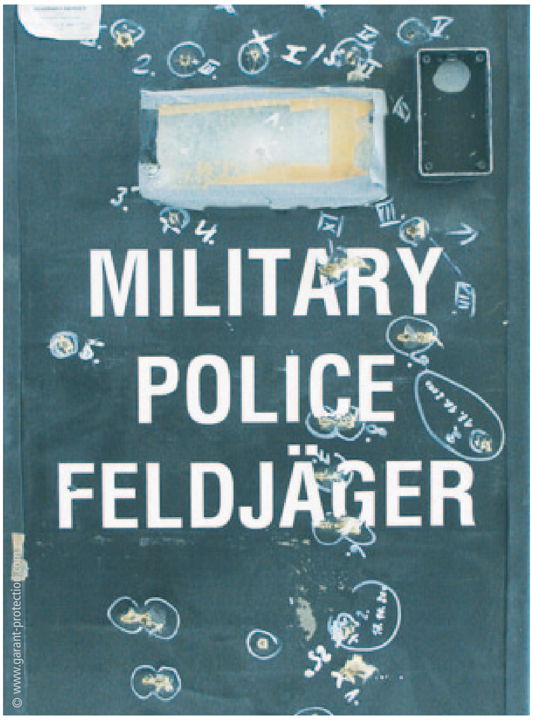
Ceramic materials for light-weight ceramic polymer amor systems

CeramTec
CeramTec-ETEC GmbH

LIGHT-WEIGHT CERAMIC ARMOR



The world has changed. Military and Security forces worldwide have been forced to adapt to new domestic and international terror threats and to the increased tempo of combat deployments in hostile territory.

Vehicles designed for a traditional land conflict are often lightly or inadequately protected from asymmetric threats such as Improvised Explosive Devices (IED's) and Explosively Formed Projectiles (EFP's) which are encountered with alarming frequency by troops on operations.

National sensitivities to casualties and strained defence budgets force engineers to continually adapt existing vehicle platforms to these constantly changing threats. The challenge to offer the highest level of protection with the lowest possible weight is a constant battle of material science, integration technologies and physics. These systems must protect from a range of threats such as direct gun fire, shaped charges, fragmentation and land mines.

Once soldiers deploy from their protected vehicles they also require lightweight body protection that allows them to operate freely at elevated temperatures and altitudes carrying a full battle load.

Military vehicles have traditionally been manufactured from high strength armor plate steel. Modern ceramic composites have largely replaced steel as the non-structural armor in combat vehicles.

Its major advantage lies in its significantly lower areal weight which allows weight savings of more than 50 per cent over conventional metallic solutions.

The most important ceramic materials today for ballistic protection are:

- Alumina (Al_2O_3)
- Silicon carbide (SiC)
- Boron carbide (BC)

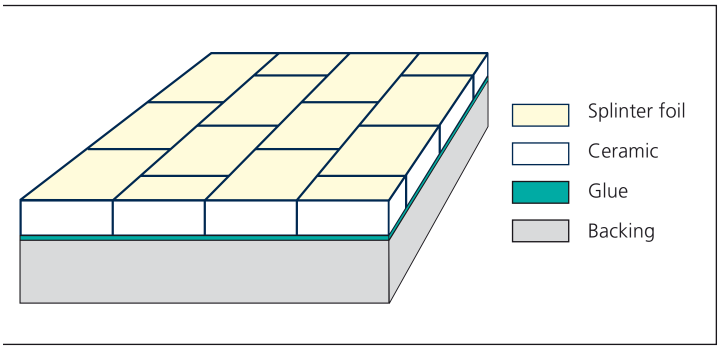
Owing to its excellent price-efficiency ratio, alumina is the preeminent ceramic armor material for vehicular applications. Only when an extremely low weight is required (e.g. for personal protection or for helicopters), silicon and boron carbide materials may be used.

