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A new promising joining technology

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This paper describes a very successful new method for laser welding of ceramics. Two beam laser welding technology, an additive free procedure, allows one to create joints, e.g. of alumina parts, which have a strength of 85% of the original material. It enables one to join parts of various shapes in only a few minutes without furnaces and in a natural atmosphere. The results achieved as well as the advantages of laser material processing like small welding seams, high flexibility, high productivity and a high degree of automation make this technology ideally suited for industrial application. Applications based on this technology are expected in several branches of technology, for instance for welding tubes or sensor elements, for the protection of electronic components against high temperatures, abrasion and/ or chemical attack.

Key words: joining, welding, gluing, shaping, ceramics, alumina.

Introduction

Ceramics are materials usually produced by a special sintering process. Depending on the composition this leads to properties such as high temperature resistance, extremely high hardness, low electrical conductivity and high thermal insulation, high chemical resistance and a lower density, compared with metals. These excellent properties are the reason for applying technical ceramics in the wide fields of electronics, automotive and chemical industries.

Currently there is no technology which produces joints of satisfactory quality between ceramic parts, preserving the excellent properties of the material.

Brazing and adhesive bonding reduce the thermal and chemical stability of the system. These disadvantages are based on an additional material (glue or solder) with completely different mechanical, chemical and thermal properties than those of ceramics. This means a critical weak point is generated at the joint. Furthermore, brazing is usually only possible after metallisation of the ceramics to improve their wettability. This process needs time and is very expensive. A very good quality joint, for example, can be achie- ved by diffusion welding. The joining mechanism is based on diffusion processes at high temperatures. This means diffusion welding needs a long processing time of about one hour. The preparation of the material is very expensive (requires a high quality surface) and a high bearing pressure is necessary (Therefore it is not suitable for joining small parts.). In addition, diffusion welding and brazing both make a vacuum atmosphere necessary.

Our presentation will demonstrate that the limits mentioned above may be overcome by a technique using two laser beams. For the first time it is now possible to produce geometries previously not practicable.

Further development of this technology will lead to an enormous expansion of the application of ceramics.

Experimental Procedures

Alumina (α-Al_2O_3) substrates of 96.0% purity and a medium grain size of 3 μm were used in our experiments. The substrates were 30 mm long and 10 mm wide, their thickness varied between 0.7 mm and 1.2 mm.

Because of the very low thermal shock resistance of alumina, a short local energy input by the laser beam will lead to cracks in the material. Thus the material has to be heated to minimise the thermal shock effect of the welding laser beam. To overcome the disadvantages of preheating in a furnace, we are employing a second laser beam (Fig. 1).

This 600 W CO_2-laser beam scans across the surface of the material at a speed of about 1 ms^{-1}. Because of the very high absorption coefficient of the wavelength of 10.6 μm, the material gets heated in seconds.

The surface temperature of the parts is measured continuously by a pyrometer. An emission value of 0.75 was used for measuring. The power of the preheating laser is automatically adjusted to maintain the desired temperature. When the necessary preheating temperature is achieved the 1.2 kW Nd: YAG laser beam welds the parts together. It penetrates about 0.8 mm deep into the material. This means that for such a low thickness the generation of a welding bath

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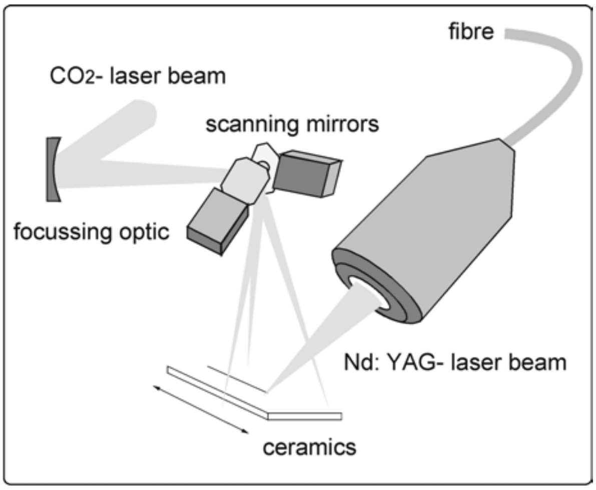


Fig. 1. Experimental setup used for laser welding of ceramics.

is nearly independent of the thermal conductivity.

