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Experimental investigation on induction brazing of diamond with Ni–Cr hardfacing alloy under argon atmosphere

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In recent years direct brazing of a monolayer of diamond crystals on a steel substrate with active filler metals has gained tremendous importance in the industry, with a view to developing tools which can out-perform the conventional galvanically bonded diamond tools. An existing proprietary process uses a specially prepared Ni–Cr filler metal to facilitate its application on a steel substrate. The brazing is done either in a vacuum or a dry hydrogen furnace. The present study has shown that a commercially available Ni–Cr hardfacing alloy, flame-sprayed on a steel substrate with an oxyacetylene gun, could be used for direct brazing of diamond particles. Induction brazing was carried out in an argon atmosphere only for short durations. During brazing under such conditions, the chromium present in the alloy segregated preferentially to the interface with diamond to form a chromium-rich reaction product promoting the wettability of the alloy. It has been further revealed that under a given set of brazing conditions, the wettability of the Ni–Cr hardfacing alloy towards diamond grits primarily depended on its layer thickness. Such dependence resulted in significant variation of topographical features of the tool and its wear mode in simulated grinding tests.

1. Introduction

The need for improved abrasive tools to cope with ever-increasing demand for higher productivity has led to numerous developments in the field of abrasive tool manufacturing. These activities have been mainly directed towards improvement of the adhesion of abrasive particles to the bonding matrix, along with increase of its strength and wear resistance.

The good compatibility of nickel-chrome alloys has already been utilized in the fabrication of abrasive tools with tungsten carbide particles by liquid-phase bonding, and quite a number of patents [1–5] have been obtained. The other constituents of these alloys are Fe and B. Sometimes Si and Mo are also present.

An abrasive article, for instance a metal-bonded diamond wheel, has been patented [6] where the bonding matrix consists of Cu, W, Fe, Ni, Cr, Sn, C, B and Si in different amounts.

The use of Ni–Cr alloy containing Si or Si and Ti in brazing graphite to stainless steel has also been reported [7]. The brazing was carried out at 1126 to 1176 °C in a vacuum furnace.

Diamond possesses a much higher hardness than tungsten carbide or other abrasive materials, and in many applications it is advantageous to use tools with a monolayer of diamond particles strongly bonded to a steel core instead of tool with a composite structure (e.g. metal bond, resin bond or vitrified bond). Such a single-layer diamond tool with galvanic bonding is already in existence and has widespread application, particularly for machining non-metallics. Instead of any galvanic bond, an Ag–Mn–Zr alloy with a high percentage of silver can be used for brazing diamond grits to a metal support [8].

The patent literature [9] refers to an abrasive tool with a monolayer of diamond grits brazed to a steel substrate using Ni–Cr-based alloy. The fabrication process appears to be somewhat cumbersome in the sense that it requires a special "braze paint". This braze paint is prepared by mixing braze alloy powder with an organic liquid. After applying the paint on a steel substrate, it is necessary to dry it at a moderate temperature for a certain time to remove excess volatile materials, before carrying out the actual brazing. Finally brazing is performed in a vacuum or a dry hydrogen furnace. In several applications, the superior performance of such brazed tools over their galvanically bonded counterparts has also been documented [10].

It is well known that the flame-spraying process is relatively simple, inexpensive and flexible for depositing hardfacing alloys on steel substrates. Conventionally, such a hardfacing alloy is meant for use on machine elements and tools subjected to a variety of wear phenomena. It can be appreciated that the tool fabrication process becomes economical if such a hardfacing alloy is creatively used for brazing the diamond grits. Similarly, induction brazing has the distinct advantage that the temperature can be raised quickly without subjecting the diamond crystals to

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a high temperature range for a long time before attaining the actual brazing temperature. The shape distortion of the tool can also be reduced to a minimum by adopting such a process. Unfortunately no information is available about the behaviour of Ni–Cr hardfacing alloy towards diamond under such conditions. Also the processes described in the existing patent literature lack systematic analysis and explanation on the fundamental cause of wetting and bonding.

Therefore the basic objectives of the present work were to study the wetting behaviour of an Ni–Cr hardfacing alloy, flame-sprayed on a steel substrate, towards diamond grits when induction brazing was carried out under an argon atmosphere, and also to study the effectiveness of such developed bonds in retaining the grits on the tool surface during grinding.

2. Experimental investigation and discussion

2.1. Microprobe analyses of the bonding alloy

A commercially available Ni–Cr hardfacing alloy was used in the present investigation. The bonding material was deposited on the top surface of cylindrical steel buttons with a spray gun using an oxyacetylene flame. The basic principle and method of using such a spray gun can be found in the literature [11].

Since no specific information was available on the composition of the alloy, it was worth analysing the coating just after spraying but before melting. The alloy powder was sprayed in a semi-molten state and the adherence between the coating and the substrate was not very strong at this stage. The as-coated surface was prepared by careful polishing for electron probe microanalyses.

The electron probe microanalyses, carried out at three different points, showed that the alloy principally consisted of Ni, Cr, Si, B and Fe (Table I). It is well known that this type of alloy contains B and Si which act as fluxing agents and melting-point depressants [11]. It was another objective of the present analyses to detect oxygen which might be incorporated in the coating during flame-spraying. It can well be realized that the presence of oxygen in the bonding alloy can inhibit the wetting of diamond. The microprobe analyses, however, clearly indicated that after flame-spraying with the oxyacetylene torch, oxygen was not present in the alloy at a significant level.

2.2. Interaction of Ni–Cr hardfacing alloy with the diamond surface

The solidus and liquidus temperatures of the alloy were 1020 and 1050 °C, respectively. After the alloy was flame-sprayed on the steel substrate, diamond particles (250–212 µm mesh width) were sprinkled on it in a single layer. This was followed by induction brazing, which was carried out at 1080 °C in a current of argon only for 30 s. The brazement thus obtained was cooled and subsequently sliced and polished to obtain the cross-sectional micrograph shown in Fig. 1. The impression that can be gained from this picture is that the Ni–Cr alloy wetted and bonded the diamond crystals quite effectively.