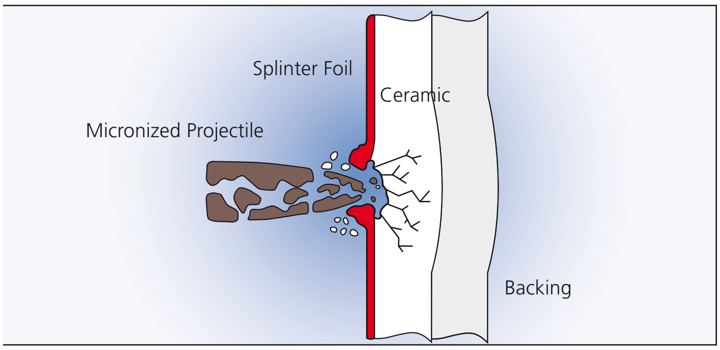
Beside these qualities, other ceramic materials have also been considered and were examined intensively for the purpose of ballistic protection.

- Silicon nitride (SN)
- Titanium boride (TiB_2)
- Aluminium nitride (AlN)
- SIALON (Silicon aluminium oxynitride)
- Fibre-reinforced ceramic (e.g. C-SiC)
- Ceramic-metal composite materials (CMC)

However, and in spite of high ballistic performance, these materials have not been established for technical and economic reasons.

CERAMIC POLYMER ARMOR SYSTEMS





In general, the construction of light-weight composite system is based on four main components:

- Spall foil
- Ceramic
- Composite substrate
- Adhesive

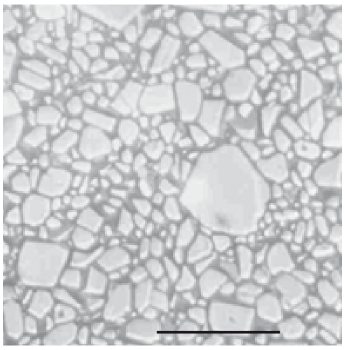
In a composite armor system, the ceramic is normally placed on the strike face, preferably perpendicular to the expected threat. Polymer fibres composed of polyaramide, polyethylene or polypropylene form the composite backing. The stiffening and structural enhancement of the individual polymer layers is achieved by impregnation and subsequent curing of the adhesive. Proper selection of adhesives, such as rubber, polyurethane or epoxies, results in the desired shore hardness, and thereby the required mechanical properties which can be tailored to the threat requirements.

This chemical bond between ceramic and composite substrate and/or between the individual polymer layers is of key significance for the performance of the entire system. In addition, spall protection is applied on the front side of the ceramic – glass fibre laminates are preferably used for this purpose.

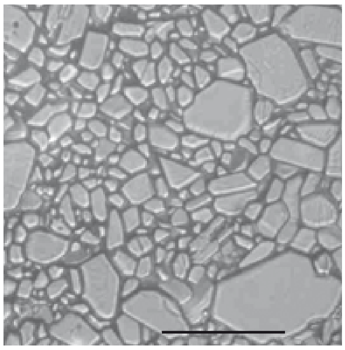
Each component within the composite system has a specific function. The hard ceramic layer reduces the speed of the projectile and micronises the projectile. The resulting low mass and the significantly reduced speed of these residual fragments, is completely absorbed by the elastic/plastic deformation in the composite substrate.

CeramTec-ETEC does not supply complete armor systems. Our expertise is in the manufacture of high-performance ceramic armor materials – cut, drilled and machined to customer specifications, and ready to assemble into protective modules without further work. We do not produce armor systems for sale.

