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Joining of alumina and steel by a laser supported brazing process

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Abstract

A laser supported method to join ceramic materials with metals has been studied. Using a CO_2-laser and an active braze filler material, Al_2O_3-ceramics have been brazed to steel. The microstructure of the interface has been examined and also the mechanical strength of the brazed joint using bending tests. Typical processing times are of the order of several minutes, which is faster than furnace brazing. The results of the mechanical tests show that the failure of the brazed metal–ceramic joint occurs within the ceramic close to the interface between the braze filler metal and the ceramic part. Thermally induced stresses may lead to cracks within the ceramic, which initiates the failure under mechanical loading. The typical bending strength varies between 40 and 80 MPa with a Weibull modulus ranging from 4.3 to 6.1.

Keywords: C. Thermal expansion; D. Al_2O_3; Laser brazing; Metal–ceramic joining; Bending strength

1. Introduction

Engineering ceramics are covering a growing application field due to their specific properties such as high temperature stability, corrosion and wear resistance. In order to construct ceramic parts and components these materials have to be machined which can be a difficult and time consuming task with respect to their high hardness and brittleness. For the integration of ceramic components into complex shapes it can be, therefore, advantageous to use joining techniques such as brazing [1,2].

Different routes or procedures have been studied to join ceramic to ceramic and metal to ceramic. Conventionally, the brazing process is conducted at high temperature within a furnace chamber in vacuum or inert gas atmosphere [3,4]. As an alternative method to the uniform heating of the component within a furnace laser beam brazing [5,6] has been studied which utilizes a localized heat input onto the joining zone.

There are two key problems associated with the brazing process of metals and ceramics. These are the poor wetting behavior of liquid metals on a ceramic surface and the commonly large mismatch in the thermal expansion coefficient and the elastic modulus. Both result in metal–ceramic joints with low mechanical strength. The first problem can be overcome by applying active filler braze materials which utilize elements like Ti or Zr for surface activation in order to improve the wetting behavior [7,8]. The second problem can be solved by using intermediate metal layers between the metal and ceramic [9,10]. This layer can be ductile in order to compensate the joining stress by plastic deformation or should have a matched thermal expansion coefficient leading to a concentration of shear stresses at the metallic interlayer and consequently to a stress reduction at the ceramic due to the grading of the thermal expansion across the metal–ceramic interface [11].

Within this paper we report on the development of a laser supported active brazing process to join steel with ceramics. Using a laser for the localized heat input in the brazing process helps to minimize the heat affected zone within the work piece, can reduce the processing time and is more flexible for joining complex shapes compared to brazing performed in furnace chambers.

2. Experimental

Two different ceramics have been included in our studies: an alumina substrate (Frialit, F99.7, Friatec) and a Zirconia

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Table 1
Material properties

	Ceramics		Steel		Braze foil
	F99.7 Al_2O_3 (Friatec GmbH)	SN80 90Al_2O_3-10ZrO_2 (CeramTec GmbH)	100Cr6	CK45	CB4 (Brazetec)
Density (g cm^{-3})	3.95	4.1	7.89	7.8	9.9
Melting point (°C)	2040	–	–	–	–
Liquidus (°C)	–	2040	1450	1510	805
Solidus (°C)	–	1870	1300	1450	780
Porosity (%)	0	0	–	–	–
Strength (MPa)	350	600	620	560	230
Youngs modulus (GPa)	380	380	212	210	72
CTE (10^{-6} K^{-1})	8.1	8.6	10.5	11.1	18.95
Grain size (μm)	10	1.5	–	–	–

toughened alumina ZTA (SN80, Ceramtec). As the steel member 100Cr6 and Ck45 have been used. Details of these materials are given in Table 1. The braze filler metal was a commercially available AgCuTi-foil (CB4, BrazeTec) with a thickness of 50 μm. The geometry of the bending beam sample was 3 mm × 4 mm × 25 mm for width, height and length, respectively. Before the laser joining process a ceramic and a steel beam were placed in a sample holder which fixed its positions and pressed it against each other with the braze foil in between. The sample holder with the positioned bending beam samples was placed in a stream of Ar-gas with a flow of approximately 300 l/h to prevent the oxidation of the steel and the brazing foil. This gas flow was sufficient to avoid any oxide formation due to the active metal Ti in the braze metal.