To understand the mechanism of wetting, a few sample analyses were made with the microprobe at various points on the sliced specimen as indicated in Fig. 1. The results are shown in Table II. The analyses at points very close to the diamond surface showed a substantially larger quantity of Cr in comparison with its bulk concentration. Similarly the amount of Ni was significantly lower compared to what was present in the parent alloy. However, the middle portion of the bonding layer was relatively rich in Ni. Thus it became evident that the Cr present in the alloy segregated preferentially to the diamond surface to form a Cr-rich reaction product, which was wetted by the alloy.

The segregation of chromium to the diamond surface can be explained by the strong affinity of chromium for carbon to form a stable chromium carbide.

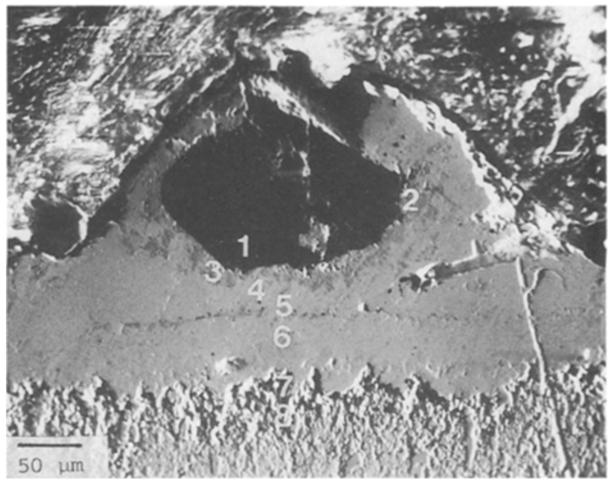


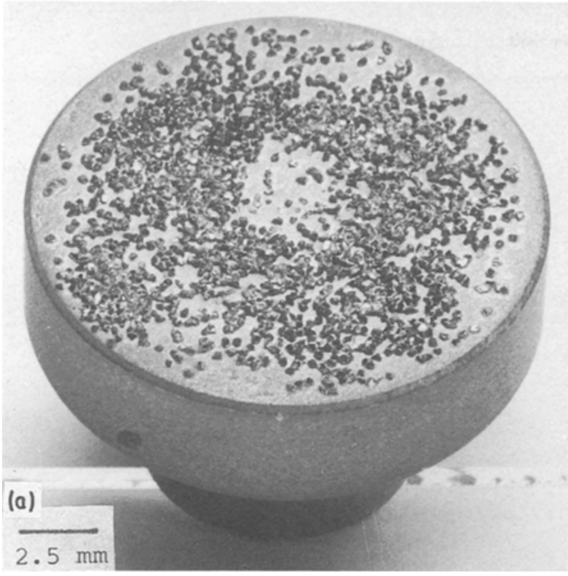
Figure 1 Wetting and bonding of diamond grit with Ni–Cr hardfacing alloy.

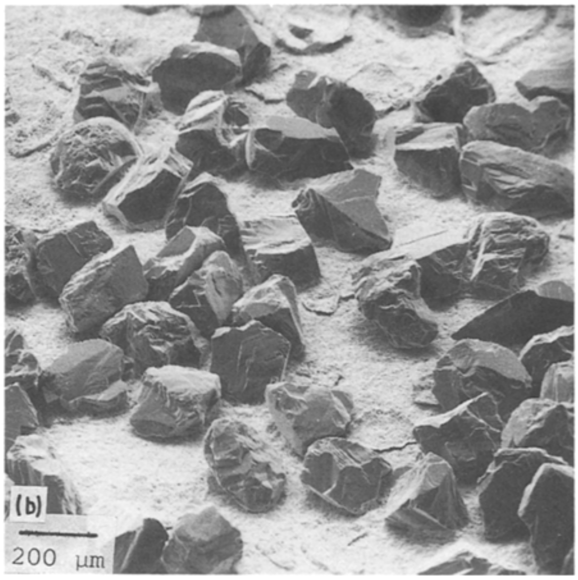
TABLE I Microprobe analyses of the Ni–Cr hardfacing alloy after flame spraying (%)

Ni	Cr	Fe	Si	B	O_2
70.588	14.393	3.213	3.400	3.135	0.455
72.348	14.366	3.471	3.560	3.267	0.654
72.063	14.211	3.681	3.627	3.445	0.378

TABLE II Analyses of elements at different points of the brazement shown in Fig. 1

Points	Composition (%)			
	Ni	Cr	Fe	C
1	–	–	–	99.87
2	14.56	63.42	11.61	12.23
3	12.44	68.43	8.02	12.18
4	29.04	31.62	10.53	15.46
5	69.67	5.49	18.12	3.79
6	10.78	49.26	24.71	32.35
7	0.2	19.44	57.7	15.80
8	0.18	9.09	71.49	16.96





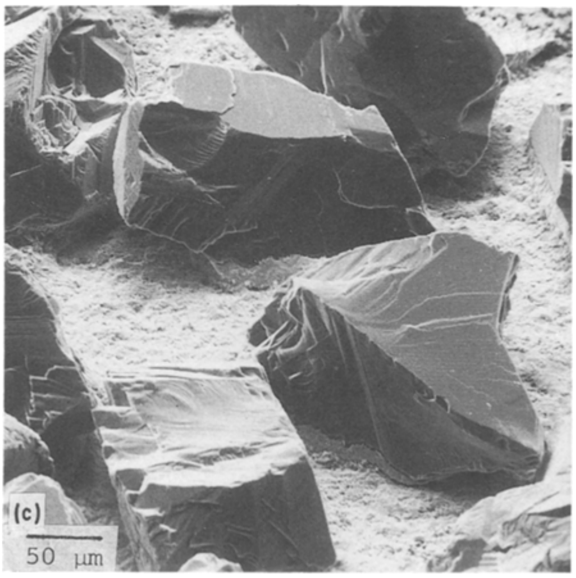


Figure 2 (a–c) Appearance of natural diamond grit button after brazing with 30 μm thick layer of Ni–Cr alloy.

