Diamond Cutting Tools with a Ni_3Al Matrix Processed by Reaction Pseudo-Hipping

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Nickel aluminide, Ni_3Al, has high hot strength, which could help overcome the high heat and the interrupted vibrations that diamond cutting tools encounter during operation. Reaction pseudo-hipping, on the other hand, require only a short dwell time at high temperatures, which are detrimental to the diamond grits. Thus, it is promising to combine the unique nickel aluminide with the unique reaction pseudo-hipping process and replace the commonly used cobalt matrix. This study reports for the first time the process and application of reaction-pseudo-hipped Ni_3Al matrix for diamond tools. In this work, mixtures of elemental nickel, aluminum, boron powder, and diamond particles are reaction-pseudo-hipped. Densities greater than 99 pct and mechanical properties comparable to those of the cobalt are attained. With high-grade diamond grits, the tools thus prepared show, under dry cutting conditions, a grinding ratio 118 pct higher than that with the cobalt matrix.

I. INTRODUCTION

TO attain a satisfactory cutting performance, the first requirement of the matrix of a diamond tool is adequate wear resistance. A wear rate that is too fast will cause premature pullout of the diamond particles, while a wear rate too slow will cause rounding of the sharp edges, commonly known as glazing, and subsequent loss of the cutting capability.[1,2] The second requirement is good retention of the diamond particles, particularly the protruding ones, which are cutting against the workpiece. The matrix must also have high hot strength and sufficient toughness to overcome the high heat and the interrupted vibrations that occur during cutting.[3,4,5] Among the various matrix materials that can meet these requirements, cobalt is the one most widely used.[4–7] However, cobalt is a strategic material and is costly. Thus, the replacement of cobalt binder phase by other materials has been the subject of many investigations.

Since diamond is not a stable material under normal pressures, it can convert to graphite easily at high temperatures. Thus, to avoid deterioration of the diamond particles, refractory metals are seldom used as the matrix material because they require lengthy sintering time at high sintering temperatures. The self-propagating high-temperature synthesis (SHS) and reactive sintering, on the other hand, require minimal sintering time to attain high densities due to the high exothermic reaction between the constituents.[8,9] Several attempts have been made to produce diamond-containing SHS materials using titanium diboride (TiB_2) and nickel aluminide (NiAl) matrix.[10,11,12] These studies indicated that the extent of diamond particle preservation depended on the time and the peak temperature that the diamond endured during the reaction.[10] As a result, several approaches were taken to reduce the diamond damages, such as adding titanium hydride to create a protective reducing atmosphere around diamond particles or using bilayer structures to adjust the combustion temperature.[10,12] Although these findings are encouraging, none of the previous studies have provided the needed information on the mechanical properties or the cutting performance of the tools thus prepared. This is probably because these two matrix materials are brittle in nature.

Boron-doped nickel aluminide, Ni_3Al, is an attractive material for structural applications at elevated temperatures.[13,14] Due to its high hot strength, Ni_3Al has been used as the matrix material for WC, TiC, and Al_2O_3 composites. To fabricate these composites, prealloyed Ni_3Al powders, not elemental powders, and refractory materials were hot pressed at a temperature between 1150 °C and 1500 °C for 15 to 120 minutes using a pressure as high as 34 MPa.[15,16] Unfortunately, these processing conditions cannot be transferred to diamond tools because of their long presence time at high temperatures. However, the boron-doped nickel aluminide, Ni_3Al, can be made using reaction sintering of elemental Ni, Al, and B powders. With a careful selection of the particle size, sintering atmosphere, sintering temperature, heating rate, and Ni/Al stoichiometry, high-density Ni_3Al parts with a good combination of hardness, strength, and toughness can be fabricated through the reaction sintering process.[17,18,19] This reaction sintering technique, however, usually leaves some large pores in the compact, and the dimensional control is difficult because of the formation of the liquid phase during sintering. To resolve these problems, hot pressing and hot isostatic pressing have been employed and found to be effective.[18,19,20]

Since the boron-doped Ni_3Al has good combinations of hardness, strength, and toughness and can be fabricated through reaction sintering, which requires a short dwell time at high temperatures, it should be worthwhile to investigate its use as a matrix material for diamond tools. To further reduce the dwell time at high temperatures and preserve the original properties of the diamond, it is even more promising to apply pressure during sintering. Thus, the objective of this study was to employ reactive pseudo-hipping on boron-doped nickel aluminides and to fabricate diamond tools with such a matrix.

