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Functionally Gradient Material and Ceramic Joining*

傾斜機能材料とセラミックスの接合

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要 約

傾斜機能材料の英訳名が、functionally gradient materialからfunctionally graded materialに替えられた。その理由はfunctionally gradient material が非文法的だと云う。しかし、私はそう思わない。この場合、gradient は形容詞である。私はfunctionally gradient materialを使い続ける。

この論文は金属箔を用いてセラミックスを接合させる方法を述べる。その方法によるとセラミックスの間に金属箔を挟み、加熱するだけで接合させることができる。金属箔は空気中で酸化されて酸化物になる。この酸化物がセラミックスと全率固溶体をつくる系を選んでおけば接合層は傾斜機能材料層になり、接合される。この論文ではマグネシアの接合にニッケルを用いることを論じたが、同様にマグネシアにコバルトを、また、アルミナにクロムを用いて接合が可能である。

接合強度は95ＭＰａに達し、実用強度である。接合機構は拡散律速であり、マグネシアと一酸化ニッケルの系を擬二元系とみなし、相互拡散係数が求められた。

ABSTRACT

This paper reports the results of an experiment using *functionally gradient material* (sometimes called *functionally graded material* or *functional gradient material*).

A metal foil was placed between two ceramic blocks, and this set was annealed in air. The metal foil entirely reacted with gaseous oxygen to form a metal oxide layer. When it was considerably heated, the two ceramic blocks were joined by contact with a functionally gradient material layer in which metal oxide was soluble in the ceramic blocks. This method was applied to magnesia/nickel/magnesia. In the same way, it can probably be applied to magnesia/cobalt/magnesia, alumina/chromium/alumina, because these systems form a complete solid solution consisting of ceramics and each metal oxide.

Key words: functionally gradient material, functionally graded material, magnesia, nickel-metal foil, joining.

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I THE TERM FGM

The FGM Forum in Japan and The International FGM Advisory Committee decided to change the term *functionally gradient material* to *functionally graded material.*[1] The main reason for this change was a grammar and usage controversy. However, the term *functionally gradient material* is quite grammatical, because the word **gradient** is an adjective, and the word **functionally** is a qualifier of the word **gradient**, and this name change was made just when the term *functionally gradient material* was firmly fixed. Moreover, the word **graded** means "divided according to stepwise grades of quality, etc."[2] and does not mean "rising or descending by continuous and smooth change of quality, etc." which the word **gradient** means.[3] These are the reasons to use the term *functionally gradient material.* [4]

II JOINING MAGNESIA CERAMICS

II — 1 Introduction

A technique was developed which is highly suitable to joining ceramic blocks into one body with a completely continuous interlayer. In this work, a nickel-metal foil was placed between two magnesia blocks, and this set was annealed in air. Nickel-metal reacted entirely with gaseous oxygen into nickelous oxide. Thus, the joining of the magnesia blocks was accomplished to form a complete solid solution of magnesia and nickelous oxide at the joining interlayer. This interlayer was a kind of functionally gradient material in which residual thermal stress is expected to be reduced in comparison to sharp interfaces. This technique may also be helpful in forming ceramics products of complicated shapes and/or very long sizes.

II — 2 Experimental Procedure

Chemical analysis of poly-crystal magnesia from the Japan Chemical Ceramics Co., Ltd. in Tokyo showed the presence of major impurities of 1 wt% lime and 1 wt% silica. Ten micro-meter and 0.05mm thick nickel-metal foils which were 99.7% grade materials, were obtained from Japan Lamp Industries Co., Ltd. in Tokyo. Two magnesia blocks, 7mm x 10mm x 20mm, were prepared. A nickel-metal foil was placed between the two 7mm x 10mm faces of the magnesia blocks. Then, the specimens were annealed in air at 1573K or 1873K for 291.6ks to 921.6ks. The microstructure and chemical compositions of the interlayer were examined. Three-point bending tests were carried out to evaluate the fracture strength of the joined magnesia blocks.

II — 3 Results and Discussion

Figure 1 shows a typical example of the microstructure and the chemical analysis of the joined magnesia annealed at 1573K for 608.4ks useing a 0.01mm thick nickel-metal foil. The joining interlayer consists of a complete solid solution of magnesia and nickelous oxide. It shows a symmetrical concentration distribution. The thickness of the interlayer is about 0.28mm and the maximum composition of nickelous oxide is about 10 mol%. .

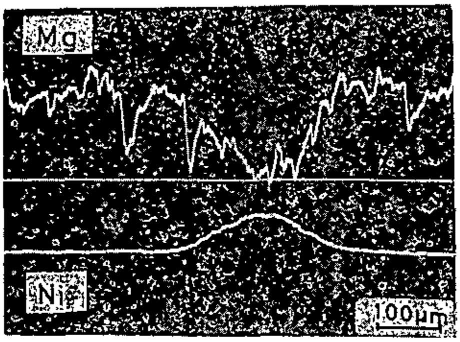

Fig 1 Microstructure and chemical analysis (Mg & Ni) of joined magnesia annealed at 1573K for 608.ks.