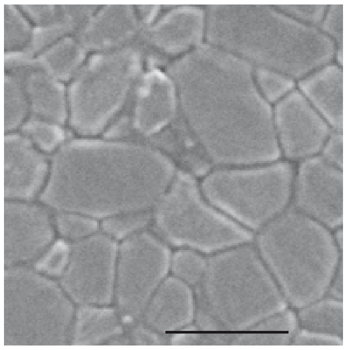
ALUMINA ARMOR MATERIALS



ALOTEC 96 SB 20 µm



ALOTEC 98 SB 20 µm



ALOCOR 100 2 µm

			ALOTEC 96 SB	ALOTEC 98 SB	ALOTEC 99 SB	ALOCOR 100
Density	ρ	g/cm3	3.75	3.80	3.87	> 3.97
Residual Porosity	P	%	< 2	< 2	< 2	< 0.1
Medium Grain Size	D	µm	5	6	10	0.85
Vickers Hardness	HV(5)	GPa	12.5	13.5	15	21
Young's Modulus	E	GPa	310	335	365	405
Bending Strength 4-Point	σ_B	MPa	250	260	280	500
Fracture Toughness	KIc	MPam1/2	3.5	3.5	3.6	4.0
Sound Velocity	v_L	m/s	10000	10200	10300	11000

Alumina Materials

Alumina with an Al_2O_3 content of 96 to 98 mass percentages is still the most important ceramic material in vehicular ballistic protection. It is characterized by good processability and economic volume production and possesses very high mechanical properties.

CeramTec-ETEC supplies the following materials for regular production:

ALOTEC 96 SB

The basis is Bayer alumina with a low alkali content. The Al_2O_3 content is 96 mass percent. Glass forming silicates are used as sintering additives which cause a lowering of the sintering temperature and regulate the grain growth.

ALOTEC 98 SB

Higher rigidity and hardness values are achieved through the reduction of the glass phase. The microstructure is similar to that of ALOTEC 96 SB. The proportion of corundum is slightly higher.

ALOTEC 99 SB

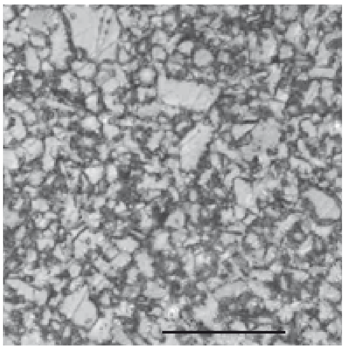
Here, sinter-reactive Bayer alumina is used for production. Induced by the lack of glass-forming substances, consolidation is achieved not by liquid-phase sintering but by solid-state sintering. Uncontrolled grain growth is avoided by adding around 400 ppm of magnesium oxide. The high proportion of corundum enhances the mechanical properties, thus enabling an increase in ballistic efficiency.

ALOCOR 100

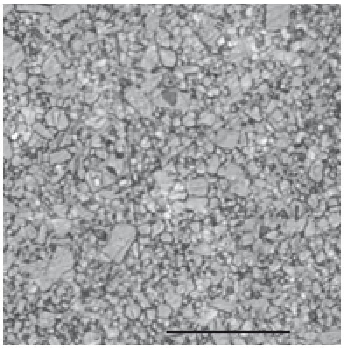
The basis of this material is synthetic, ultrapure corundum with an Al_2O_3 content of above 99.95 per cent. An ultrafine-grained microstructure with grain sizes < 1 µm can be generated by applying a two-step sintering process. This is the prerequisite for the achievement of extremely high mechanical properties and increased ballistic efficiency.

This material was developed by CeramTec-ETEC over several years of intensive research. Currently, prototype production is under way, and commercial production is planned for 2010.

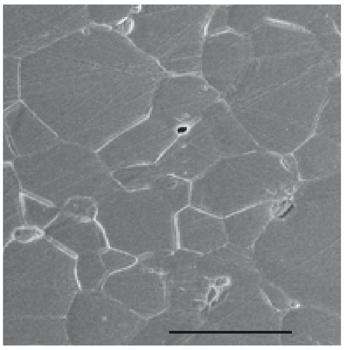
CARBIDE ARMOR MATERIALS



SICADUR F 20 µm



SICADUR T 20 µm



BOCADUR 5 µm

			SICADUR F	SICADUR T	BOCADUR
Density	ρ	g/cm³	3.1	3.21	2.48
Residual Porosity	P	%	< 2.5	< 1.5	0.5
Medium Grain Size	D	µm	< 5	< 2	< 15
Vickers Hardness	HV(5)	GPa	26	22	32
Young's Modulus	E	GPa	410	420	420
Bending Strength 4-Point	σ_B	MPa	400	550	450
Fracture Toughness	K_{Ic}	$MPam^{1/2}$	3.2	5.0	3.0
Sound Velocity	v_L	m/s	12000	12000	

