramics and therefore significantly reduces their ability to defeat a second or third hit. Thus, a type of material is needed which combines the hardness of a ceramic with a sufficient toughness that restricts fracture in order to achieve an armor system with multiple hit capability.

Candidate materials for this application are ceramic metal composites. The ballistic performance of aluminum alloys, reinforced with $Al_2O_3$- or SiC-particles has been tested with tungsten projectiles in Depth of Penetration (DOP) test arrangements by Vaziri et al. and Bless et al. [1, 2]. The experiments demonstrated a superior ballistic resistance of the cermets compared to aluminum alloys. The volume fraction of the ceramic particles in those tests had been 10–30%.

In the study reported here a different approach with respect to the materials was chosen. The main part of the $Al_2O_3$-Al cermets consisted of ceramic phase. The metal fraction ranged from 15% to 30% only. A low purity aluminum oxide ceramic ($Al_2O_3$-92%) was selected as reference material for the assessment of the ballistic performance of the new materials.

# MATERIALS

The Swiss Federal Laboratories for manufactured three cermet material versions based on different $Al_2O_3$-ceramic preforms of different porosity and structure. The ceramic preforms were infiltrated with the high strength aluminum-alloy AlCu4Mg1 by squeeze casting. The ceramic volume fraction in the materials was 70% with Cermet 1 and Cermet 3, and 84% with Cermet 2. The ceramic preforms of Cermet 1 and 3 were manufactured by EMPA, the preforms of Cermet 2 were a commercially available porous ceramic of Haldenwanger Company. Whereas the ceramic phase of the Cermets 1 and 2 exhibits a continuous structure, Cermet 3 was manufactured from a preform processed by dry spraying and cold compaction consisting of a tri-modal mixture of alumina particles that were not sintered together. The structure of the different materials is illustrated in the micrographs of Figures 1a–1c. Cermet 1 mainly consists of sintered spheric agglomerates of finest alumina particles (gray) completely infiltrated with and surrounded by aluminum (white). Cermet 2 features a sintered structure of coarse and fine alumina particles clearly illustrating the continuous ceramic structure. Cermets 1 & 2 consist of percolating alumina and aluminium networks. The structure of Cermet 3 is basically different, as evidenced in Figure 1c. The individual alumina particles are isolated and completely surrounded by the aluminum matrix.

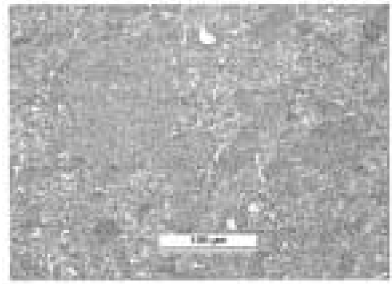


Figure 1a: Micrograph of Cermet 1.

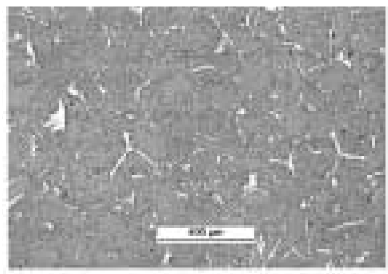


Figure 1b: Micrograph of Cermet 2.

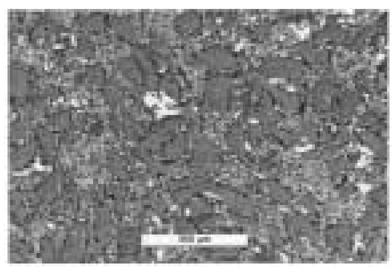


Figure 1c: Micrograph of Cermet 3.

An $Al_2O_3$-ceramic ($Al_2O_3$-92%) of the same density as Cermet 1 was chosen as a reference material for the assessment of the ballistic resistance of the new materials. Mechanical and physical properties of the cermets and the reference ceramic are listed in Table 1.

