LONG ROD DEPTH-OF-PENETRATION RESULTS FOR TWO GRADES OF COLD-PRESSED SILICON CARBIDE CERAMICS WITH AND WITHOUT HIGH PRESSURE DENSIFICATION

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Two different grades of cold-pressed silicon carbide ceramics were investigated with respect to their ballistic protection performance against long rod penetrators with the depth-of-penetration (DOP) method. The results were compared to those for a grade of hot-pressed silicon carbide developed for armor applications.

The first grade is a pressureless sintered, single-phase silicon carbide material, characterized by a high hardness. The second grade is a liquid-phase sintered material. Additional sintering aids and applying gas pressure at the end of the sintering cycle lead to improved mechanical strength and toughness, but also a slightly reduced hardness.

The DOP results in dependence of the areal density indicate that the aforementioned improvements in material quality do not result in better ballistic protection properties. The pressureless sintered grade comes closer to the ballistic performance of hot-pressed silicon carbide.

INTRODUCTION

Ceramic materials for ballistic applications combine high hardness with relatively low density. In order to save weight in armor applications, the ballistic protection properties of these ceramics have been investigated since decades. For a recent overview, see [1,2]. The hardness of silicon carbides is only exceeded by the hardness of diamond, cubic boron nitride and boron carbide. Due to amorphization of boron carbide at high pressures [3,4], silicon carbides are an excellent choice to design armor against threats at high impact velocities [5,6].

In this paper long rod DOP results of a test series with two grades of cold-pressed silicon carbides are presented. These two grades are produced by cold-pressing of powder and subsequent pressureless high-temperature sintering. The second grade in addition is densified with gas pressure at the end of the sintering cycle. The cold-pressed ceramics have been developed for civil applications.

The intention of the test series was to evaluate the ballistic protection efficiency of these alternative materials against kinetic energy penetrators. For comparison a hot-pressed silicon carbide was also included in the test series and the differential mass efficiency factors of the three materials were determined for different tile compositions.

MATERIALS

The mechanical properties of the tested ceramics are listed in Table 1 and indicate the high Knoop hardness values up to 24.5 GPa. The microstructure of the cold-pressed grades is shown in Figure 1.

Grade A is a single phase silicon carbide, containing only small amounts of doping (boron) and impurities. It is characterized by a high hardness, good thermal conductivity, resistance to high temperatures and to corrosion, and an excellent thermal shock resistance. Typical applications are mechanical seals, sliding bearings, valves, nozzles and uses in heat exchangers. It is the most inexpensive of the tested ceramics.

The production process of grade B, based on a different powder composition containing oxidic sintering aids with aluminium and yttrium, is initially similar to grade A. The second step of liquid phase sintering and applying gas pressure at the end of the sintering process improves the flexural strength and toughness of the material and leads to a dense and fine-grained microstructure. Applications are rotary valves, gas sealing rings, and miniaturized components.

The hot-pressed silicon carbide (grade C) is manufactured by pressure assisted densification, which means simultaneous appliance of high temperature and mechanical pressure. In grade C a very high hardness and flexural strength are combined. Applications are in the field of ballistic protection.

An advantage of the processing with cold-pressing is that it is also economic for small and complex geometries, whereas the pressure-assisted densification is well suited for the production of relatively large components.

Table 1: Material properties of the tested ceramics.

	Grade A	**Grade B**	**Grade C** [#]
Processing	cold-pressed	cold-pressed high pressure densification	pressure assisted densification
Density [g/cm³]	3.15	3.25	3.20
Percentage of maximum density	> 98	> 99	> 99.5
Average grain size [μm]	5	1-2	3-5
Flexural Strength [MPa]	400	550	580
Young's Modulus [GPa]	410	420	460
Fracture Toughness [MPa·m$^{0.5}$]	4	6	4.4
Hardness Knoop HK 0.1 [GPa]	24.5	21.0	23.5[*]

[#] material properties taken from [7]

