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Glass binder-bonded copper slag grains to form abrasive tools

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Presented are the results of investigations aiming at assessing the effects taking place in baking ceramic-bonded abrasive tools with copper slag used as an abradant. As a binder, borosilicate glass was used. In the process conducted at optimum temperatures within 1000 to 1050° C, grain–binder bonds of chemical character are produced. This makes it possible to obtain abrasive tools of sufficiently high strength.

1. Introduction

Investigations aiming at using up waste materials produced in various technological processes have been markedly intensified in recent years. This arises from the shortage of many ceramic raw materials as well as from the drive towards lowering production costs. Particular interest in this respect is attracted by slags of all types. A very interesting type of waste product among these is the copper slag produced in copper metallurgy.

At present, the interest in copper slag is related to using it as a raw material for ceramic bodies [1] and as an abradant [2–4]. The authors have been particularly interested in using copper slag as an abradant for ceramic-bonded abrasive tools. Such an application of the slag abradants imposes a number of requirements on the slag, especially as to its physical properties. This has made it necessary to explore its full characteristics, since on the knowledge of these depends the appropriate selection of binder and the heat treatment parameters applied to the tools produced. This paper presents selected results of the respective investigations.

In selecting the appropriate binder for the abradant (i.e. for the copper slag), the optimum baking temperatures for the tools should be considered. This temperature should provide an optimum slag grain setting in the tool. The degree of bonding of the copper slag grains by the ceramic binder is assessed, among others, by the chemical composition and hardness of the bonding bridges in the products and by the tensile strength of the products baked at various maximum temperatures.

2. Characteristics of copper slag abradant intended for ceramic binder bonding

The production of ceramic binder-bonded abrasive tools involves heat treatment at high temperatures. These high temperatures affect all components of the baked products, including the abrasive grains contained therein. Hence, it is useful to know all parameters of the slag related to the effect of high temperatures. It is necessary to carry out thermal analysis and structural investigations of the copper slag and to determine its linear thermal expansion. Essential also is a knowledge of the melting point of this waste material.

The object of the investigations was copper slag granulate from an electric furnace of the Glogów Copper Mill, the average composition of which is presented in Table I.

The thermal analysis shown in Fig. 1 indicates that heat effects occur in the interval 800 to 900° C connected with phase changes leading to the development of akermanite ($2CaO \cdot MgO \cdot 2SiO_2$), calcium magnesium silicate ($Ca_2Mg \cdot Si_2O_2$), anorthite ($CaO \cdot Al_2O_3 2SiO_2$), diopside ($CaO \cdot MgO \cdot 2SiO_2$) and fassolite [1, 2].

Examinations of copper slag carried out by using a high-temperature microscope have shown that the softening and melting points are contained in the regions of 1180 and 1200° C, respectively. These results show that slag abradants cannot be used with traditional ceramic binders. The baking temperatures for tools made by using this binder are between 1250 and 1400° C, i.e. in the range which would make the slag melt. Consequently, low-melting ceramic binders of glass type with baking temperatures within 800 to 1100° C should be used for bonding copper slag

TABLE I Chemical composition of copper slag and borosilicate glass used as a binder

Component	Composition (wt %)	
	Copper slag	Borosilicate glass
SiO_2	38.44	71.4
Al_2O_3	9.12	2.2
CaO	15.83	0.2
Fe_2O_3	22.23	–
MgO	4.38	0.1
Na_2O	0.47	3.7
K_2O	3.45	0.3
B_2O_3	–	15.2
PbO	0.12	6.1
Zn	0.99	–
Cu	0.24	–
BaO	–	0.3
Sb_2O_3	–	0.6