A similar Ti segregation to the interface formed with diamond by Cu–Ti and Cu–Sn–Ti alloys which wetted the former has also been reported [12, 13]. The analyses further revealed that the bond between the hardfacing alloy and the steel button was established through inter-diffusion of Fe and Cr and probably the formation of (Fe_x, Cr_y) C-type carbide.

2.3. Effect of initial thickness of the alloy on wetting of the diamond grits

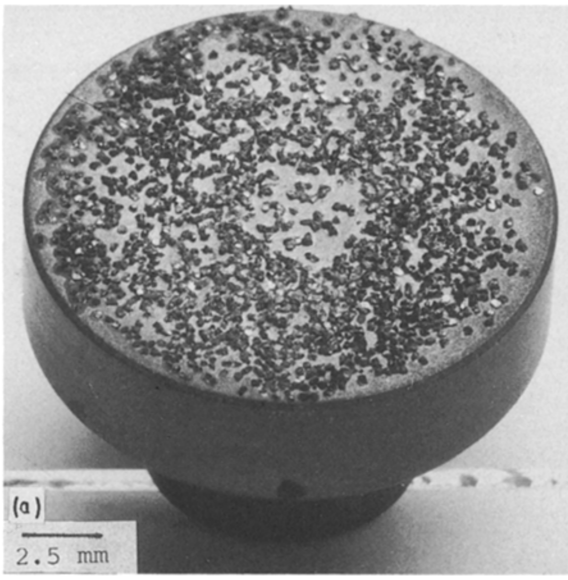
The efficiency of a grinding tool can be strongly influenced by the topography of its active surface, e.g. grit protrusion and level of bond, which are controlled by the wettability of the bonding material towards the abrasive particles. Under a given set of brazing conditions, the initial amount of brazing material (or in other words the initial thickness of the flame-sprayed layer) can influence the wetting pattern of the abrasive crystals. To study this influence five buttons were prepared with initial thicknesses of 30, 50, 80, 150 and 230 μm of the alloy. The uncoated natural diamond grits (250–212 μm) were taken for bonding to the steel buttons. After melting and subsequent solidification, different wetting and spreading patterns were obtained.

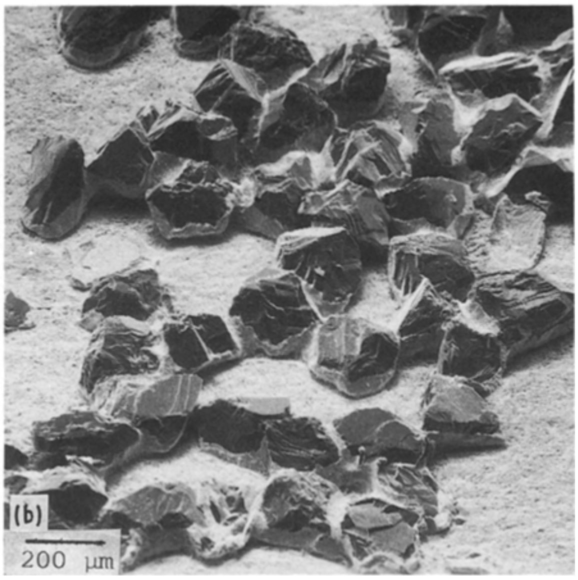
The macrograph of Fig. 2 gives the impression that a 30 μm thick layer of the alloy could not wet the grit surface effectively. The SEM micrographs of the same figure clearly indicates the same. With a layer thickness of 50 μm the wetting pattern changed a little. Although such a feature is not very clear in the macrograph of Fig. 3, the SEM micrographs reveal that only a fraction of the grit height was wetted by the alloy to form a "metal sheath" around the grits.

With a layer thickness of 80 μm of the hardfacing alloy, the natural diamond grits could be wetted quite satisfactorily. This is evident from Fig. 4. The irregular shape and relatively rough surface of natural diamond can also be well visualized from the same figure.

Attempts were also made to braze synthetic diamond grits in a monolayer with the same bonding alloy. The layer thickness was 80 μm. From Fig. 5 the diamond particles can be characterized by well-defined faces and sharp edges with cubo-octahedral morphology. The hardfacing alloy could wet the crystals effectively. The wetting, however, was not uniform on all the faces of the crystals. The relative difference in wettability or affinity at various planes of diamond might be due to a difference in surface energy per unit area of the respective planes.

With an initial thickness of 150 μm the situation was different. The alloy not only filled the space between the particles, unlike the previous cases, but also flowed over the surface of the grits, thus covering them with a layer. This is evident from Fig. 6a. Fig. 6b also reveals that the sprayed layer with a thickness of 230 μm completely covered the entire mass of diamond particles, thus hindering the cutting capability of those particles. Such a tool surface can be made effective only after opening up the grits by a dressing





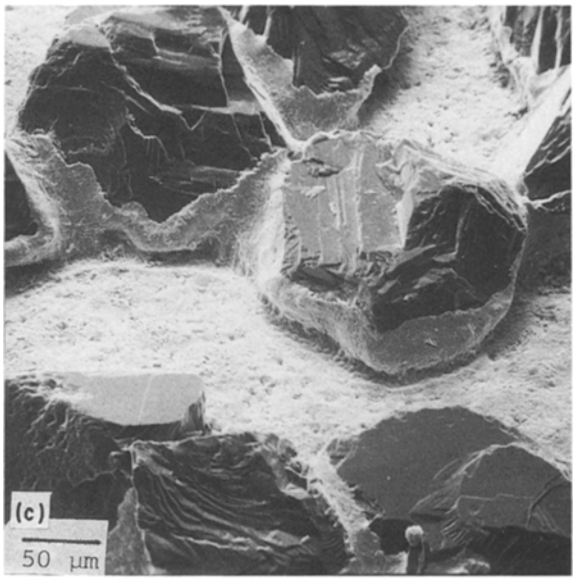


Figure 3 (a–c) Appearance of natural diamond grit button after brazing with 50 μm thick layer of Ni–Cr alloy.

operation, as is done in the case of metal-bonded tools.