Silicon Carbide and Boron Carbide Materials
Aside from alumina materials which are widely in use today, silicon and boron carbide will be used more frequently in the future where significant weight reduction or increased mechanical properties are required. If carbide materials are selected, it must be taken into account that many diverse qualities are offered, distinguished by the selection of the original powder and production technologies. These parameters have a strong influence on the material microstructure, its physical properties and material cost.

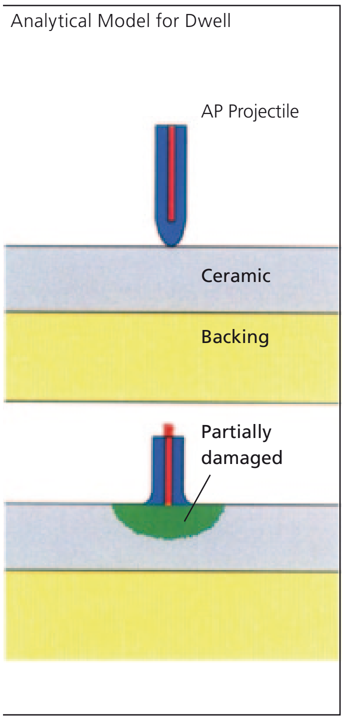
The CeramTec-ETEC material program includes the following carbide materials:

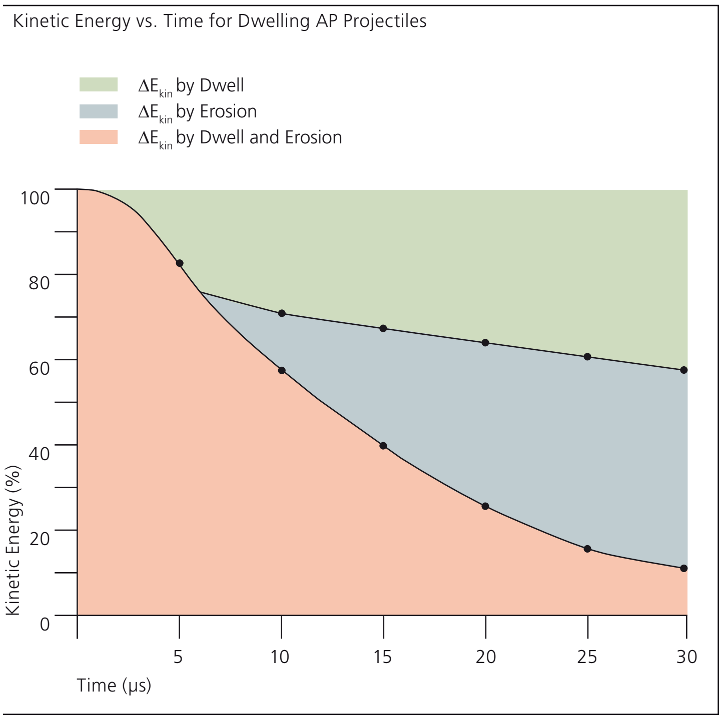
SICADUR® F (SSiC)
SSiC is produced by solid-state-sintering. The sinter additives, boron carbide and carbon, lie at 1 mass %. The material is nearly nonporous; its hardness lies in the range of 25 GPa, though the fracture toughness is slightly lower than that of LPSSiC.