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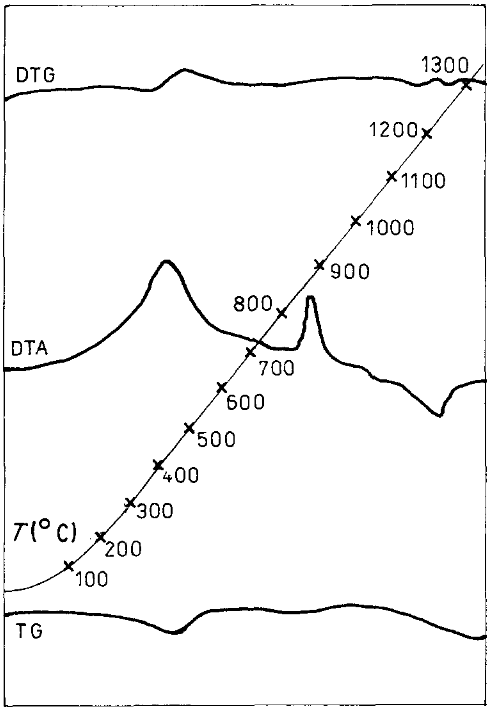

Figure 1 Thermal studies of copper slag: thermogravimetric analysis (TG), differential thermal analysis (DTA) and derivative thermogravimetric analysis (DTG).

grains. The copper slag (being an amorphous body) crystallizes while exposed to these temperatures on baking the abrasive tool. This increases considerably the hardness and mechanical strength of the slag grains [2], resulting in an improvement of the operational properties of the abrasive tool produced.

The dilatometric curve obtained from copper slag by using a Chevenard dilatometer and shown in Fig. 2 allows one to determine the coefficients of linear heat expansion (Table II). These coefficients are close to those of traditional abradants (aloxite, silicon carbide).

In view of the mechanical properties of the final abrasive tool it is beneficial to select as a binder such glass types whose linear thermal expansion coefficients are lower than that of copper slag. In operation, when heated, favourable compressive stresses are produced. To take advantage of these properties of copper slag grains, borosilicate glass was selected as a binder.

TABLE II Coefficients of linear thermal expansion of copper slag and borosilicate glass

Material	Coefficient of expansion, $\alpha_{t_1}^{t_2}$ (10^{-7} K^{-1})*				
	α_{20}^{100}	α_{20}^{200}	α_{20}^{300}	α_{20}^{400}	α_{20}^{500}
Copper slag	120.7	93.5	84.0	86.8	89.2
Borosilicate glass	53.7	44.7	44.1	40.4	42.1

*Temperature in °C.

3. The process of bonding copper slag grains with borosilicate glass

The chemical composition of the borosilicate glass used for investigation is shown in Table I. Its softening and melting points are 755 and 1260° C, respectively. The angle of wetting the copper slag grains by this glass varies in this range of temperatures within the interval 108 to 35°.

By using the dilatometric curve of borosilicate glass shown in Fig. 2, the values of its coefficients of linear thermal expansion were determined and are presented in Table II. They are considerably below the respective coefficients of linear thermal expansion of copper slag, which means a favourable matching of abrasive grain and binder.

The process of bonding copper slag grains with borosilicate glass was investigated on standard "8-shaped" test pieces with the characteristics of 46Q 6V*. Assessed were selected mechanical and physicomechanical parameters associated with the bonding process, such as the chemical composition of the bridges bonding the copper slag grains and the variation of hardness with the maximum baking temperature of the test pieces. Apart from the investigations on the bonding bridges, the variation of mechanical tensile strength of the test pieces with the maximum baking temperature was determined.

The microhardness of the bonding bridges was measured by using a Vickers intenter and the