The variations in the wetting pattern of diamond grits with the initial thickness of the braze alloy are shown schematically in Fig. 7.

2.4. Simulated grinding tests

A test simulating grinding was conducted to obtain preliminary information about the expected behaviour of abrasive tools fabricated under different conditions, with particular reference to their ability to resist premature grit dislodgement and bond rupture. For this purpose, a cup-shaped wheel made of Al_2O_3 was mounted on the spindle of a tool and cutter grinder. The wheel specification was A120 L8V [14]. The wheel was made to rotate with a surface speed of $15\ m\ s^{-1}$. The diamond grit button, clamped in a specially designed fixture, was held against the rim of the alumina disc with a constant thrust force of 10 N for the necessary grinding action.

Fig. 8 reveals that the abrasive button fabricated with a layer thickness of 30 μm suffered from bulk grit

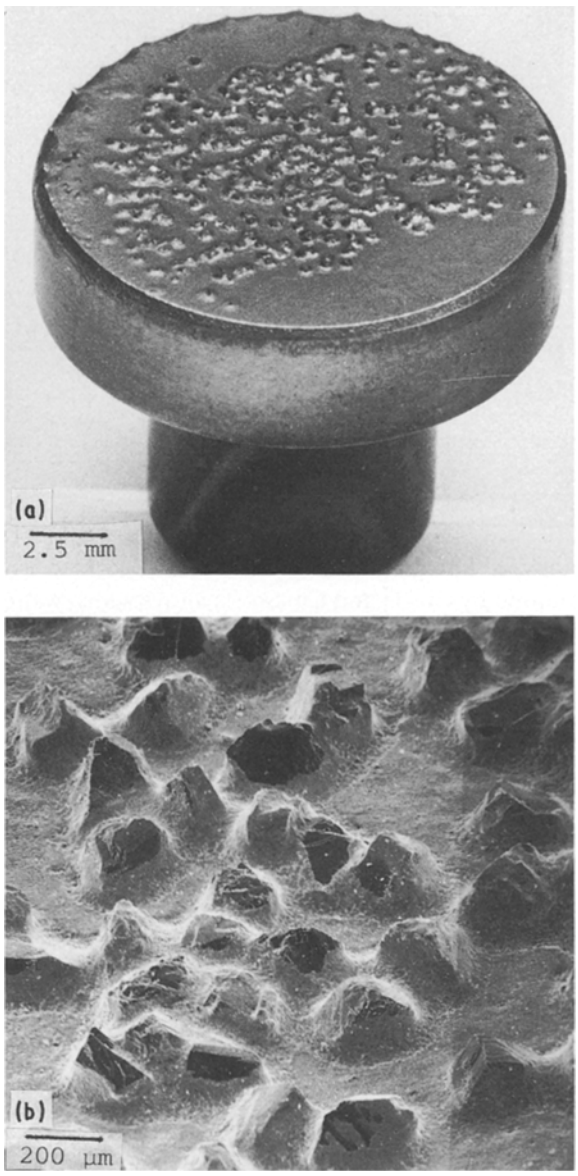


Figure 4 (a, b) Appearance of natural diamond grit button after brazing with 80 μm thick layer of Ni–Cr alloy.

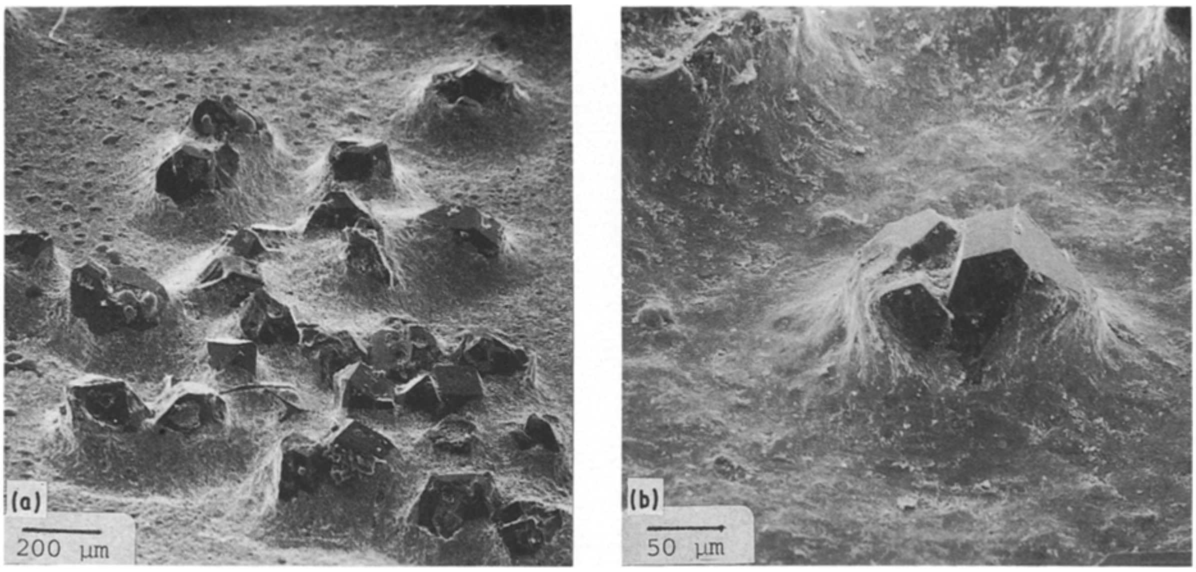


Figure 5 (a, b) Appearance of synthetic diamond grit button after brazing with 80 μm thick layer of Ni–Cr alloy.