Table 1: Material properties

| Material | Ceramic fraction Vol. % | Density [g/cm$^3$] | 4-Point Bending Strength [MPa] | E-Modulus [GPa] |
|---|---|---|---|---|
| Cermet 1 | 70 | 3.56 | 651 | 246 |
| Cermet 2 | 84 | 3.74 | 302 | 300 |
| Cermet 3 | 70 | 3.53 | --- | --- |
| $Al_2O_3$-92 % | 100 | 3.57 | 247 | 285 |

# BALLISTIC RESISTANCE

The main field of a possible application of the cermets will be lightweight armor against small caliber AP projectiles. For this reason the targets, employed for the ballistic performance assessment of the cermets, ought to be similar to real configurations with respect to material combinations and total weight.

## Residual Velocity

Two layer targets which consisted of a cermet and an aluminum (AlCuMg1) plate were employed for the assessment of the ballistic performance against 7.62 x 51 mm AP (steel core) ammunition. The cermet tiles of the dimensions 100 mm x 100 mm were fixed to the aluminum plates by a polyorethane glue. Figure 2 shows the residual velocity $v_R$ versus impact velocity $v_P$ for seven different target configurations. Three of the ceramic materials were tested in combination with aluminum plates of 4 mm and 6 mm thickness. Cermet 3 was tested only in combination with a 6 mm aluminum plate. The seven target configurations corresponded to only two different total areal densities, 47 $kg/m^2$ with the 4 mm aluminum plate and 52 $kg/m^2$ with the 6 mm aluminum plate. The total weight of the targets including Cermet 2 was slightly higher because of the higher density of the cermet. The reference target ($Al_2O_3$-92% + Al) with the 6 mm aluminum plate was not perforated at impact velocities of 840 ± 10 m/s. A reduction of the aluminum plate thickness by 2 mm lead to a drop of the ballistic limit velocity $v_{BL}$ of about 200 m/s. It can be recognized from Figure 2, that with all materials there was a wide zone of mixed results, where the residual velocity $v_R$ could be either zero or a few hundred meters per second. Thus, an estimate of the ballistic limit velocities was difficult. The dashed $v_R$-$v_P$-curves are approximations of the experimental data based on a Recht equation [3]. The $v_R$-data in Figure 2 show that the ballistic performance of Cermet 1 and Cermet 3 was significantly lower than the performance of the reference aluminum oxide. The ballistic limit

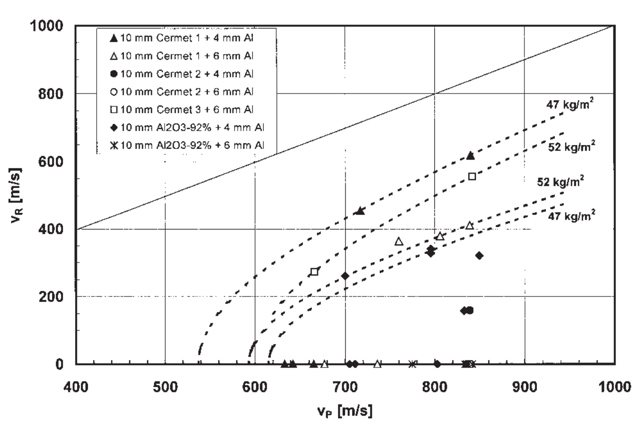



Figure 2: Residual velocity $v_R$ versus irnpact velocity $v_P$ for two layer targets with cermets and $Al_2O_3$.

velocity of the 52 kg/m2 target with Cermet 1 was about 250 m/s below that of the reference. With the 47 kg/m2 target the difference in $v_{BL}$ is less than 100 m/s. The ballistic resistance of Cermet 3 targets was even lower compared to Cermet 1. Only the Cermet 2 targets exhibited a ballistic performance similar to the reference material.

## Residual Penetration

A few additional penetration tests were conducted with specimens of Cermet 1 and Cermet 3. The cermets were glued to a thick aluminum (AlCuMg1) backing and the residual penetration $P_R$ of the steel core of the 7.62 mm projectiles into the aluminum was measured. In these tests the cermet tiles were laterally confined in a steel frame. The penetration data are depicted in Figure 3. The $P_R$-curves show the inferior ballistic resistance of Cermet 3 compared to Cermet 1.