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Table I. Characteristics of the Matrix Powders Used in This Study

	Ni	Al	B	Co
Designation	Ni-123	Al-1182	B-1121	Diamond-grade P
Supplier	Inco, Wyckoff, NJ	Cerac, Milwaukee, WI	Cerac, Milwaukee, WI	Viridian, Fort Saskatchewan, Alberta, Canada
Average particle size (Fisher subsieve sizer), μm	6.4	14.7	18.2	4.7
Pycnometer density, g/cm^3	8.89	2.69	3.51	8.87
Carbon content, pct	0.081	0.025	0.068	0.220
Oxygen content, pct	0.196	0.330	0.313	0.592
Nitrogen content, pct	0.002	0.014	0.008	0.010

II. EXPERIMENTAL PROCEDURE

The powders selected in this study include elemental nickel, aluminum, cobalt, and boron. The characteristics of these powders are listed in Table I. Two grades of diamond particles, SDB1100 and SDA85+ (De Beers, Shannon, Ireland), were selected. The SDB1100 diamond has higher high-temperature strength and is synthesized using Ni-base catalysts. The SDA85+ diamond is processed using Co-base catalysts. The particle sizes of these two diamond particles were between 40 and 50 mesh. Their characteristics are given in Table II.

In the first phase of the study, Ni_3Al specimens without diamond grits were produced so that the intrinsic mechanical properties could be measured properly. To prepare the matrix material, elemental nickel and aluminum powders in the atomic ratio of 76 to 24, which is based on previous studies,[17,18] were weighed and then mixed with the boron powder in a V-cone mixer for 1 hour. The powder mixture was compacted at a pressure of 400 MPa into 70 pct dense plates of 31.7 × 12.7 × 6 mm. For reaction sintering, specimens were heated at 30 °C/min to 700 °C and held for 10 minutes.

Since the density thus obtained was lower than 92 pct and with large pores present, the reaction pseudo-hipping process was then employed. Segments of about 40 × 8 × 3 mm were compacted, also at a pressure of 400 MPa. The preforms were then placed into a graphite die and were surrounded by approximately 2-mm-thick alumina powders on all sides. The alumina powder served as the pressurizing media and also as a heat insulator so that when the exothermic reaction occurred, the heat generated would not escape to the ambient through the highly thermally conductive graphite mold. The compacts in the mold were heated at the rate of 30 °C/min to 700 °C and held for 5 minutes. The pressure employed was 20 MPa. The specimens were examined for completeness of reaction sintering with an X-ray diffractometer.

To compare the mechanical properties of the new matrix material to those of the cobalt, cobalt powder compacts of 31.7 × 12.7 × 6 mm were also prepared using the pseudo-hipping process. The specimens were heated at the rate of 30 °C/min. The sintering was carried out at 820 °C for 15 minutes under a pressure of 20 MPa.

To prepare the diamond tools, diamond grits at the concentration of 0.88 Karat/cm^3 (5.0 vol pct or 2.4 wt pct) were added to the metal powder mixture. The admixed powder was precompacted and then pseudo-hipped using the same procedure as described earlier. To determine if the properties changed after sintering, diamond grits were extracted from the matrix first by immersing the sintered compact in aquaregia solution. The grits were examined using a scanning electron microscope (SEM) and then sandwiched between two alumina plates, and were crushed in a compression machine at the crosshead speed of 0.5 mm/min. The strength data reported are an average of 20 grits. These extracted diamond grits were also examined with a Raman spectrometer to verify if graphitization occurred during sintering.