In order to optimise the quality of the welding seams and to enhance the strength of the joints, investigations were concentrated mainly on process, preheating and welding parameters.

The surface as well as cross- sections of the welded seams were investigated by optical and scanning electron microscopy (SEM).

The strength of the joint was determined by a 4-point- bending test.

Results

Preheating

Three major problems had to be solved:

1. What minimum preheating temperature is necessary to achieve crackfree joints?
2. What maximum heating and cooling rate are possible?
3. What maximum temperature gradients across the surface are possible?

A locally homogenous preheating across the whole substrate surface was carried out. The welding took place after the final stationary temperature had been achieved, which we varied in steps of 100 K. The joined materials were investigated for cracks. It was found that 100% crackfree joined materials were generated at a preheating temperature of 1500ºC.

However, investigations of cross- sections of the welding seams showed a minimum of porosity at a preheating temperature of 1600ºC. Lower preheating temperatures as well as higher ones increased porosity within the solidified welded seam.

For a cost effective technology the processing time is of special importance. Therefore the time for preheating and cooling was minimised to a degree, which still guaranteed a crackfree result. It was not possible to define a specific heating rate for achieving 1600ºC. A heating rate varying from 20 Ks^{-1} to 30 Ks^{-1} can be used up to a temperature of 1400ºC. The temperature range around 1500ºC is critical as the highest stresses occur there. A hold time permits stress reduction by reorien- tation of the grains. After that the Nd: YAG-welding laser beam can generate crackfree welded parts.

A thermally-influenced cooling of the welded specimens is recommended in the upper temperature range above 1500ºC. Below that temperature, no cracks were produced by normal cooling down in the surrounding air.

For larger pieces lateral homogenous preheating is unsatisfactory because of the long processing time and high energy demand. Therefore maximum temperature gradients in relation to the distance to the welded seam were determined in a one-dimensional direction across the surface. The variation of the energy input was realised by changing the scanning lines of the CO_2-laser beam per area with a maximum concentration at the welded seam. As a result a maximum temperature gradient of 70×10^3 Km^{-1} is possible across the surface. At a distance of more than 20 mm from the weld the temperature is less than 500ºC. Therefore, such pieces can be clamped and moved by conventional methods. In a furnace special and expensive high-temperature-resistant materials would be necessary.

Welding

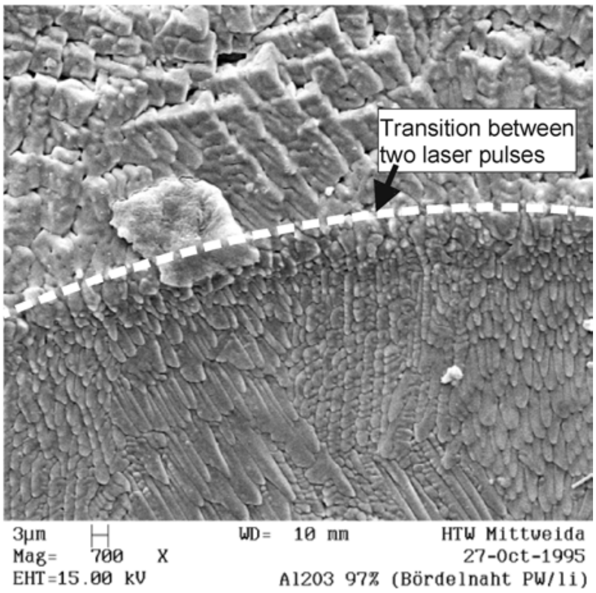
The quality achievable of the joints depends, apart from the wavelength, on four factors in general:

1. the mode of the welding laser beam
2. the focus position of the welding laser beam
3. the power of the laser welding beam
4. the velocity of welding.