[*] Hardness Knoop HK 0.3 – no direct comparison with HK 0.1 possible

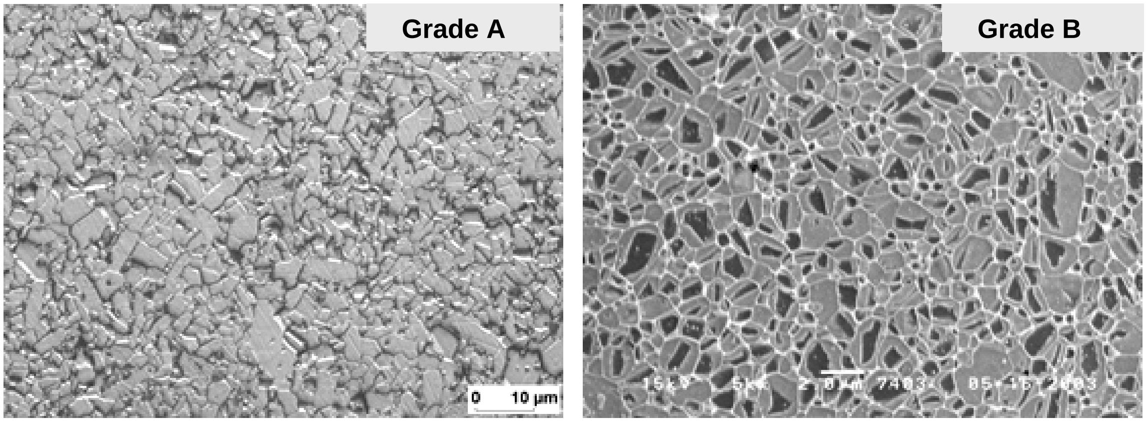

Figure 1: Microstructure of the cold-pressed silicon carbides (ESK Ceramics).

EXPERIMENTAL SET-UP

The ceramic targets were composed of tiles with lateral dimensions of 100 mm x 100 mm and variable thicknesses. As backing semi-infinite rolled homogeneous armor (RHA) with a hardness of 341 HV20 was used. The targets were laterally confined and set up by layering the ceramic tiles without any intermediate layer to total thicknesses between 10 und 50 mm. A schematic drawing of the target arrangement is shown in Figure 2.

Long rod penetrators with a length of 100 mm and a diameter of 5 mm were used as projectiles. The penetrator material was tungsten-sinter-alloy (WSA) with the following properties: density 17.6 g/cm^3, hardness 432 HV10, ultimate tensile strength 1370 N/mm^2 and ultimate strain 11%. The projectiles were launched by a two-stage light-gas gun at Fraunhofer EMI with discarding sabot technique. The projectiles are shot normally at the targets with an impact velocity of 1600 m/s.

Flash x-ray systems are used to determine the impact velocity with a relative accuracy better than $3 \cdot 10^{-3}$ and to measure the yaw angles of the projectile in front of the target.

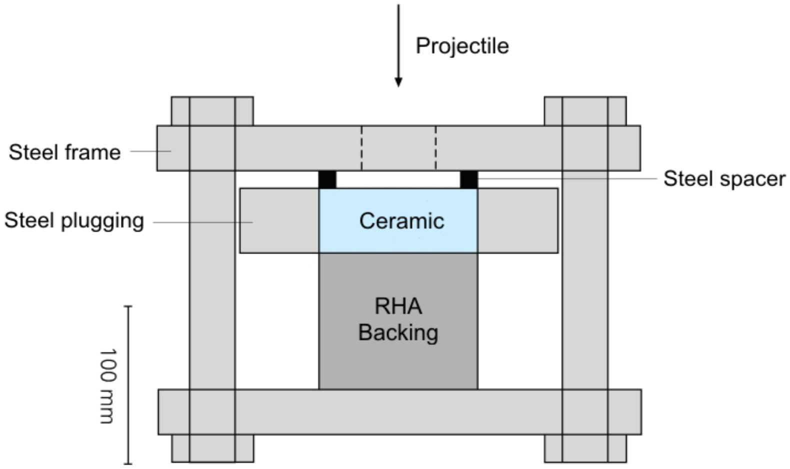

Figure 2: Schematic drawing of the target arrangement (side view).