Table II. Characteristics of the Diamond Particles Used in This Study

Type	SDA85+	SDB1100
Catalyst	Co-base	Ni-base
Strength (25 °C)*	7	9
Thermal strength (900 °C)**	7	9
Thermal strength (1100 °C)†	5	8

*Index of diamond strength at room temperature.
**Index of diamond strength after heat treatment at 900 °C.
†Index of diamond strength after heat treatment at 1100 °C.

To evaluate the cutting performance of the tools, sintered compacts, frequently called cutting inserts, were welded at opposite ends of a circular steel plate of 180-mm diameter. The inserts were addressed and the assembled saw was balanced before the cutting tests started. The cutting was performed against supreme black granite blocks. The cutting speed was 30 m/s and the feed rate was 0.2 mm per cut. The grinding performance was assessed by the grinding ratio, which is the volume removed from the granite block divided by the volume worn from the diamond tools. Since the width and length of the insert almost remained the same after grinding, the worn volume depended mainly on the difference in height before and after grinding.

III. RESULTS

The results are separated into the following three sections: (1) the processing and properties of the matrix, (2) the properties of the diamond particles, and (3) the cutting performance.

A. *Nickel Aluminide Matrix*

To determine whether the properties of Ni_3Al were compatible to those of cobalt, the optimum processing parameters and the amount of the boron addition were investigated in the first phase of this study. Figure 1 shows that the density of the plain reaction-sintered nickel aluminide was only 6.75 g/cm^3, or 90 pct of the theoretical density. With 0.1 and 0.3 wt pct boron addition, the density increased slightly to 6.82 and 6.94 g/cm^3, respectively. When pseudo-hipping was employed, the density of the boron-free compact improved significantly to 7.49 g/cm^3, or 99.8 pct. With the addition of 0.1 and 0.3 pct boron, the absolute density decreased slightly to 7.42 and 7.29 g/cm^3, respectively.

The X-ray diffractometer analysis indicated that all nickel and aluminum had reacted completely and formed Ni_3Al. A typical diffraction pattern of the pseudo-hipped compact is shown in Figure 2. When 0.1 pct boron was added, Figure 3 shows that the hardness, tensile strength, and elongation all improved significantly and were HV273, 700 MPa, and 12.2 pct, respectively. These properties were close to the 722 MPa tensile strength and 10 pct elongation reported previously by German and Bose on reaction hipped specimens.[20] With 0.3 pct boron, the hardness and tensile strength continued to increase. However, the elongation decreased from 12.2 to 6.4 pct. To decide whether 0.1 or 0.3 pct boron should be used for the subsequent experiments, a comparison of their mechanical properties to that of the cobalt was made, as shown in Table III. Considering that the 0.1 pct boron addition had an elongation of 12.2 pct, closer to the 15 to 22 pct of the cobalt, and was more compatible in hardness, it was selected for making the diamond tools in the following experiments.

B. *Diamond Grits*

After adding diamond grits in the concentration of 0.88 Karat/cm^3, the hardness, bending strength, and density of the specimen decreased slightly, as shown in Figure 4. The different grades of the diamond did not show significant differences. However, the SEM examinations, as shown in Figure 5, indicated that some SDA85+ diamond grits were fractured during the bending test while the SDB1100 grade retained their cube-octahedron shape. To analyze the property changes of these two diamonds after sintering, specimens were immersed in aquaregia to dissolve all the nickel aluminide and to extract the diamond grits. The crushing test on the recuperated diamonds indicated that the strengths of the SDA85+ particle decreased by about 60 pct, while the SDB1100 lost about 20 pct. A closer examination of the extracted diamond particles, as shown in Figure 6, further revealed that cracks were present in the SDA85+, but not in the SDB1100 grade. These cracks were mostly likely caused by the fast heating of the reaction and the mismatch of the thermal expansion between the diamond and the metallic catalysts remaining in the particle.