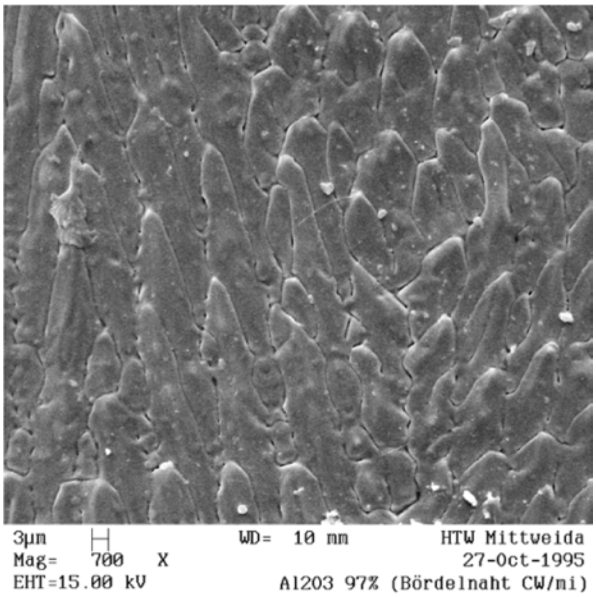
A laser beam can be generated as a continuous beam or as a pulsed beam. Both variants are used in laser material processing. The mode is very important for laser welding of ceramics. In pulsed welding, more power is needed for welding material of the same thickness as it is necessary to compensate for the breaks between the pulses. This affects the temperature distribution in the welded seam as well as the solidification of the welding bath directly. The results are shown in Figs. 2 and 3.

Comparable parameters for welding 0.8 mm thick tiles lead to a different solidification structure. Pulse mode (pm) welded specimens show an inhomogenous solidification of crystals. In the middle of every pulse (here the highest temperature existed) the structure is coarse-grained and friable. The border area of every pulse is characterised by columnar crystals oriented to the middle of every pulse, which are caused by radial temperature gradients within the pulses.

The continuous (cw) laser beam welded specimens show a more homogenous structure. A grain growth of about five times that of the original could be obtained. The structure is dense and approaches that of the

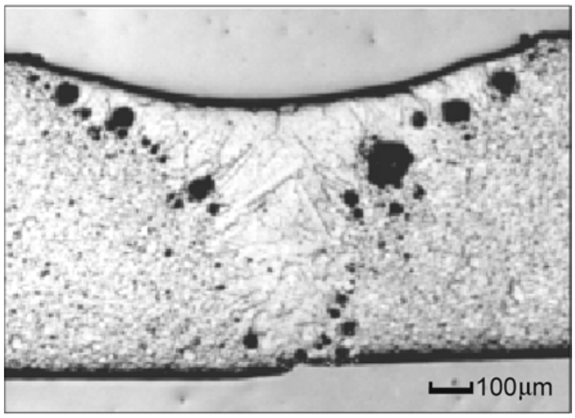


(a) Welded seam generated by a pulsed laser beam

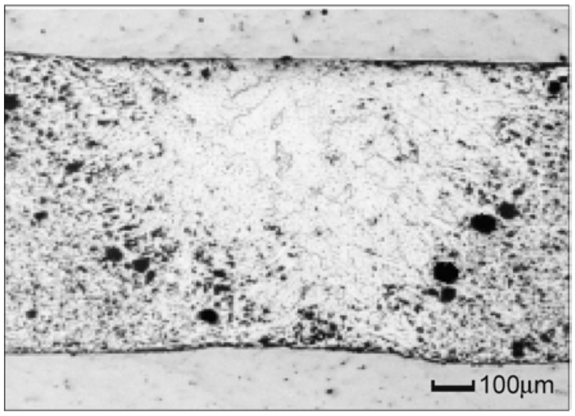


(b) Cw welded seam

Fig. 2. SEM- view of the laser welded surface of the welded seam.



(a) pm welded seam



(b) cw welded seam

Fig. 3. Cross section of laser welded Al_2O_3 (butt welding).

original at the border of the seams.