RESULTS

Table 2 summarizes the results of the DOP-tests. Additional data of tests against semi-infinite RHA is used to calculate the reference penetration in semi-infinite RHA. A linear behavior is assumed in this velocity range. The residual penetration into the RHA backing is plotted against the areal density $\rho_{F,Cer}$ (= density · thickness) of the ceramics in Figure 3. Because of the limited number of experiments no distinction is made between single plate targets and layered targets.

Table 2: Test results and calculated reference penetration in semi-infinite RHA.

Material	Tiles, No. x Thickness [mm]	Areal Density [kg/m²]	Impact Velocity [m/s]	Yaw Angle Hor. /Vert. [°]	Reference Penetration in Semi-infinite RHA [mm]	Residual Penetration [mm]	E_{Diff}
Grade A	1 x 12.5	39.4	1606	-0.5 / -1.8	78.9	64.3	2.9
Grade A	1 x 12.5	39.4	1603	0.2 / 0.9	78.6	63.1	3.1
Grade A	2 x 12.5	78.8	1601	0.8 / -1.8	78.4	52.4	2.6
Grade A	2 x 12.5	78.8	1579	-1.7 / 0.3	76.3	48.9	2.7
Grade A	3 x 12.5	118.1	1638	-0.2 / -0.4	81.9	41.0	2.7
Grade A	3 x 12.5	118.1	1593	1.3 / -0.6	77.7	33.3	2.9
Grade A	4 x 12.5	157.5	1603	1.0 / 0.1	78.6	29.5	2.4
Grade A	4 x 12.5	157.5	1616	0.9 / -0.7	79.8	15.2	3.2
Grade B	1 x 12.5	40.6	1648	-1.4 / -0.6	82.9	70.8	2.3
Grade B	1 x 12.5	40.6	1587	-0.2 / 0.6	77.1	63.3	2.7
Grade B	2 x 12.5	81.3	1613	0.5 / -1.7	79.6	44.4	3.4
Grade B	2 x 12.5	81.3	1580	1.1 / 1.9	76.4	50.3	2.5
Grade B	1 x 30	97.5	1619	-0.1 / -0.1	80.1	46.2	2.7
Grade B	1 x 30	97.5	1606	0.8 / 0.5	78.9	43.9	2.8
Grade B	3 x 12.5	121.9	1650	- / -	83.1	49.0	2.2
Grade B	1 x 40	130.0	1612	-1.6 / 0.2	79.5	42.1	2.3
Grade B	1 x 40	130.0	1603	-1.4 / 1.6	78.6	42.7	2.2
Grade B	1 x 40	130.0	1619	1.1 / -1.1	80.1	40.3	2.4
Grade B	4 x 12.5	162.5	1602	-1.0 / -0.8	78.5	30.6	2.3
Grade B	4 x 12.5	162.5	1586	- / -	77.0	28.6	2.3
Grade C	1 x 10	32.0	1604	0.2 / 0.3	78.7	64.4	3.5
Grade C	2 x 10	64.0	1610	-0.7 / 0.3	79.3	53.7	3.1
Grade C	1 x 20	64.0	1593	0.1 / 0.5	77.7	48.4	3.6
Grade C	1 x 20	64.0	1612	- / -	79.5	45.0	4.2
Grade C	3 x 10	96.0	1610	0.0 / 0.5	79.3	27.0	4.3
Grade C	3 x 10	96.0	1596	0.3 / -0.5	77.9	37.9	3.3
Grade C	4 x 10	128.0	1597	-0.1 / 0.0	79.5	27.1	3.1
Grade C	5 x 10	160.0	1597	0.1 / -0.1	78.0	9.1	3.4
Grade C	1 x 50	160.0	1590	- / -	77.4	32.5	2.2
Grade C	1 x 50	160.0	1619	1.1 / -1.1	80.1	17.6	3.1