C. *Cutting Performance*

Figure 7 shows the grinding ratio of SDA85+ and SDB1100 diamond inserts when cutting was performed with cooling fluids. In the case of SDA85+, the cobalt matrix shows a grinding ratio of 2380, better than the 1780 of the

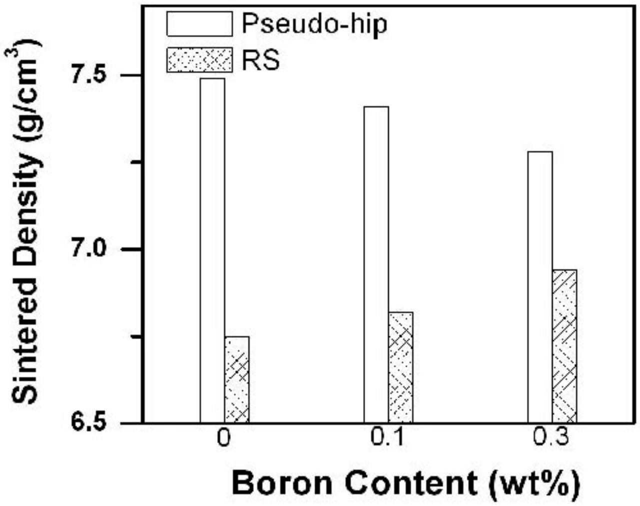


Fig. 1—The sintered densities of reaction-sintered and reaction-pseudo-hipped nickel aluminides without boron and with 0.1 and 0.3 wt pct boron additions.

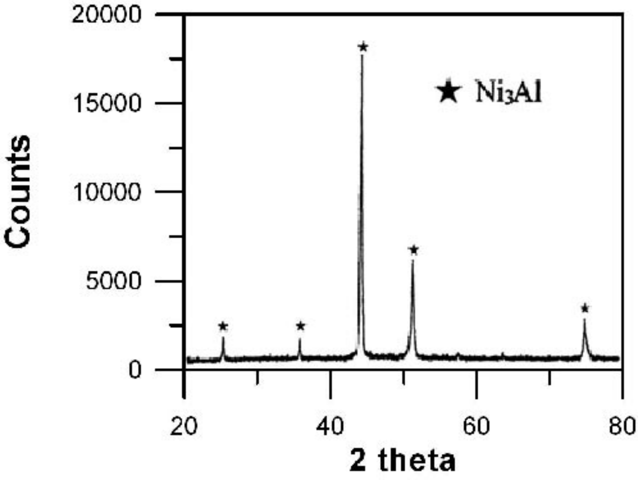


Fig. 2—The X-ray diffraction pattern of the reaction-pseudo-hipped nickel aluminide with 0.1 pct boron addition.

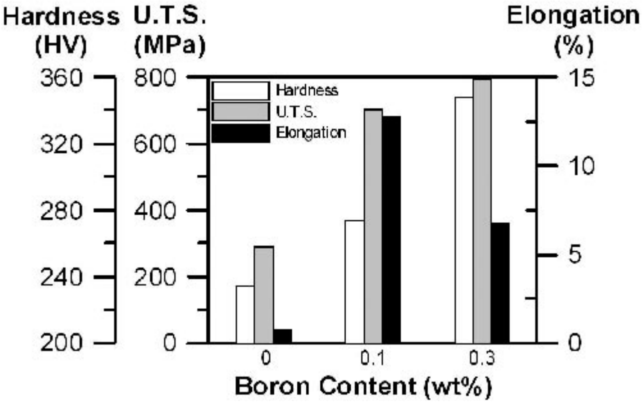


Fig. 3—The hardness, tensile strength, and elongation of the reaction-pseudo-hipped nickel aluminide without boron and with 0.1 and 0.3 wt pct boron additions.