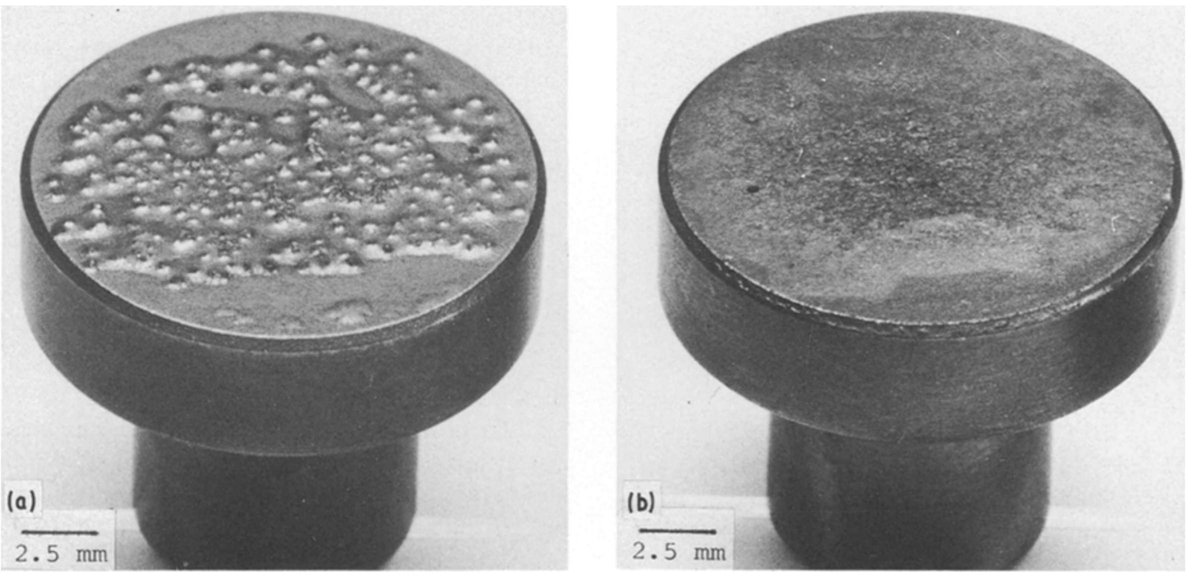


Figure 6 Appearance of natural diamond grit button after brazing with Ni–Cr hardfacing alloy (a) with 150 μm thick layer and (b) with 230 μm thick layer.

pull-out within 15 s of cut. Inadequate wetting and bonding of diamond with such a layer thickness under the given set of brazing conditions was the main cause of the tool failure.

The situation did not improve much with a layer thickness of 50 μm. Within 15 s of cut, a large number of grits was uprooted from the brazed layer. This can be well understood from Fig. 9. Comparing the macrographs of Figs 8 and 9, one can realize that still only few grits were held in the cutting zone of the button prepared with a 50 μm thick layer. The micrographs of Fig. 9 show such grits, which developed fracture marks during cutting but held in the bond. For practical purposes, such a tool cannot qualify as an efficient one. It was strongly felt that the mechanical strength of the bond could also influence grit retentivity. It may not be unreasonable to speculate that the pulsating force developed during cutting could cause rupture of the metal sheath around the grits, finally resulting in break-out of the grits from the bond. However, it needs further study to establish this. The brazing temperature and time were respectively 1080 °C and 30 s. Investigation should also be carried out on the influence of these two parameters on wetting and bonding.

In both cases, with the removal of most of the grits from the cutting zone the button surface was exposed to the alumina disc, which started rubbing on the steel button and produced scratches as is evident from Figs 8 and 9.

With the present bonding technique and the conditions used, a layer thickness of 80 μm of the alloy provided very satisfactory and reproducible bonding. Fig. 10 reveals that even after 15 min of grinding there was no sign of grit dislodgement from the button surface fabricated with natural diamond; rather, the grits underwent fracture. The adhesion of diamond particles to the matrix was so strong that in one case the core part of a grit was ruptured and separated, leaving a crater, but the diamond–braze interface was found to be intact as shown in Fig. 10. Few grits, however, can be seen to develop smooth surfaces known as "wear flats" because of attritious wear.

The grinding test also showed that the bonding matrix was integrated with the synthetic diamond crystals, as can be seen from Fig. 11, and during the course of grinding the grits broke down to a level wetted and covered by the bonding alloy. The SEM micrographs further reveal that in that situation the abrasive work material tended to drag the softer matrix, and as a result the worn and fractured surface of diamond grits became smeared with the brazing alloy.