The laser beam of a high power CO_2-laser (FEHA) was adjusted to point on the joining zone with a small offset towards the steel part. The beam was defocused to a spot size with a diameter of about 5 mm. During the brazing process the laser power was ramped up to a power level varying between 300 and 360 W, while the temperature at the surface of the joining zone was monitored by a pyrometer. A typical temperature–time trace is shown in Fig. 1. When the temperature level reached the working temperature of the braze foil the laser power was switched off after different pre-adjusted duration times. This time period was chosen in order to allow the braze metal to wet the metal and ceramic interface completely. The time duration of the whole laser process was typically between 140 and 160 s. After the end of the laser heating time the joined sample was allowed to cool down to room temperature.

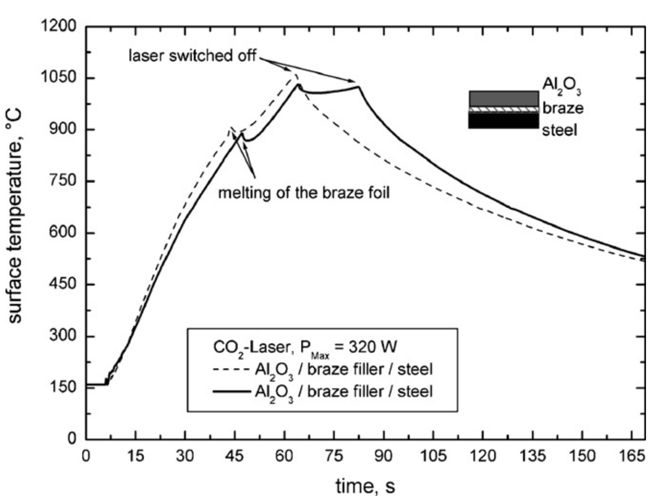

Fig. 1. Typical temperature–time trace measured by a pyrometer during the laser process.

The four-point bending tests were performed with a universal testing machine based on the standard EN 843-1 for ceramic flexural testing [12,13] with a specimen geometry of 3 mm × 4 mm × 50 mm. The test geometry is schematically shown in Fig. 2. The maximum bending strength σ_B was calculated using the maximum bending force F_B, which leads to failure of the joined ceramic–steel system:

$$\sigma_B = \frac{3(l_1 - l_2)F_B}{2w^2h}$$

where w is the width, h the height of the sample, and l_1, l_2 are the distances of the two lower and upper support points, respectively.

After the mechanical test the surfaces of the brazed zone on the metal and the ceramic side were inspected by SEM (Scanning Electron Microscopy) and an analysis of the element distribution was performed with EDX (Energy Dispersive X-ray).

3. Results and discussion

The wetting behavior of the braze filler material (CB4) on an Al_2O_3 surface is shown in Fig. 3. The figure has been obtained

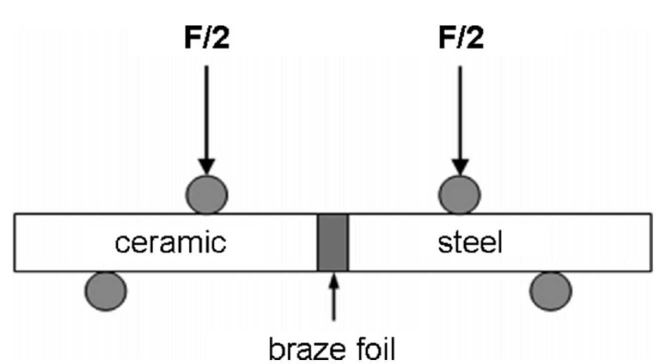

Fig. 2. Test geometry for the four-point bending tests.