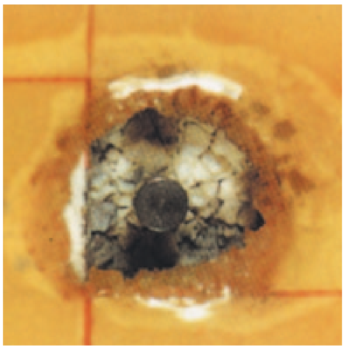
SICADUR® T (LPSSiC)
Liquid-phase-sintered SiC is a highly consolidated material with a density of $\rho = 3.23$ g/cm³ and a fine microstructure. Sinter additives are Al_2O_3 and yttrium oxide in quantities of approx. 10 mass %. The material has high fracture toughness and fracture strength.

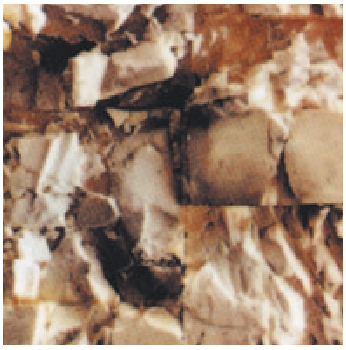
BOCADUR®
Hot-pressed boron carbide is the lightest, hardest, but also most expensive material being used today in series of ballistic protection. The emphasis of its application is on personal protection as inserts for armor vests.

As compared to the above mentioned carbide materials, reaction-bonded silicon carbide (RBSiC) is of little use as a ballistic material. It is very brittle owing to its high proportion of metallic silicium of approximately 10 mass percentages.






Stopped bullet in cracked ceramic


Cracked ceramic caused by fragment fire

Penetration mechanism

The mechanism of reducing the kinetic energy of an armor piercing penetrator can be explained through analysis of flash X-ray data.

When the projectile impacts the surface of the ceramic, its kinetic energy is greatly reduced without penetrating the ceramic. This is caused by the dwell effect. In that phase the projectile experiences a highly ductile deformation. After approx. 15 to 20 µs, the projectile actually penetrates the ceramic body, and in the process the kinetic energy of the projectile is reduced further by erosion. The shattered fragments of the projectile completely penetrate the ceramic after approx. 30 µs. The residual energy of these fragments amounts to only about 15 % which can be fully absorbed by the backing.

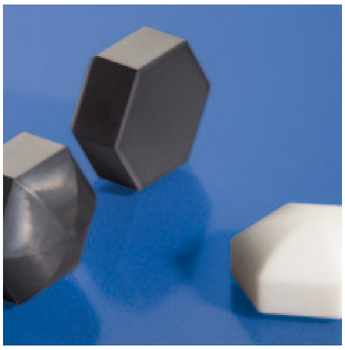
This means:
ΔEK due to dwell is to approximately 35 per cent
ΔEK by erosion is approximately 50 per cent
ΔEK by backing is approximately 15 per cent

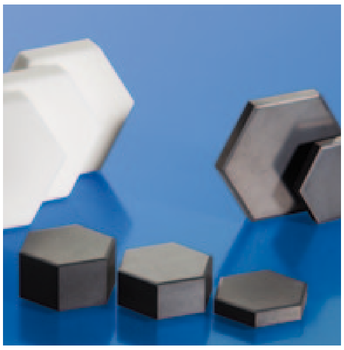
(The ΔEK values due to dwell are material-specific).