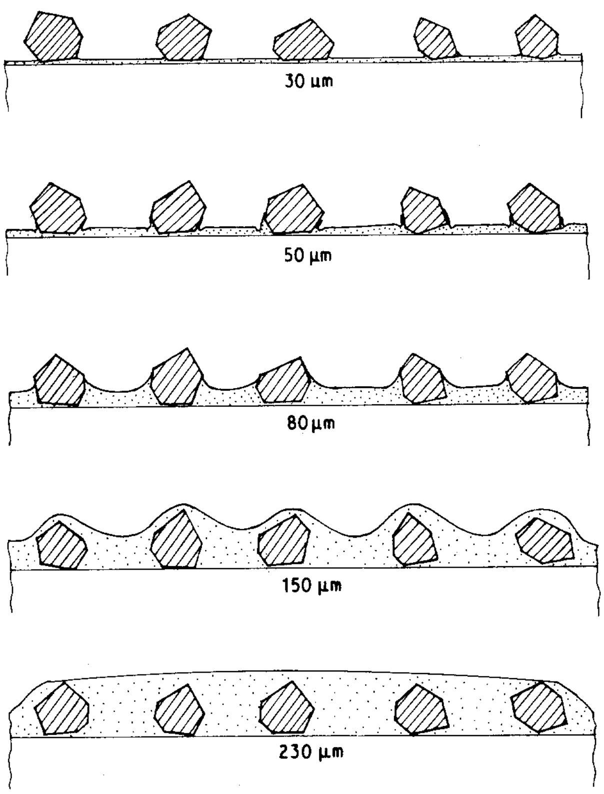


Figure 7 Schematic representation of variations in the wetting pattern of diamond grits with the initial thickness of Ni–Cr alloy.

Attempts were also made to study the effectiveness of a Cr-free Ni alloy containing B and Si, in wetting and bonding diamond crystals. An abrasive button was prepared with a 75 µm thick layer of the alloy. The same brazing conditions were used as described earlier. The button thus fabricated was submitted to grinding for assessment of adhesion of the abrasive particles to the Ni-based alloy. The grinding test clearly indicated that the alloy was not an effective bonding material. Although the Ni-based alloy wetted the surface of the steel substrate, it failed to exhibit satisfactory wetting characteristics towards the diamond particles. The poor bond resulted in dislodgement of the grits within 15 s of grinding, leaving small pockets. These pockets were subsequently rubbed against the workpiece and were smoothed out. The rough surface of the rotating disc also produced deep grooves in the matrix layer as can be seen in Fig. 12a.

Another button was fabricated using the same Ni-based alloy. In this case the layer thickness was raised to 230 µm and the brazing time at 1080 °C was extended to 10 min. The grinding test, however, showed that such a change of parameters did not exact any influence on the quality of the bond. Within 15 s of grinding, the grits were removed almost completely and the alumina disc started to cut the matrix, as can be seen in Fig. 12b.

3. Conclusions

1. Ni–Cr-based hardfacing alloy flame-sprayed on a steel substrate could braze both uncoated synthetic and natural diamond grits when brazing was carried out by induction heating at 1080 °C for just 30 s in

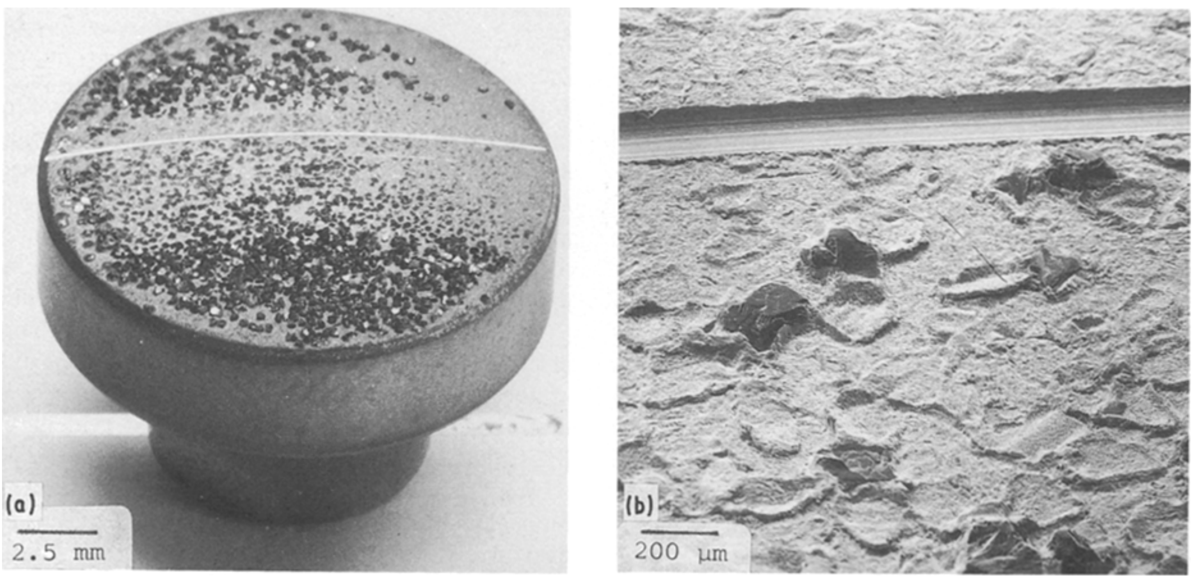
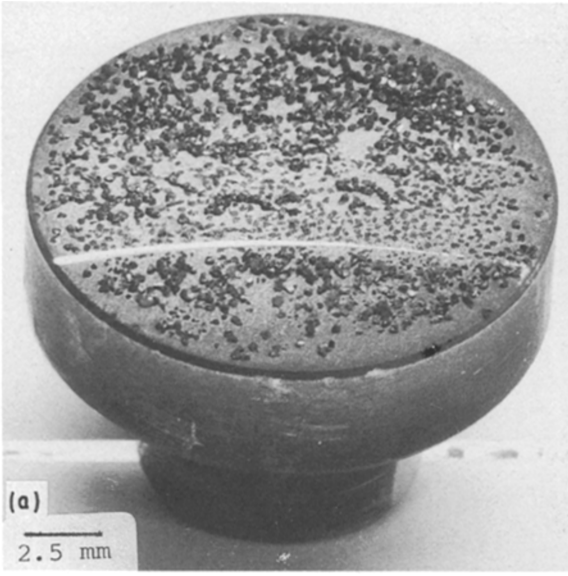
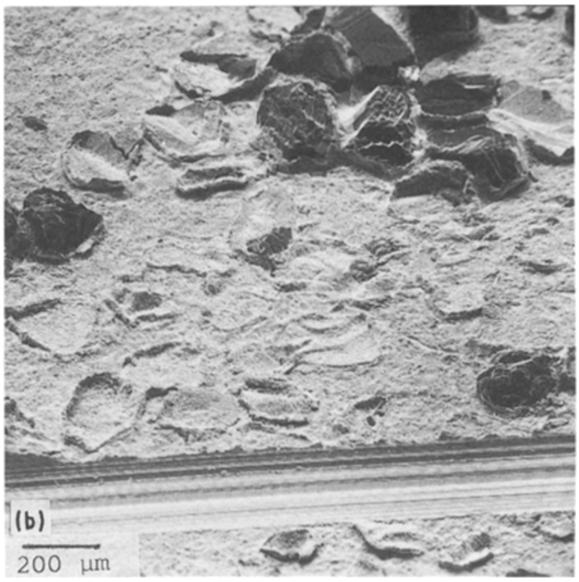