Table III. Comparison of the Tensile Strength, Elongation, and Hardness of Ni_3Al + 0.1 Wt Pct B and Cobalt

			Hardness		
Material	Tensile Strength, MPa	Elongation, Pct	HV	HRB	Source
Ni_3Al + 0.1 wt pct B	700	12.2	273	—	this study
Ni_3Al + 0.3 wt pct B	795	6.4	346	—	this study
Co	760 to 860*	15 to 22*	(203, converted)	92**	Refs. 2**, 21*
	—	—	(229 to 365, converted)	96.5 to 109.5	Ref. 22**
	—	—	272		this study**

*Annealed strip.
**Hot pressed.

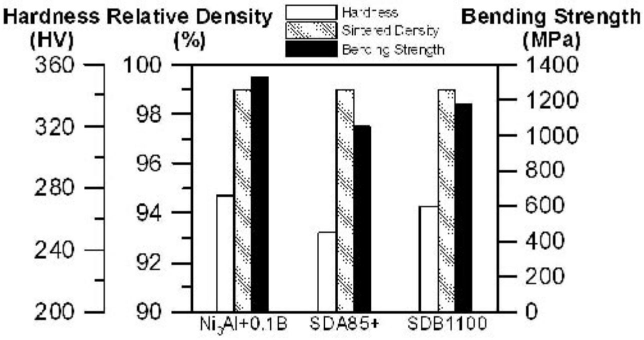
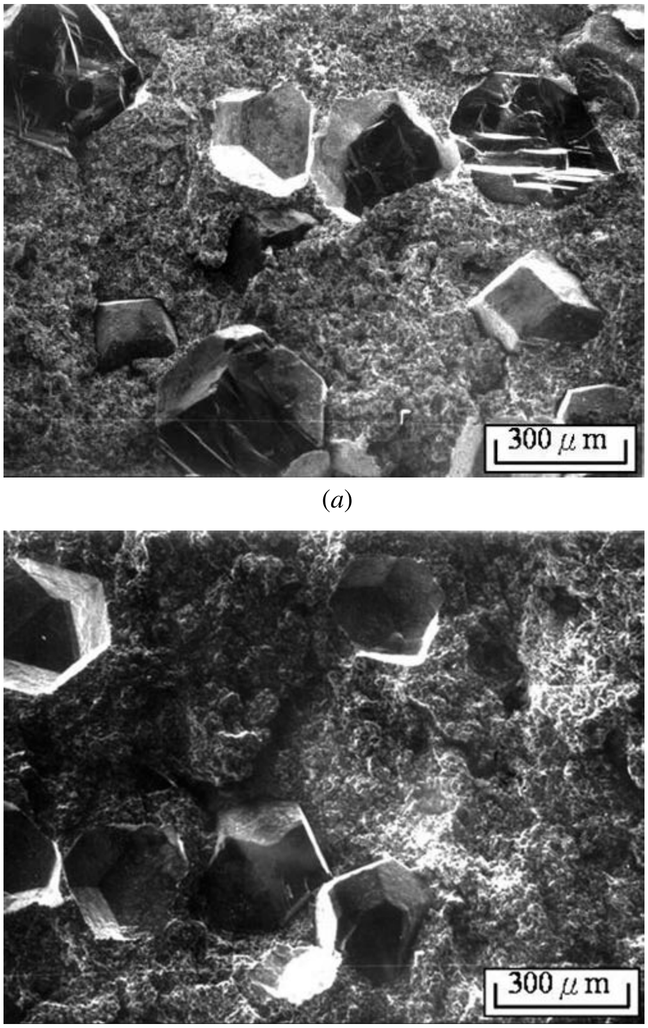


Fig. 4—The relative density, hardness, and bending strength of the reaction-pseudo-hipped nickel aluminide that contains 5 vol pct SDA85+ or SDB1100 diamond grits.