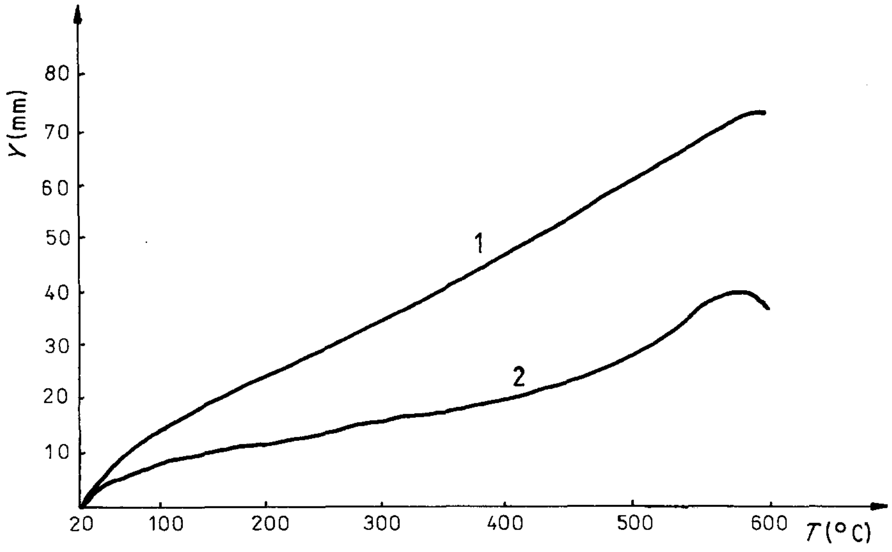

Figure 2 Dilatometric curves: (1) copper slag, (2) borosilicate glass.

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*(46) represents the graininess = 425 to 355 μm, (Q) the porosity, V_p = 31.5%, (6) the volume of abrasive grains in relation to the abrasive tool volume, V_z = 50%, and (V) the vitrified bond.

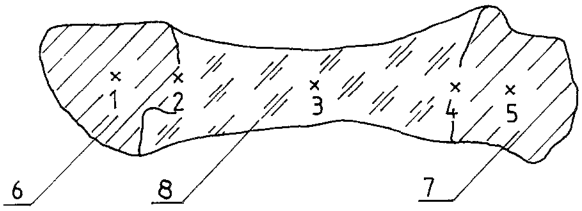

Figure 3 Pattern of microhardness measurements of bridges bonding grains into an abrasive product: (1, 5) indentations on the grain, (2, 4) indentations on the grain–binder interface, (3) imprint on the binder, (6, 7) copper slag grains, (8) glass binder.

measurements followed the pattern shown in Fig. 3. They were carried out for specific, selected maximum baking temperatures of the test pieces. The results obtained are shown in Fig. 4.

The results of microhardness testing correlate fairly well with the results obtained in testing the mechanical tensile strength of the test pieces (Fig. 5). The results show that maximum hardness and mechanical strength are obtained in the temperature range 1000 to 1100° C. It can also be seen that the microhardness of the bonding bridge increases only slightly with the baking temperature. The temperature of 1200° C cannot be applied as a baking temperature, since this temperature makes the copper slag soften with a detrimental rounding effect on the cutting edges of the grains.

Both the microhardness and the mechanical tensile strength depend on the physicochemical effects that may take place in the slag–glass interface and the structural changes in the grains and, possibly, in the binder, during thermal treatment of the test pieces.

Good bonding of copper slag grains by the glass binder is confirmed by the way the binder is located in the abrasive test piece (Fig. 6). This makes it possible to interpret the bonding mechanisms which are, probably, mainly based on the chemical reactions taking place between the bonded materials. This may be confirmed, if by nothing else, then by the lack of a sharply defined interfacial border in the grain–binder interface, as seen in Fig. 7.

In order to interpret properly the mechanical properties of the copper slag abrasive test pieces, especially the microhardness of the bonding bridges, the distribution of elements on the grain–binder bond was determined by means of X-ray microanalysis. Microsections of the test pieces were prepared and then analysed by using the Japanese Jeol Co. JXA-3A apparatus. An electron beam of ~ 3 μm diameter was used. A properly placed specimen was shifted at 20 nm min^{-1} in the chosen direction in such a way that X-ray emission was excited by the electron beam from microregions of the specimen lying in the plane of the microsection along a straight line crossing the border between binder and grain. Analyses were made of the linear distribution of the components in the abrasive test pieces along a region of a straight line, the beginning of which lay in the region of the binder while its end lay in the central region of a grain. For analysis, the *K* series emission lines of the investigated