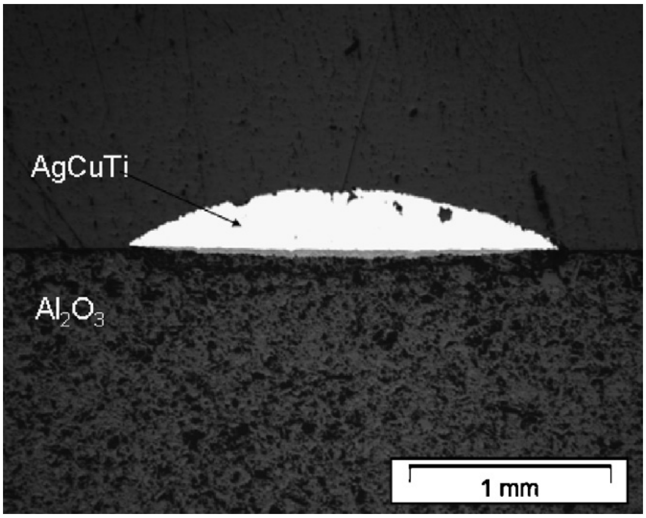

Fig. 3. Wetting behavior of the braze metal (CB4) on Al_2O_3 substrate.

by placing a four-layer stack of the brazing metal foil with a thickness of 50 μm for each layer on top of an Al_2O_3 substrate. After heating to a temperature of 950 °C with a heating rate of 20 K/min, a holding time of about 5 min and subsequent cooling a cross-section has been prepared in order to examine the wetting and spreading behavior of the braze metal and also the structure of the ceramic–metal interface. The wetting angle could be estimated to 30° which clearly shows that an excellent adhesion can be achieved with this active braze material. Additionally, a reactive zone at the braze metal–ceramic interface which is visible as a light gray region in Fig. 3, has been developed which is an indication of a strong mechanical coupling between the braze metal and the ceramic. Further studies with longer holding times in order to determine an equilibrium wetting angle have not been accomplished since this is not important due to the relatively short interaction times in laser brazing.

A typical cross-section of the interfacial area of joined steel–ceramic system is shown in Fig. 4. Due to its excellent wetting behavior the molten braze foil has established a close coupling to the ceramic and to the metal side, respectively. Close to the ceramic and metal interfaces a Ti-rich zone could be observed, which is visible as a narrow gray band in the SEM image. Between the Ti-rich reactions zone there are Ag-rich regions, in which an Ag–Cu phase is embedded.

The results of the mechanical tests are summarized in a Weibull plot [14] shown in Fig. 5. From this diagram an average bending strength of $\sigma_0 = 80 \pm 3$ MPa and a Weibull modulus $m = 6.10 \pm 0.28$ [15] can be extracted. The linear regression shows a standard deviation of 0.26 and coefficient of correlation of 0.97. The average bending strength of the steel–ceramic system is lower than the corresponding strength of the ceramic which is shown as a reference. The modulus of the joint is also lower than that of the ceramic. The reason for these reduced values can be probably attributed to thermal stresses acting predominantly on the metal–ceramic interface during the laser brazing, since it could be observed that the failure of the braze joint always occurred within the ceramic close the interfacial zone with the braze foil. A part of the cracks is starting at the interface and extending into the ceramic. But also cracks within the ceramic running nearly parallel to the interface are visible. This crack arrangement may be due to a different expansion behavior of the ceramic and the steel part on heating and cooling [16,17].

Similar to the melting experiments of CB4 on alumina presented above, the wetting behavior of braze metal on the ZTA has been investigated. A small AgCuTi-foil piece (CB4) has been placed on a ZTA plate and heated up to temperatures above the liquidus point of the braze metal ($T_L = 805$ °C). After rapid cooling a cross-section of the sample was prepared and analyzed. For SN80 the first homogenous wetting is observed at $T = 950$ °C as demonstrated in Fig. 6. The formation of a reaction zone can be observed in Fig. 6 and has been confirmed by EDX-analysis. A reaction zone containing Al, Cu and Zr as well as oxygen is found on the ceramic surface whereas the silver migrates apart from the ceramic