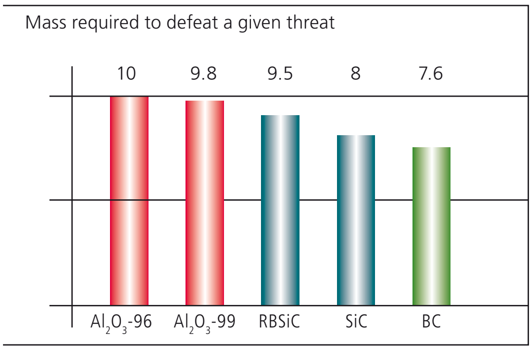
Selection of Materials

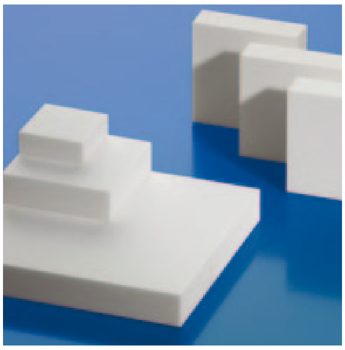
The mechanical properties of the ceramic materials are the single greatest consideration for high ballistic efficiency. Ceramics used in armor systems must demonstrate a defined microstructure with high grain size stability combined with high homogeneity. In spite of significant scientific investigations, it has not yet been possible to establish an exact relationship between ceramic properties and ballistic efficiency. However, it is indisputable that high hardness and high sonic velocity are necessary for ballistic efficiency. High modulus of elasticity and high relative density are the prerequisites for high sonic velocity. It is not yet understood what part mechanical strength (pressure, bend and shear resistance) and fracture resistance play in the overall performance of the ceramic as compared to other properties in a ballistic event.

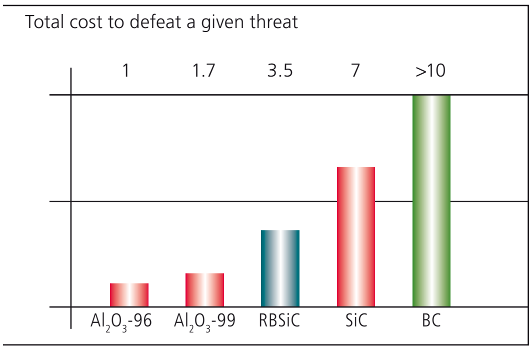
The same is valid for the fluidity of ceramic at high compressive loads. This implies that extensive ballistic testing by the system designer is mandatory to determine the correct ceramic material in conjunction with the most appropriate backing or substrate. A comparison of different protection materials and/or of different material qualities is possible by means of the DOP (depth of penetration)* test for the determination of ballistic mass efficiency. The DOP* test is merely a tool to aid in the selection of ceramic in ceramic-polymer composite systems; rather, tests with the complete composite system must be conducted for final determination.











Ceramic Materials

The aim of every system development must be to find the lowest weight and most cost-effective solution for a specified threat. Smaller structural shapes like cylinders and hexagons may be used for countering direct gun fire – especially for high multi-hit threats. On the other hand, larger components are advantageous for protection against fragments and IEDs. The thickness of the ceramic components depends on the specified threat level and can vary, but is normally between 4 and 25 mm.

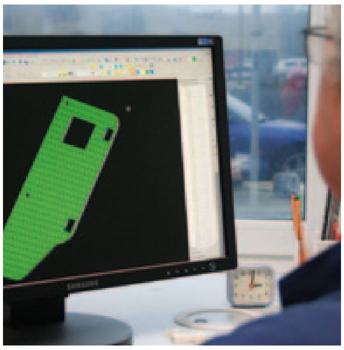
Weight reduction strategies:

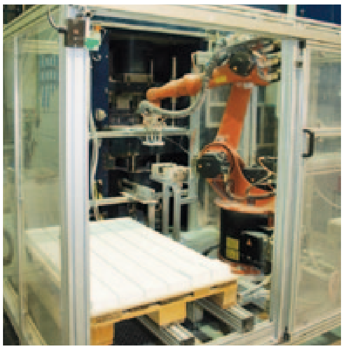
- A reduction of the ceramic thickness
- A revised composite backing system to account for a modified ceramic thickness
- Replacement of the composite backing system with a lighter or higher performance material
- The use of ceramic materials with high ballistic efficiency and low material density