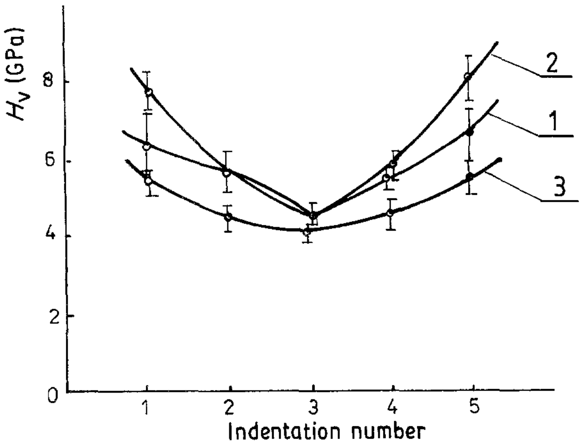

Figure 4 Microhardness of glass binder and copper slag bridges depending on the maximum baking temperature: (1) 900° C, (2) 1000° C, (3) 1100° C. Designation of indentation numbers according to Fig. 3.

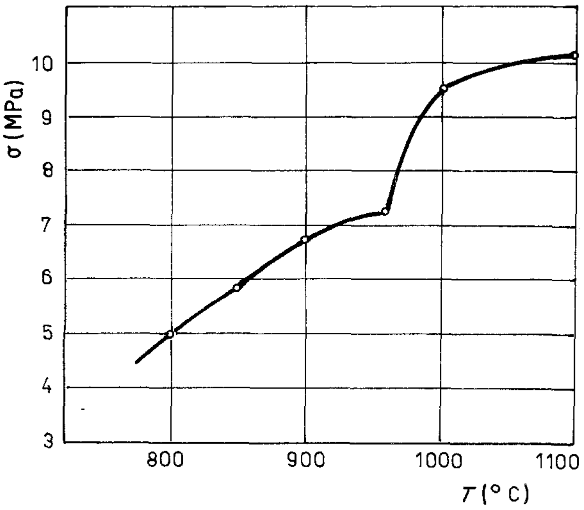

Figure 5 Mechanical tensile strength of glass binder-bonded copper slag test pieces baked at various temperatures.

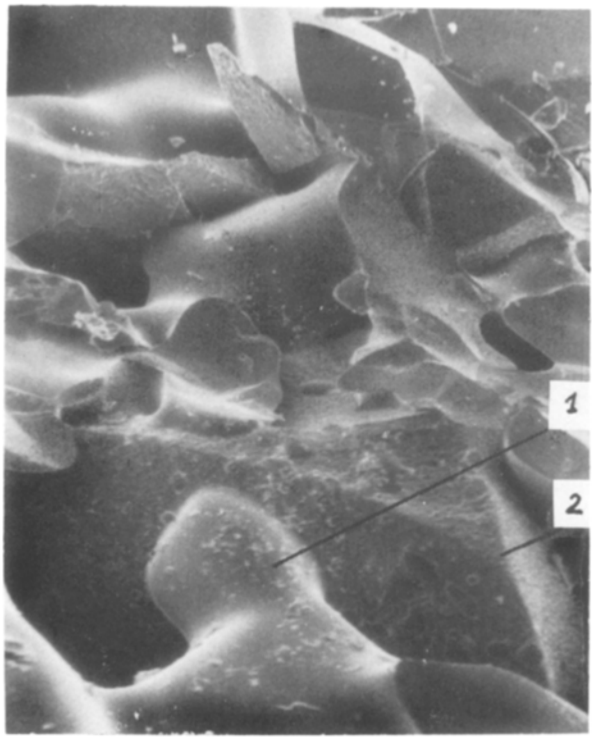

Figure 6 Fracture surfaces of glass binder-bonded copper slag abrasive test piece baked at a maximum temperature of 800° C: (1) binder, (2) abrasive grain; 260 ×.