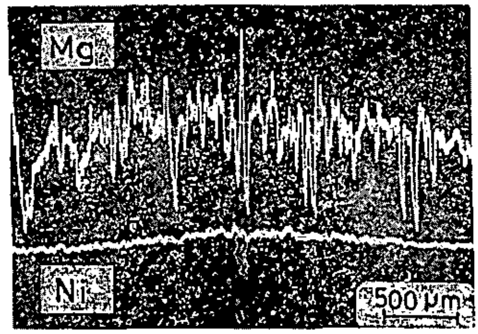

Fig 2 Microstructure and chemical analysis (Mg & Ni) of joined magnesia annealed at 1873K for 230.4ks.

Figure 2 shows the microstructure and the chemical analysis of joined magnesia annealed at 1873K for 230.4ks. The distribution of nickelous oxide is almost gradient-free because it was annealed at high temperature. Considering the relation between the concentration distribution and the annealing time, I conclude that the mechanism of this joining is controlled by the diffusion phenomena, the evidence of which is shown below. Thus, the penetration curves shown in Fig.3 were used to determine the mutual diffusivity of the system magnesia and nickelous oxide. Assuming a quasi-binary system, and using the plane source method because nickelous oxide initially was a very thin layer, we have

$$C=[M/\sqrt{(\pi Dt)}]\exp(-x^2/4Dt) \qquad \text{Eq.1}$$

where, C, M, x and t are the concentration of diffusing nickelous oxide, its total mass, diffusing distance and diffusing time, respectively. Figure 4 shows the linear relation between lnC and x^2. This is evidence that the joining is a diffusion controlled process. From the slope, i.e. $-1/4Dt$, the average mutual diffusion coefficient D of 3.3×10^{-15} m²/s at 1573K was obtained. In previous work[5] on the joining process of magnesia and nickel metal values, the same order of magnitude was obtained.

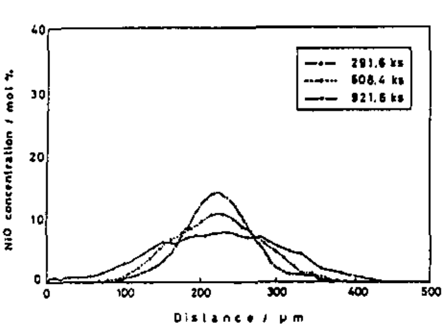

Fig 3 Penetration curves of nickelous oxide at 1573K for several times.

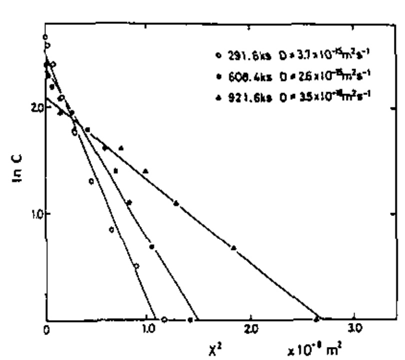

Fig 4 Relationship between ln C and x^2

Figure 5 shows the fracture strength of the joints under several conditions. Three-point bending tests were carried out using the Simadzu Autograph, IS5000, with a 30mm span distance and 0.5mm/min cross head speed. Specimens were polished to prevent the effect of surface cracks. For the joints annealed at 1573K, fracture strength increased with the increase of annealing times up to 256 hr. For long times it decreased with the increase of annealing times. However, on the joints at 1873K, fracture strength ranged 50MPa to 95MPa regardless the annealing times. The value scattering is caused by thermal etching of inside grain boundary structures. The average value reached about 70% of the strength of original magnesia samples. The crystallization of the magnesia was readily brought about by higher temperature. At the initial stage of this joining, using a nickel metal foil is useful for good adhesion of two blocks of magnesia

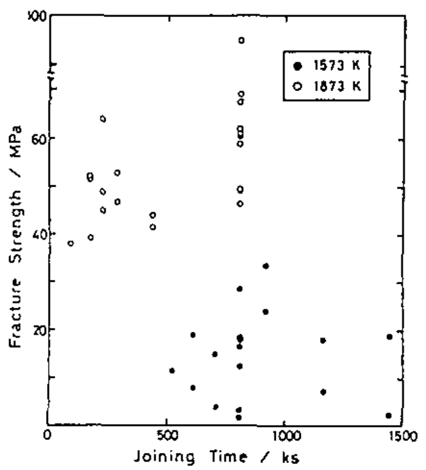

Fig 5 Fracture strength of joints at 1573K or 1873K as a function of annealing time.

II—4 Conclusion

A highly suitable technique of joining ceramics into one body was developed.

(1) Joining of magnesia ceramics was carried out by annealing a nickel-metal foil sandwiched between two blocks of magnesia.

(2) FGMs-interlayers consisted of a complete solid solution of magnesia and nickelous oxide.

(3) The mutual diffusivity of the nickelous oxide in magnesia deternined by their penetration curves, assuming a quasi-binary system, was 3.3×10^{-15} m^2/s at 1573K.

(4) The fracture strength of the joined magnesia annealed at 1573K was low, but that of the joint annealed at 1873K reached 95 MPa.

(5) A nickel metal foil is useful for joining magnesia blocks at an initial adhesion stage.

Reference

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