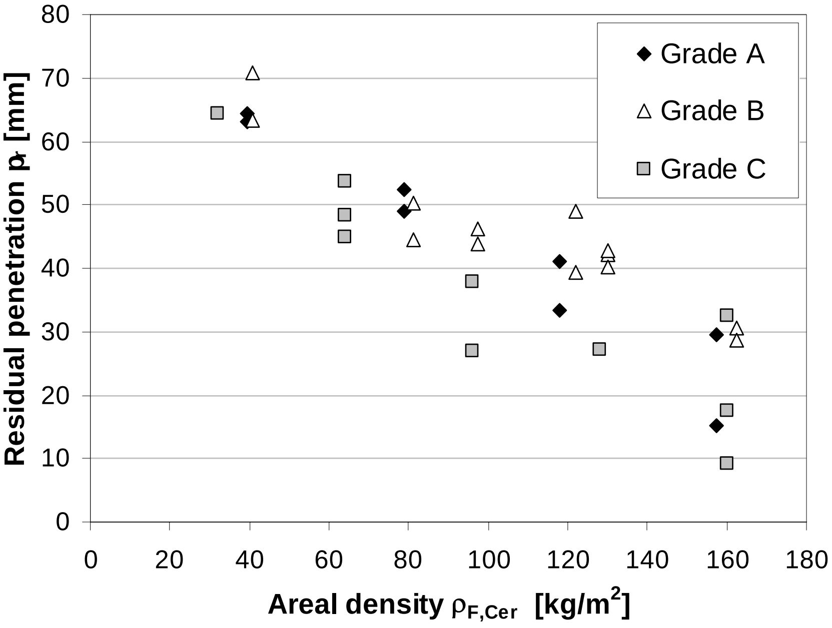

Figure 3: Residual penetration in RHA in dependence of the areal density of the ceramics.

The residual penetration is lowest for hot-pressed silicon carbide, followed by grade A. A quantitative measure for evaluating the protection properties is the differential ballistic mass efficiency,

$$E_{Diff} = \frac{\rho_{RHA}(p_{ref} - p_r)}{\rho_{F,Cer}} \quad , \tag{1}$$

where ρ_{RHA} denotes the density of the RHA, $\rho_{F,Cer}$ the areal density of the ceramics, p_r the residual penetration, and p_{ref} the penetration into the reference target of semi-infinite RHA. For each test p_{ref} is interpolated in order to take account of errors due to the scattering of the impact velocity. The quantity E_{Diff} compares the areal density of the layer of ceramics to that of a reference target (here RHA) with the same protection effect. The experimental results for the average differential mass efficiencies E_{Diff} of the different grades are as follows:

Grade A	2.8 ± 0.3
Grade B	2.5 ± 0.3
Grade C	3.4 ± 0.6

DISCUSSION

The results for E_{Diff} indicate that the improvements in flexural strength, fracture toughness and fine-grained microstructure for the cold-pressed silicon carbide do not result in a better ballistic protection. It is grade A, the ceramic without high pressure densification, but higher hardness, which shows the better ballistic performance in the DOP arrangement.

In the target arrangement confinement is used on the rear and the lateral sides. Thus the influence of the flexural strength and the fracture toughness on the penetration process is reduced whereas hardness and compressive strength are important.

In comparison to the hot-pressed silicon carbide, grade A results in 84% of the ballistic mass efficiency.

Although the comparison of the hardness values is limited due to different measurement methods of the manufacturers, other results of hardness measurements [8] point into the direction that the hot-pressed silicon carbide is harder than the cold-pressed grades.

SUMMARY

Two grades of cold-pressed silicon carbides, which have been developed for civil applications, were investigated with respect to their ballistic protection performance against long rod penetration with the DOP method. An advantage of the production process with cold-pressing is that it is also economic for small and complex geometries.

The mean differential mass efficiencies E_{Diff} are 2.5 ± 0.3 for the grade manufactured with high pressure densification and 2.8 ± 0.3 for the grade without. Accordingly, the improvements in flexural strength and toughness do not lead to a better ballistic performance. These values of E_{Diff} above compare to 3.4 ± 0.6 for a hot-pressed silicon carbide well-known in the armor market. The results confirm the correlation of ceramic hardness with ballistic protection performance in the used target arrangement.

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