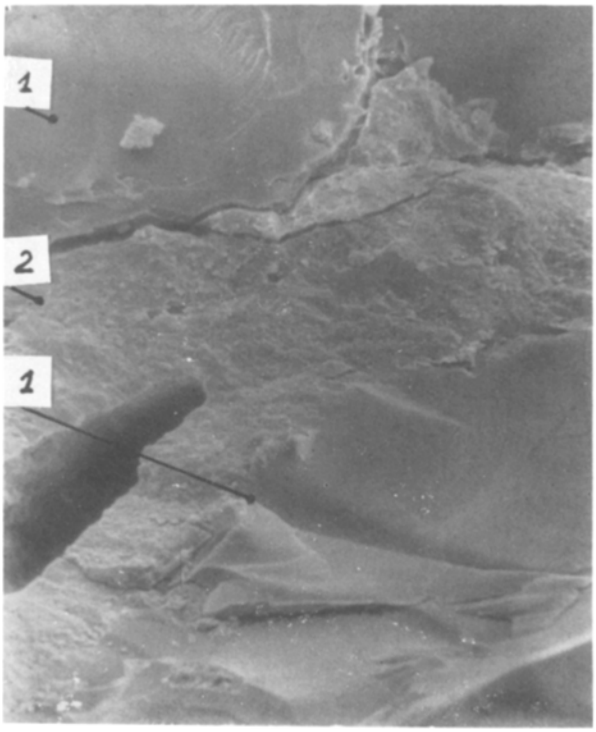

Figure 7 Fracture surface of glass binder-bonded copper slag abrasive test piece baked at a maximum temperature of 1050° C: (1) abrasive grain, (2) binder; 870 ×.

elements were used. Because of the great similarity in chemical compositions of the copper slag grains and the glass binder, special attention was focused on analysing those components, the content of which differed considerably in the materials fused together. These were, for example, Al_2O_2, CaO, K_2O, Na_2O, B_2O_3 and Fe_2O_3. The latter two chemical compounds are present in only one of the fused materials.

The results for the bonds between the abrasive grain and the glass binder shown in Figs 8 to 11 indicate that from 800° C and above, due to decreasing viscosity of the binder, reactions and dissolution take place between the components of the binder and the grains. At 1050° C a defined boundary between the bonded components, glass and grains, is no longer visible. The extent of the diffusion of the particular components depends on the reactivity of the binder and grains. As the maximum bonding temperature increases, so also does the Al_2O_3 content in the binder. The Al_2O_3 content in the slag is 10 times higher than that in the binder. Figs 8 and 10 show distinctly the differences in the aluminium content in the grain–binder contact zone. With increasing distance from the grain surface a decrease of the aluminium content, similar to that of calcium and iron, can be seen. A previously formed intermediate (transient) zone of $\sim 20\,\mu m$ thickness affects the microhardness distribution in the grain-bonding bridge in cases where the microhardness of the grain exceeds that of the binder.

Both the diffusion of Al_2O_3 and that of other grain components (e.g. CaO, Fe_2O_3) may be the cause of local mineralization of the binder on the grain boundary. This accounts for the increased microhardness in that region.

The results of the investigations on the distribution of the elements indicate that an increased heat treatment temperature, while intensifying the course of the