Figure 8 (a, b) Appearance of natural diamond grit button fabricated with 30 µm thick layer of Ni–Cr alloy after 15 s of grinding.





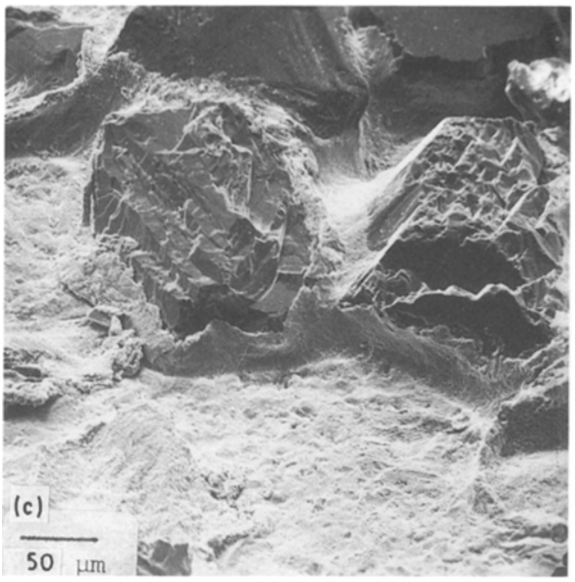


Figure 9 (a–c) Appearance of natural diamond grit button fabricated with 50 μm thick layer of Ni–Cr alloy after 15 s of grinding.

a current of argon, without use of any vacuum or dry hydrogen furnace. The relatively smooth surface of synthetic diamond grit did not cause any difficulty in achieving a strong bond with the matrix.

2. During melting, Cr of the hardfacing alloy segregated preferentially towards the bare surface of diamond to form a chromium-rich reaction product which was readily wetted by the alloy. Bond erosion by loose abrasive grinding swarf was also not observed.

3. Under a given set of brazing conditions, wettability of the Ni–Cr alloy towards diamond grits was greatly affected by the initial layer thickness of the alloy, resulting in a significant change of topography of the tool surface.

4. Grinding tests have shown that the grits were not released from the matrix during grinding when the initial thickness of the alloy was 80 μm. The grits suffered fracture at different levels during the course of grinding. However, it was observed that premature grit dislodgement had been the major cause of tool failure when the layer thickness of the alloy was

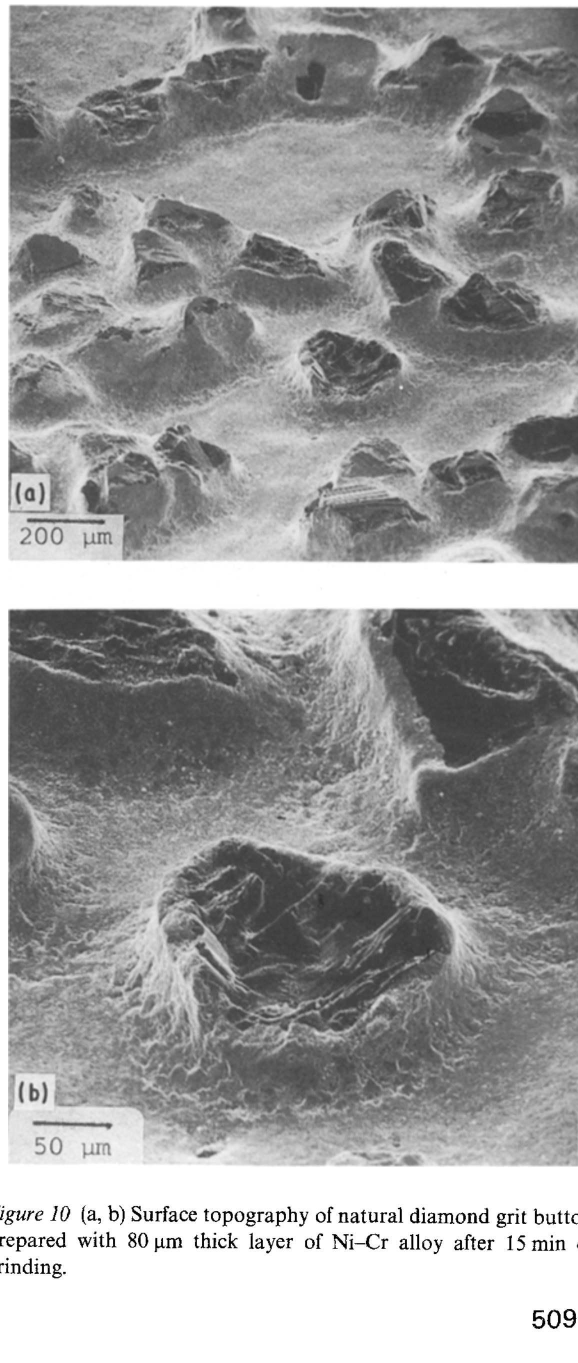


Figure 10 (a, b) Surface topography of natural diamond grit button prepared with 80 μm thick layer of Ni–Cr alloy after 15 min of grinding.