In addition, Fig. 3 shows the distribution of pores in a cross-section. Pores are mainly located at the sides of the welding bath. They arise from vaporisation of impurities, and/or from agglomeration of pores, existing in the material. Pulsed-welded specimens showed higher porosity than continuously welded seams, probably because of the very high temperatures in the middle of the pulses.

The position of the focus (the point of the highest intensity of a laser beam) influences the solidification of the melt, too. Three cases have been investigated:

1. The focus is positioned above the material surface.

This leads to a flat welded seam of a homogenous solidification.

2. The focus is positioned on the material surface.

The solidified welding bath shows a hemispherical form of a homogenous solidification and distribution of porosity.

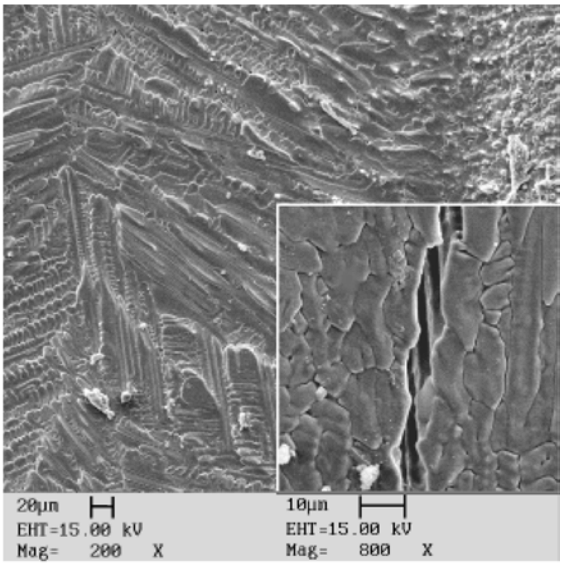
3. The focus is positioned within the material.

This leads to a material densification in the middle of the seam and to very large pores at the borders.

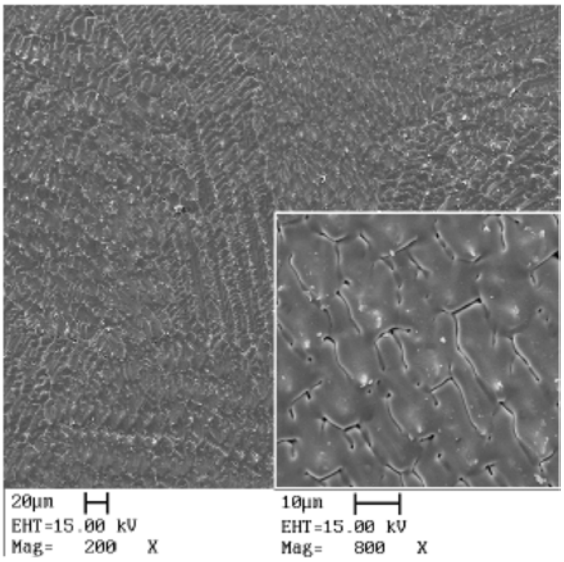
In our opinion the second variant should be favoured.

Laser beam power and welding velocity are related to the path energy. The path energy describes the power-to-velocity ratio. However, a constant path energy at varying power and velocity leads to different solidification structures. For instance, a twofold incre- ase in laser power, and velocity (same path energy) means that only half the time is available for heat transfer processes, mainly for thermal conductivity. The importance of this circumstance is shown in Figs. 4(a), (b) and (c).