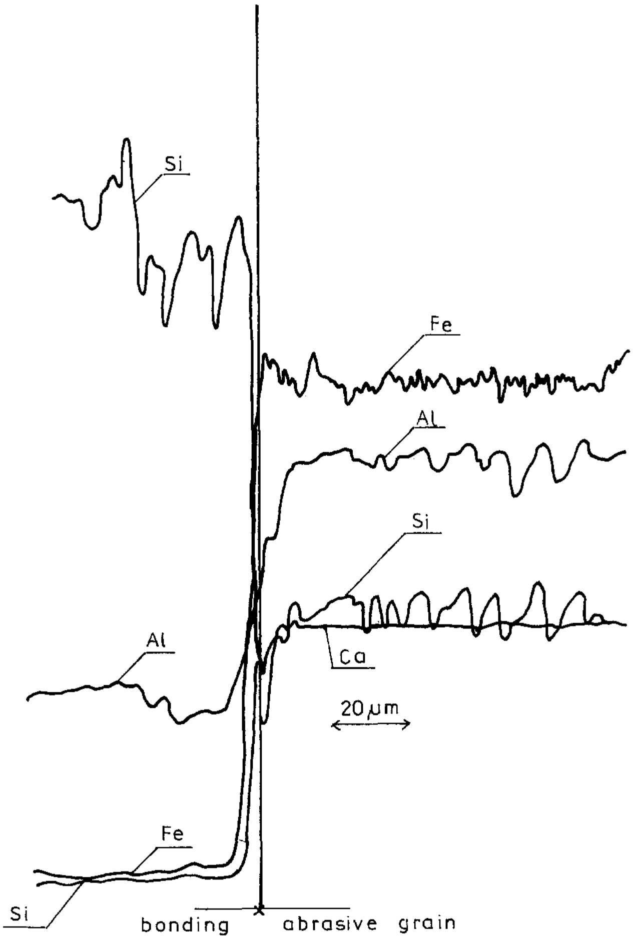

Figure 8 Content distribution of selected components in the copper slag–glass binder bond baked at a maximum temperature of 800° C.

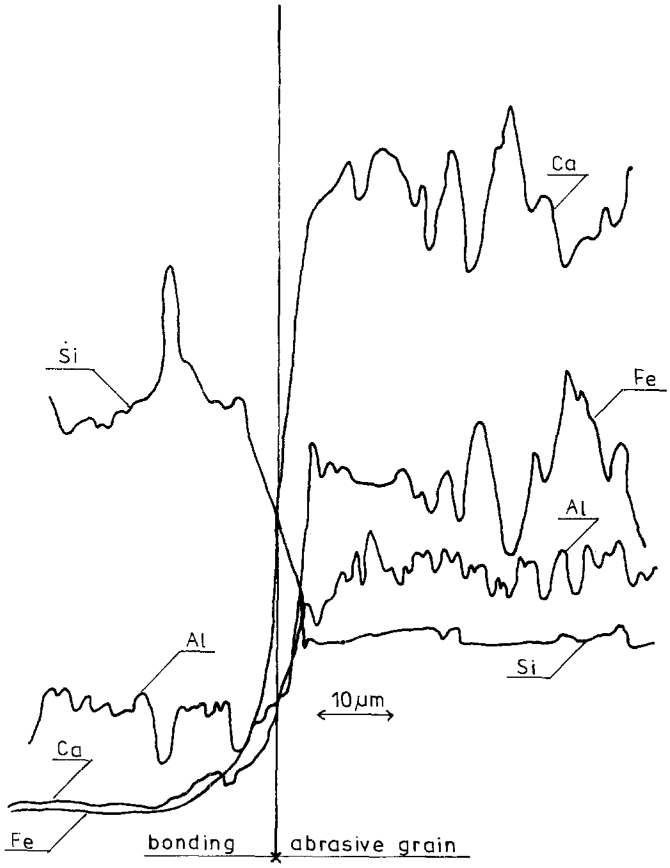

Figure 9 Content distribution of selected components in the copper slag–glass binder bond baked at a maximum temperature of 900° C.