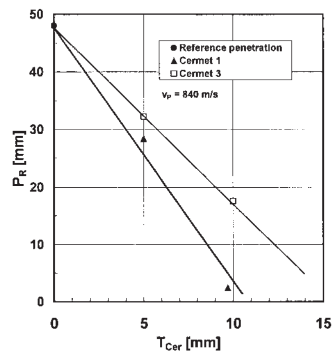
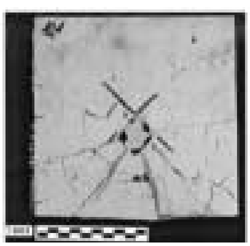


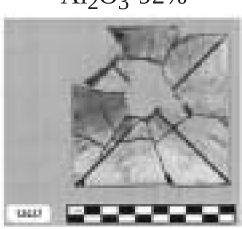
Figure 3. DOP-data for cermets.

# IMPACT DAMAGE

Not only the ballistic resistance, but also the impact damage behavior are decisive factors for the quality of a material for multi-hit capable armor. Figure 4 illustrates the impact damage in the cermet tiles under similar conditions. The photograph on the upper left side shows a specimen of the reference ceramic after perforation. The dimensions of the reference ceramic plate were 180 x 180 mm in contrast to the cormet specimens, which were 100 x 100 mm. The pictures show that impact damage in Cermet 1 is very similar to the reference ceramic, or even worse.


$Al_2O_3$-92%


Cermet 1


Cermet 2

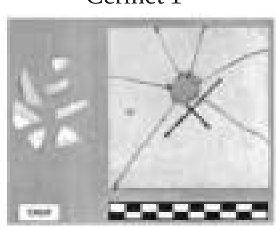

Cermet 3

Figure 4. Comparison of impact damage in cermets and reference ceramic.

However, a significant reduction of damage can be recognized with the Cermets 2 and 3. Only six radial cracks were formed, probably due to bending of the cermets in a late phase of the perforation. While Cermert 2 still exhibits a fairly large zone (maximum diameter ≈ 40 mm) where the ceramic material is completely fragmented, Cermet 3 exhibits a perforation crater of about 15 mm diameter and a zone of about 40 mm diameter where fragments broke off the rear side of the cermet. This is demonstrated in Figure 5, which shows the backside of the Cermet 3 specimen. In the DOP-tests the diameter of the crater in the cermet was reduced to the diameter of the projectile's steel core at the bottom, as the photographs of the front and back side of a cermet 3 specimen in Figure 6 show.

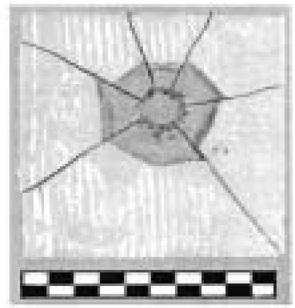


Figure 5: Backside of perforated Cermet 3.

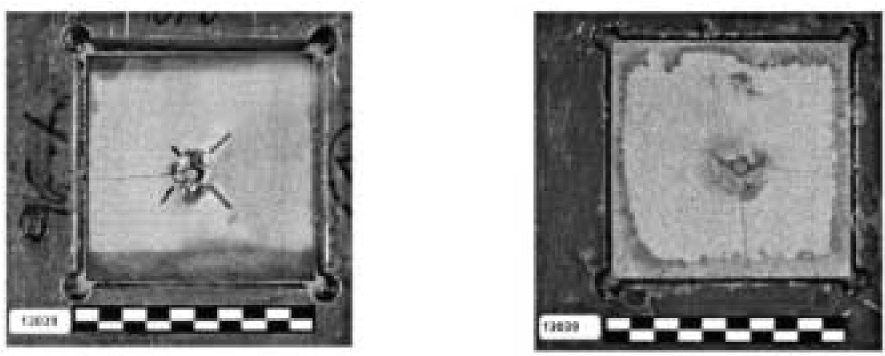


Figure 6: Impact side (left) and back side (right) of a Cermet 3 specimen in a DOP configuration.