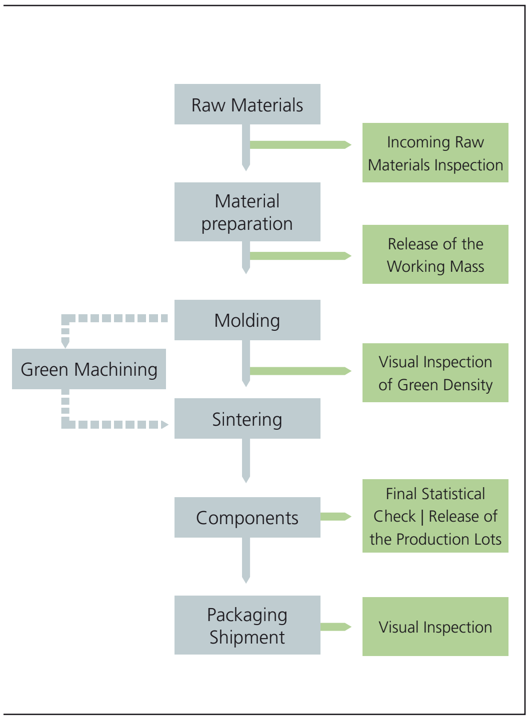
The first two strategies result in only minor weight reduction – if the composite is of the same family with similar density. Complete replacement of the backing material can provide significant advantages, for instance by the use of functionally graded materials.

Since the ceramic component is the major player in system weight, the selection of a different material quality is often the only solution. If, for instance, Al_2O_3 is replaced by SiC, a reduction of system weight is possible. However, this is associated with a corresponding and significant increase in cost.

CERAMIC PRODUCTION TECHNOLOGY







The ceramic production process is fundamentally different from other conventional technologies such as metals, glass and polymers. After the raw material synthesis and formulation the material is pressed into the desired shape and thickness. CeramTec-ETEC presses armour tiles with multiple uniaxial high tonnage presses. The pressed green bodies are then stacked for the sintering process or transferred to the mechanical finishing area.

Ceramic materials require sintering in high temperature kilns where the ceramic microstructure is formed by consolidation of the original powder. The characteristic properties of the ceramic are created by the sintering process at temperatures of 1600° C for alumina, and more than 1900° C for carbide materials. This process is associated with a distinct reduction in the dimensions of the preshaped component. The loss in general dimensions is about 15 to 20 per cent and the volume loss is about 50 per cent.

The finishing of materials and/or components by means of remelting, post curing, reshaping – as is usual in the case of metals – is not possible in the case of ceramics.

Mechanical finishing of the ceramic components is expensive since only diamond cutting tools are used for this purpose. The production of specially shaped components (e.g. edge plates) takes place prior to the sintering process in the so-called green stage, by sawing, cutting, milling and drilling.

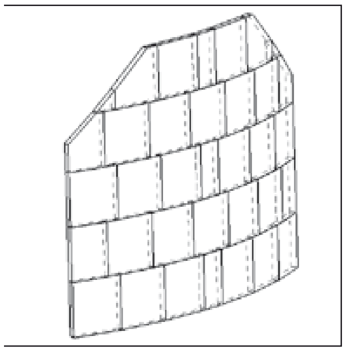
Each process step influences the properties of the final ceramic component. Errors that have occurred during a previous process step cannot be rectified through subsequent processes. A stringent Quality Assurance process is rigidly followed throughout all phases of production.

Ceramic technology permits the production of a large variety of different components. In commercial production, pressing tools for the most diverse shapes and dimensions are used.

Consistent product quality is guaranteed by cooperation with highly respected and experienced raw material producers, by the use of modern production technologies and by a mature Quality Assurance System (according to DIN ISO 9001.2008 standard).

As an additional service to its customers, CeramTec-ETEC offers ceramic CAD engineering of the tile matrix layout for armor panels. Furthermore, preassembling of the armor panels has proved to be a major labor saving exercise for many of our customers. These pre-assembled panels can be directly inserted into the production process for the composite assembly.