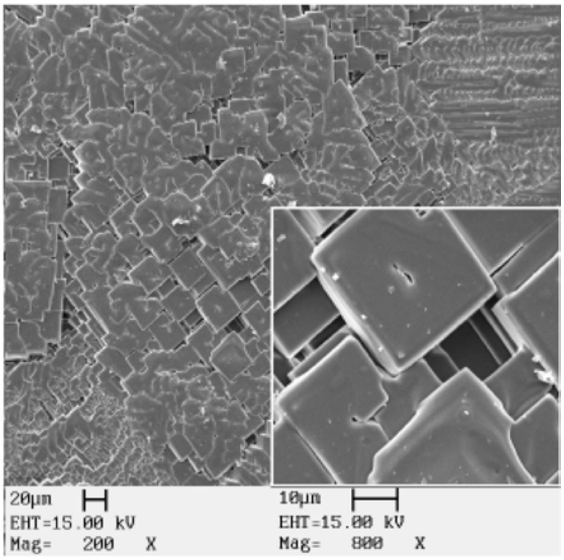
Figure 4(a) shows a typical surface for flat welded seams. There is no root at the underside. Low laser power and a low welding velocity lead to a rapid heat transfer into the base material. A solidification starting from the bath borders leads to the formation of columnar crystals oriented to the centre of the bath. Impurities will be concentrated into the regions melting at



(a) Power : 22 W
Velocity : 0.22 mms^{-1}
Path energy : 100 Jmm^{-1}



(b) Power : 50 W
Velocity : 0.5 mms^{-1}
Path energy : 100 Jmm^{-1}



(c) Power : 100 W
Velocity : 1.0 mms^{-1}
Path energy : 100 Jmm^{-1}

Fig. 4. Surface morphology at constant path energy and varying ratio of power and velocity.

lower temperatures. At the same time a contraction occurs at both solidification fronts and leads to hot cracks which are similar to those found when welding metals.

In Fig. 4(b) a well-balanced ratio between energy input and energy losses due to thermal conductivity allows solidification in a homogenous and nearly isotropic manner. The cross-section of these joints is comparable with those shown in Fig. 3(b). The crystal growth is limited to the threefold value of the original. These joints are also gas-tight.

In Fig. 4(c) the centre of the welding bath is characterised by big grains of up to 100 µm, enclosed by high porosity. This results from high temperatures induced by the high welding velocity and the thereby minimised thermal transfer. Impurities have been mostly vaporised. The borders of the seam show columnar crystals up to a length of 200 µm.

Strength

The strength of the welded specimens was determined by a 4- point-bending method. Two pieces measuring 30 × 7 × 0.8 mm^3 were welded together in a pulsed and a continuous welding mode. The resulting

	σ_o / MPa	σ_{rel} / %
cw-welded specimen	183	85
pm-welded specimen	72	38
unwelded specimen	191	100

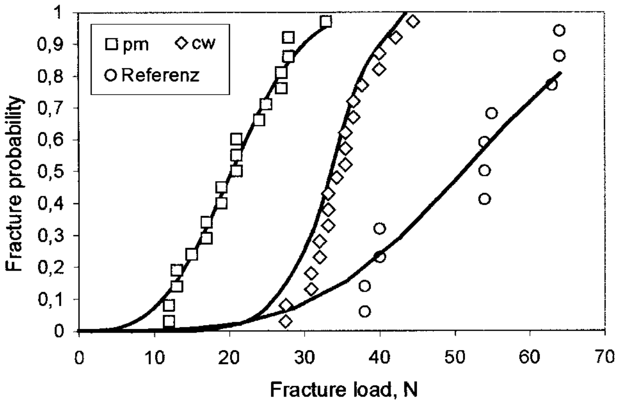


Fig. 5. Fracture probability and fracture load.

strength (σ) compared with that of the original material is shown in the following table:

The investigation of 20 specimens makes a statistical evaluation possible. For an industrial application the relation between fracture probability and fracture is of special importance (Fig. 5).

The steepness of the curves characterises the spread of the measured data. As a result the continuously welded specimens show a smaller spread of fracture load compared with pulsed-welded specimens as well as with unwelded specimens. Up to now this result is not really clear but it has been confirmed several times. It is assumed, that the welded seam acts as a favoured point of fracture.