## EDGE-ON IMPACT TESTS

In order to examine the fracture behavior of the cermets Edge-On Impact test (EOI-tests) were conducted. The EOI-test is designed for the visualization of fracture propagation during impact in ceramics. [4]. In the EOI-test one edge of the ceramic specimen of typical dimensions 100 mm x 100 mm x 10 mm is impacted by a steel cylinder and fracture propagation is observed by means of a Cranz Schardin high-speed camera. The EOI-technique has been applied to many types of monolithic ceramics which have been characterized by their macroscopic damage patterns, damage velocities (crack front velocities) and single crack velocities as a function of impact velocity. The EOI-technique has also been successfully employed for the evaluation of damage models [5, 6].

Different types of alumina have been examined in EOI-tests before [7]. With almost all tested alumina a steep rise of the damage velocity $v_D$ in the range of impact velocities from 20 m/s to 200 m/s was followed by a flat part of the $v_D$-$v_P$-curve, where $v_D$ only slowly increased with impact velocity. The maximum damage velocities observed extended from 75% to 90% of the longitudinal wave velocity $c_L$, which is typically in the range from 9500 m/s to 10500 m/s for that class of materials.

## Phenomenology with Cermets

In this study Cermet 1 was tested by means of the EOI-technique. As the micrograph in Figure 1 reveals, the ceramic grains of that material are partially surrounded by aluminum. Ultrasonic wave speed measurements yielded a longitudinal wave velocity $c_L$ = 5060 m/s, which indicates that wave propagation is dominated by the metallic phase. This result was confirmed by first EOI-tests at impact velocities of about 600 m/s [8]. Those tests yielded on one hand damage velocities of ≈ 4200 m/s (≈ 80% of $c_L$) and on the other hand a significant delay in the onset of fracture. During the first 20 µs after impact only a wave could be observed which propagated at a velocity of 1154 m/s. In recent experiments at higher impact velocities ($v_P$ > 700 m/s) neither a delay in the onset of fracture nor wave propagation was observed. Figure 7 shows a selection of 12 high-speed photographs from a test at $v_P$ = 724 m/s. It is remarkable that the initial cracks in the cermet plate, which can be recognized across the specimen, had no influence on the dynamic fracture propagation.

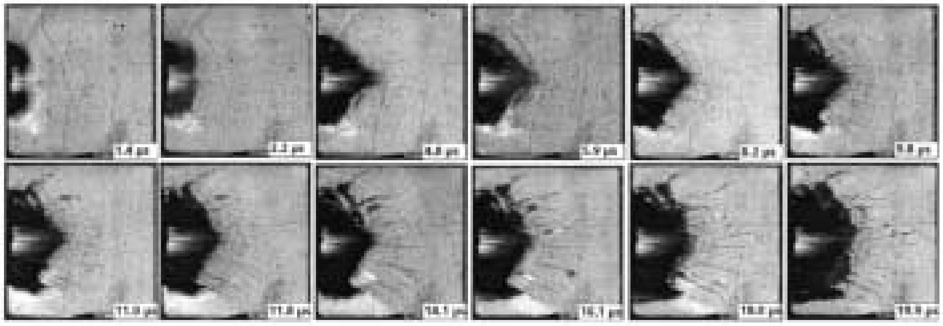


Figure 7: Selection of high-speed photographs from EOI-test with Cermet 1 at $v_P$ = 724 m/s.

## CONCLUSION

For an evaluation of the results different aspects have to be considered. Two opposing requirements have to be met with a material capable of defeating multiple projectile impact: Hardness and strength should be sufficiently high for a good ballistic performance against AP projectiles and the ductility should be high enough to prevent severe fracture formation. Thus the solution will be a compromise. In order to obtain multi-hit capability a reduction in ballistic performance can probably not be avoided. The crucial point is the appropriate adjustment of the material properties, especially the volume fractions of the materials and the architecture of the ceramic phase. Two important conclusions can be drawn from the experiments:

1. In order to obtain a ballistic performance of the order of magnitude achieved with monolithic ceramics, the ceramic volume fraction of the cermet has to exceed 70 % significantly.
2. A continuous ceramic structure causes a fracture behavior similar to monolithic ceramic. In order to reduce impact damage a ceramic structure of densely packed, but isolated grains should be selected.

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