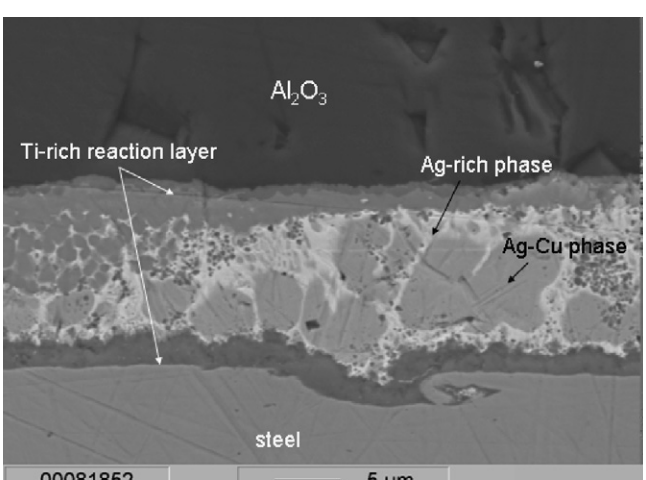

Fig. 4. Scanning electron micrograph of the cross-section of a laser joined steel (100Cr6) and ceramic using an AgCuTi braze filler.

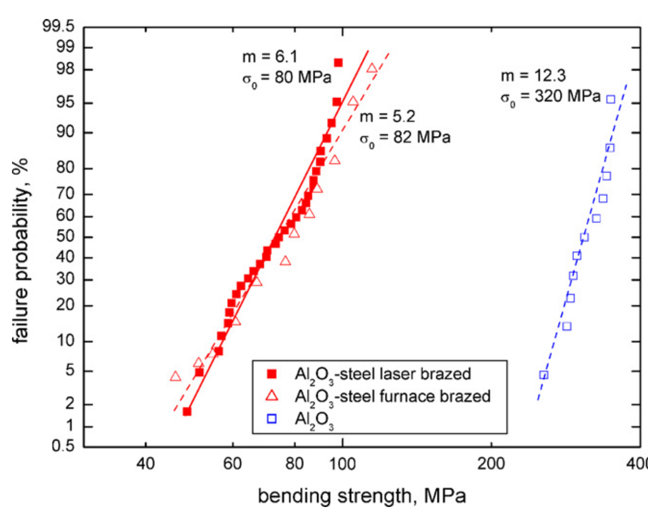

Fig. 5. Weibull plot of the laser joined steel–ceramic system (black squares). The corresponding plot for the ceramic is shown for comparison (open triangles).

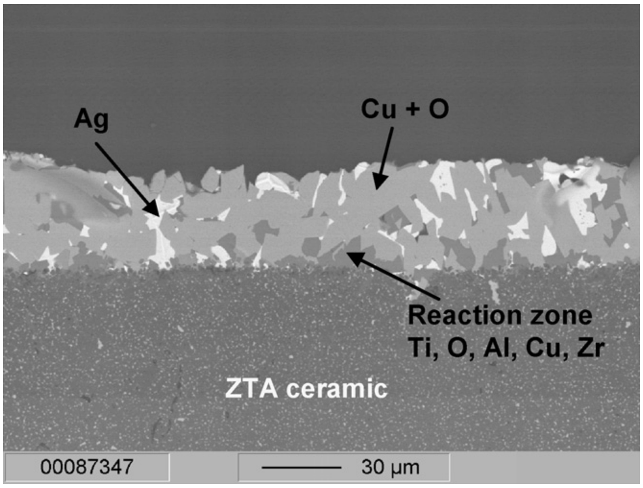

Fig. 6. Scanning electron micrograph of the wetting behavior of the braze metal (CB4) on ZTA substrate at $T = 950\ ^\circ C$.