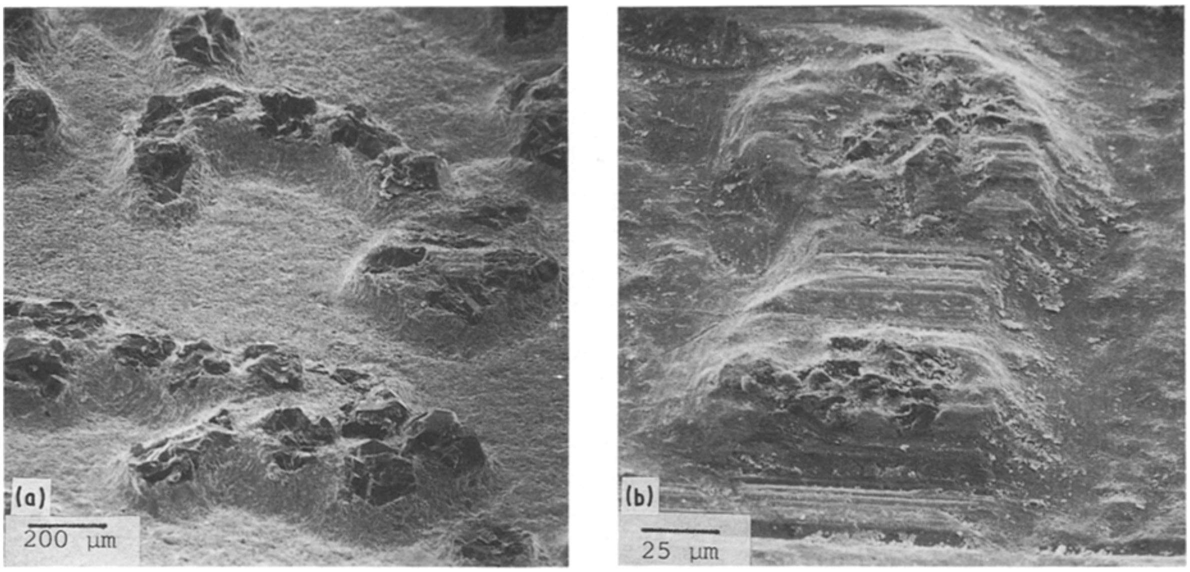


Figure 11 (a, b) Surface topography of synthetic diamond grit button prepared with 80 µm thick layer of Ni–Cr alloy after 15 min of grinding.

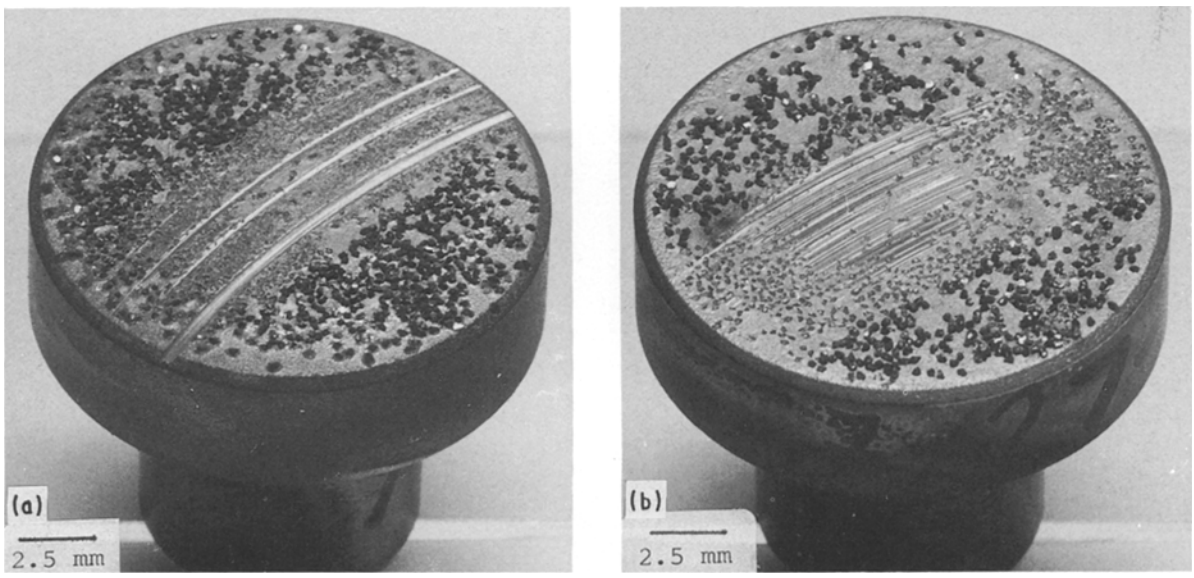


Figure 12 Appearance of diamond grit buttons after 15 s of grinding, fabricated with Cr-free Ni-based alloy (a) with 75 µm thick layer and 30 s brazing time, and (b) with 230 µm thick layer and 10 min brazing time.

30 µm. The situation did not improve much when the thickness was raised to 50 µm.

5. Nickel, which is mostly used for bonding diamond grit by galvanic deposition on a steel substrate, could not effectively bond bare diamond by liquid-phase bonding. A greater amount of bonding alloy or a prolonged brazing time did not improve the quality of the bond either. This can be explained by the non-reactivity of nickel towards diamond under brazing conditions.

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