Welded assemblies

The following laser welded assemblies can be presented:

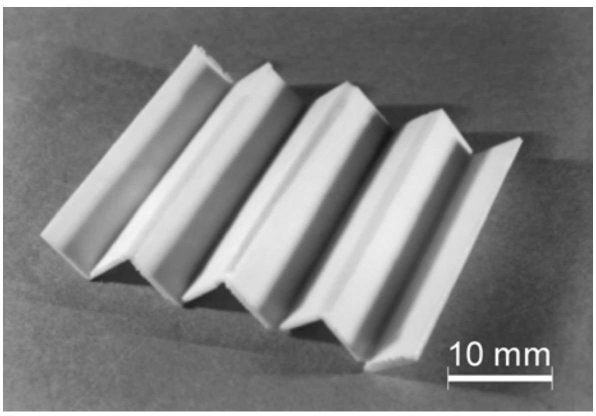


Fig. 6. Laser beam welded wave structure.

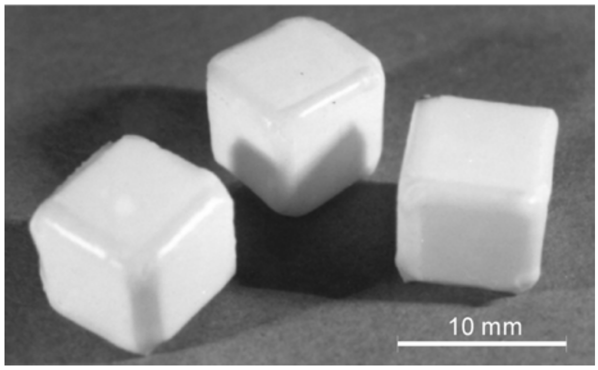


Fig. 7. Laser beam welded hollow cubes.

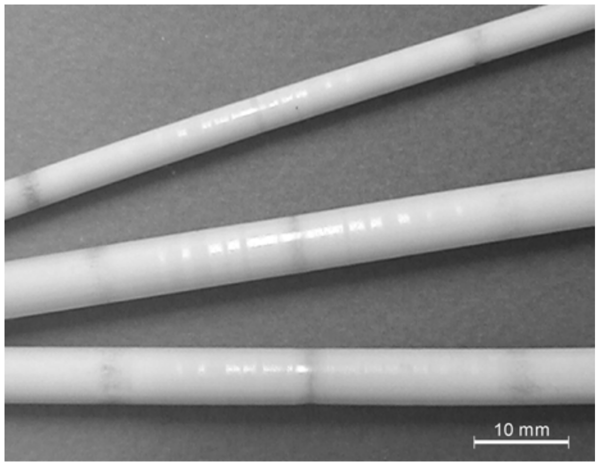


Fig. 8. Laser beam welded tubes.

Summary

Extensive investigations of laser welding of ceramics, mostly alumina of a purity of 96%, by Nd: YAG laser beam were carried out for the first time.

The welding was done employing a two beam laser method.

The preheating of the material, necessary to achieve crackfree joints, was done by a second, scanning CO_2-laser beam. This technology is very well suited for laser welding technology. Particularly when compared with the alternative method of preheating in a furnace, the advantages are obvious:

- high processing speed
- high flexibility
- temperature fields can be generated and varied very quickly
- creation of temperature gradients saves energy
- material can be clamped by conventional methods
- direct observation of the process is possible.

On the other hand, material thickness is limited to about 2 mm because of the low thermal conductivity of the material used.

Furthermore it could be determined, that the wavelength of the Nd:YAG laser beam as well as the continuous mode are very well suited for a homogenous solidification structure within the welded seam, especially for thin materials. The reasons are the absorption behaviour of alumina, the energy distribution typical for a laser beam transmitted by a fibre and the avoidance of a vapour-phase.

The high quality is confirmed by a bending strength of 85% of that of the base material.

The results mentioned promise properties of the joints at high temperatures and/or in a corrosive atmosphere near them of the base material.

The first experiments to join ordinary alumina to transparent alumina of a purity of more than 99.9% and with some metals were very promising, and should be investigated further.

Due to the technology-related limitation of the material thickness and the very small welding seams of about 1mm, multisectoral applications for small parts are expected in a number of fields like the chemical industry, analytic, measuring, mechanical engineering, and micro systems, leading to products and processes with improved performance for the user.

Reference

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