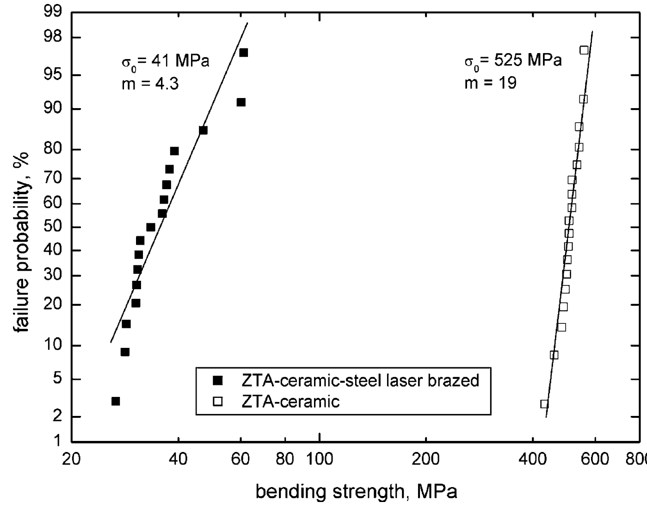

Fig. 8. Weibull plot of the laser joined steel–ZTA ceramic system (black squares). The corresponding plot for the ceramic is shown for comparison (open squares).

boundary. The figure proves the good adherence of the active braze metal to the ZTA.

A similar element distribution has been detected in the ceramic–steel brazed joints. A representative cross-section showing the steel–braze metal interface as well as the braze-filler-ceramic boundary is presented in Fig. 7. The Ti-rich reaction zone on the ceramic and the metal side are visible as a continuous ligament on the joint surfaces but this zone is significantly thicker on the metal joint partner. The reaction layer on the ZTA surface contains the braze metal elements Ti and Cu but also a fraction of aluminum out of the ceramic. This implies that diffusion has occurred at the ceramic interface which has lead to a formation of a strong bond between the braze filler and the ceramic. At the interface between the steel and the braze-metal Fe and C were detected in addition to Ti as the reactive element which may be also due to diffusion during the heating process. Additionally, two further areas could be identified in the braze-metal layer: a light gray area close to the ceramic and an almost white zone which is shifted to the steel interface. The EDX analysis proved that the light gray area is a Cu-rich zone and the white area contains of high amount of Ag.

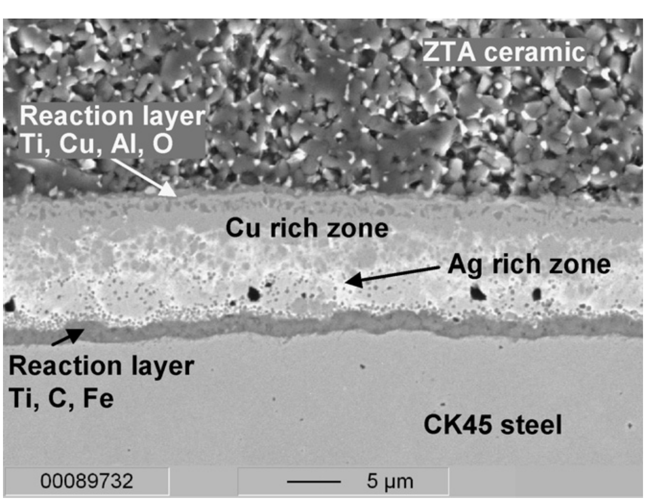

Fig. 7. Scanning electron micrograph of the cross-section of a laser joined steel (CK45) and ZTA ceramic using an AgCuTi braze filler.

The Weibull-statistics in Fig. 8 presents the results of the four-point bending tests which have been applied to measure the strength of the brazed ZTA–steel joints. The corresponding data of the ZTA ceramic have been included as a reference. The ceramic exhibits an average bending strength of $\sigma_0 = 525 \pm 6$ MPa and a Weibull modulus of $m = 19.0 \pm 0.1$. These very high values of the strength and its statistical distribution are not achieved by the brazed joint. The brazed metal–ceramic component has an average joint strength of $\sigma_0 = 41 \pm 4$ MPa ($F = 63.2\%$) and a Weilbull modulus of $m = 4.3 \pm 0.3$. These values were obtained by a linear regression with a standard deviation of 0.32 and correlation coefficient of 0.96. The failure of the joints occurred predominantly in the ceramic. The analysis of the ceramic and metal bending beams after the four-point bending tests indicates that the cracks start either from the interface of the braze metal and the ceramic or very close to the interface within the ceramic. It is presumable that the cracks are induced by thermal stresses that develop during the laser brazing process [16]. Micro-cracks can appear during the rapid localized heating by the laser beam and grow upon cooling due to the different thermal expansion coefficients and lead to a high failure rate at relatively low bending stresses.