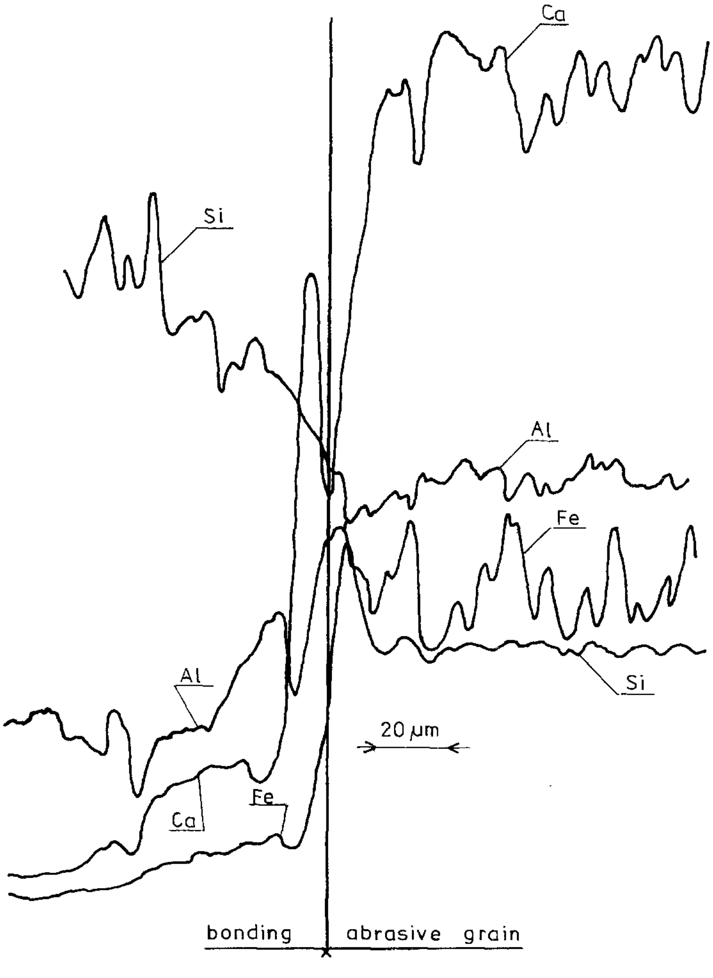

Figure 10 Content distribution of selected components in the copper slag–glass binder bond baked at a maximum temperature of 1050° C.

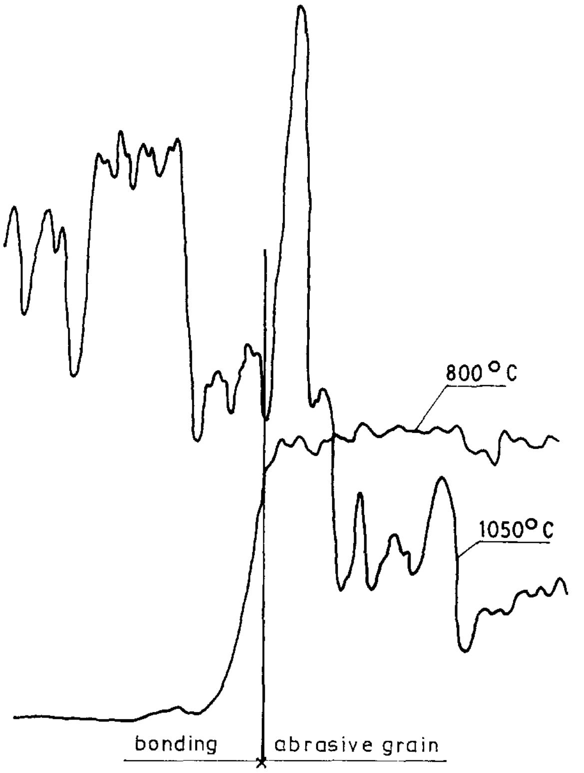

Figure 11 Distribution of potassium content in the copper slag–glass binder bond baked at maximum temperatures of 800 and 1050° C.

reactions in the final stage (i.e. in the baking temperature proper of 1050 to 1100° C), also leads to changes in the chemical composition of the binder due to diffusion of some components and chemical interactions. At this temperature, the liquid silicate melt is capable of digesting the diffusing grain components, e.g. K_2O (Fig. 11). The cohesion of the glass structure is slackened, thus enabling other components to migrate, which is manifested for example by the presence of calcium and iron in the binder. In the transitional zone, on the grain–binder boundary, conditions exist for anortite ($CaAl_2SiO_2O_3$) and diopside ($CaO \cdot MgO \cdot 2SiO_2$) to originate at the maximum baking temperature because of the presence of diffusing calcium and aluminium compounds. Also other complex oxide phases are likely to arise, not only on the grain surfaces but also in the central part of the bridges. The effect of a partial change in chemical composition of the bonding bridge may manifest itself more markedly after the secondary heat treatment, i.e. after the crystallization process. These effects will be the object of further investigations.

4. Conclusion

The bonding of copper slag abrasive grains with a fusible ceramic binder is of a chemical nature, the condition being met that the copper slag be wettable by the selected binder. As a consequence of these effects it is possible to obtain abrasive tools of sufficient strength at temperatures much below those for obtaining conventional tools. The tools obtained in this way may also replace conventional tools in the abrasive machining of certain materials, especially non-ferrous metals.

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