BODY PROTECTION



Conventional soft armor protection vests provide protection from smaller calibers such as hand guns and submachine guns; however they have inadequate protection from larger rounds fired by service rifles. According to the type of construction the vests can be upgraded by inserting rigid polyaramid fiber plates as protection against hand guns, or by ceramic composites plates against rifle fire. The requirements of the upper protection levels can be met by using ceramic-composite inserts, e.g. DIN 52290 level 4 and 5, NIJ Standard level III and IV, European Standard level B5, B6 and B7.

Today, ceramic monolithic plates are used as inserts for armor vests. They can be shaped to accommodate male and female body shapes by using a multi-curved shape which provides additional comfort to the wearer. Depending on the requirements of the individual protection levels, the plate thickness can vary accordingly.

CeramTec-ETEC supplies a number of standard plates ranging from flat or single curved to multi curved shapes. Thanks to the variety of production technology for ceramic materials, it is also possible to produce designs according to customer's specifications. The multi-hit resistance can be improved by utilizing new composite systems.

In addition to monolithic inserts, CeramTec-ETEC supplies inserts based on single curved ceramic tiles with radii between 200 and 400 mm. They consist of small standard tiles 50 x 50 mm, providing an improved multi-hit protection. For special applications it is also possible to produce customized layouts and sizes.

CERAMICS FOR VEHICLE PROTECTION

Fox

ASV (M 1117)

VAB


Dingo

YAK

Fennek

Piranha

Boxer

Puma

Faun

Mungo

Tanker

AMPV

Police car

Toyota

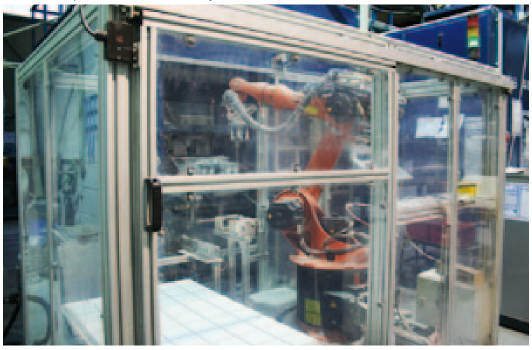
T45


Container

NH 90

CeramTec-ETEC Lohmar Germany


Modern production facility



Ceramic Experience Worldwide

CeramTec-ETEC is an integral part of CeramTec AG since November 2008, and is one of the most important suppliers of solutions for industrial wear and corrosion protection and for armor components worldwide.

More than 25 years of experience in the field of ceramic production, modern plants and equipment and a world-wide distribution network enable CeramTec-ETEC to produce a variety of different components with high dimensional accuracy.

Made in Germany

CeramTec-ETEC employs a highly skilled team of ceramic material specialists and experienced technicians, in a production plant equipped with the latest equipment including full CAD engineering, advanced quality assurance equipment and high-tech production machinery.

In this way, it is possible to guarantee the production of high-quality products to extremely tight tolerances with en serial scale. By means of a highly sophisticated quality assurance system – certified according to ISO 9001 – it is possible to ensure the production and supply of products with a continuously high quality, thus enabling CeramTec-ETEC to comply with the high standards required by our customers.

CeramTec
CeramTec-ETEC GmbH

CeramTec-ETEC GmbH
An der Burg Sülz 17
53797 Lohmar
Germany

Phone: +49 2205 9200-0
Fax: +49 2205 9200-144
info@etec-ceramics.de
www.etec-ceramics.com

Indexes and parameters for ceramic substances: In order to profile ceramic substances certain parameters are indicated. The crystalline nature of these substances, statistical fluctuations in the composition of the substances and in the factors that impact on the production processes indicate that the figures quoted are typically mean values and hence the substance parameters quoted in this brochure are only standard, recommended or guide values that might differ given dissimilar dimensions and production processes.

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