4. Summary and conclusion

The results of our studies show that alumina can be brazed to steel using a laser beam. Typical processing times are of the order a few minutes compared to hours in conventional furnace braze. Furthermore, since a closed process chamber is not needed for the laser process, the joining procedure is highly flexible and can be easily adapted to complex component geometries.

However, one important result of this study is that the average joint strength and the Weibull modulus are lower than that of the original ceramic. This behavior can be attributed to the thermally induced stresses, which occur during the laser process and upon cooling down to room temperature. Therefore, the laser process has to be optimized with the focus on a reduction of stresses since this appear to be the main reason for the failure of the joint.

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References

[1] M. Schwartz, Ceramic Joining, ASM International, Materials Park, OH, 1990.
[2] R.M. do Nascimento, A.E. Martinelli, A.J.A. Buschinelli, Recent advances in metal-ceramic brazing, Ceramica 49 (2003) 178–198.
[3] W. Lippmann, J. Knorr, R. Wolf, R. Rasper, H. Exner, A.-M. Reinecke, M. Nieher, R. Schreiber, Laser joining of silicon carbide—a new technology for ultra-high temperature resistant joints, Nuclear Eng. Des. 231 (2004) 151–161.
[4] H. Haferkamp, F.-W. Bach, F. von Alvesleben, T. Mai, K. Kreutzburg, Laserstrahllöten von Metall-Keramik-Verbindungen, Schweissen Schneiden 48 (1996) 853–859.
[5] S. Huang, H. Tsai, S. Lin, Effects of brazing route and brazing alloy on the interfacial structure between diamond and bonding matrix, Mater. Chem. Phys. 84 (2004) 251–258.
[6] S.D. Peteves, M. Paulasto, G. Ceccone, V. Stamos, The reactive route to ceramic joining: fabrication, interfacial chemistry and joint properties, Acta Mater. 46 (1998) 2407–2414.
[7] M.G. Nicholas, T.M. Valentie, M.J. Waite, The wetting of alumina by copper alloyed with titanium and other elements, J. Mater. Sci. 15 (1980) 2197–2206.
[8] P. Kritsalis, L. Coudurier, N. Eustathopoulos, Contribution to the study of reactive wetting in the CuTi/Al_2O_3-system, J. Mater. Sci. 26 (1991) 3400–3408.
[9] Y. Zhou, F. Bao, J. Ren, T. North, Interlayer selection and thermal stresses in brazed Si_3N_4-steel joints, Mater. Sci. Technol. 7 (1991) 863–868.
[10] M.R. Locatelli, B.J. Dalgeish, K. Nakashima, A.P. Tomsia, A.M. Glaeser, New approaches to joining ceramics for high-temperature applications, Ceram. Int. 23 (1997) 313–322.
[11] J.W. Park, P.F. Mendez, T.W. Eager, Strain energy distribution in ceramic to metal foils, Acta Mater. 50 (2002) 883–899.
[12] EN 843-1, ‘‘Advanced technical ceramics–monolithic ceramics—mechanical properties at room temperature–Part 1: determination of flexural strength’’, 1995.
[13] M. Turwitt, Bending test for active brazed metal/ceramic joints—a round robin 1994, DKG 71 (7) (1994) 406–410.
[14] W. Weibull, A statistical theory of the strength of materials, in: Proc. Ing. Vetenskapakad, No. 151, Stockholm, 1939.
[15] D.R. Thoman, L.J. Bain, C.E. Antle, Inferences of the parameters of the Weibull distribution, Technometrics 11 (1969) 445–460.
[16] D. Munz, Y.Y. Yang, Stress singularities at the interface in bonded dissimilar materials under mechanical and thermal loading, Trans. ASME, J. Appl. Mech. 59 (1992) 857–861.
[17] O.T. Iancu, D. Munz, B. Eigenmann, B. Scholtes, E. Macherauch, Residual stress state of brazed ceramic/metal compounds, determined by analytical methods and X-ray residual stress measurement, J. Am. Ceram. Soc. 73 (1990) 1144–1149.