nickel aluminide matrix. This was most likely caused by the deterioration of the diamonds during reaction pseudo-hipping. However, when the better grade of SDB1100 was used, the cutting performance between the two matrixes was comparable with the grinding ratio of about 4000. Although the new matrix did not show any advantage over the cobalt during wet cutting, significant differences were noticed during dry cutting, as shown in Figure 8. When SDB1100 was used, the grinding ratio of the nickel aluminide was 1850, more than twice that of the cobalt matrix at 850. In the case of the SDA85+ diamond, the grinding ratio of the new matrix remained slightly lower than that of the cobalt matrix due to the damage resulting from the exothermic reaction.

IV. DISCUSSION

The results presented in Section III show that the consolidation of nickel aluminides relies on the exothermic heat released during the reaction sintering. This heat, however, could be lost easily through the graphite mold, which has a high thermal conductivity. In the early stage of the study, no alumina powder was used between the specimen and the die. The specimen was in direct contact with the graphite die and the punches. Due to the high thermal conductivity of the graphite, the heat loss was significant. As a result, the density after hot pressing was only 80 pct and the reaction was incomplete, as was indicated by x-ray analysis. To reduce the heat loss, the specimen was embedded in alumina powders, the thermal conductivity of which is about one tenth that of the graphite. The pseudo-hipped density was improved from 80 to 99 pct.

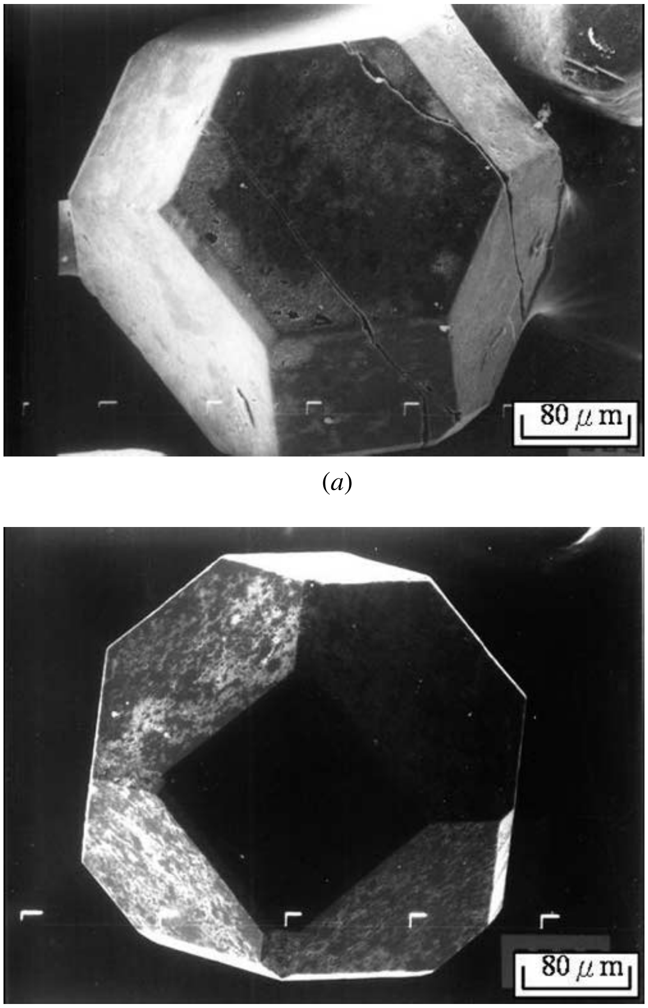


(*a*)

(*b*)

Fig. 5—The fracture surfaces of bent specimens that contain (*a*) SDA85+ and (*b*) SDB1100 diamond grits showing that some SDA85+ diamonds are fractured.

In contrast, if too much exothermic heat is absorbed, the diamond grits could be damaged. To monitor the temperature rise during sintering, a thermocouple was embedded in the specimen. The *in-situ* temperature reading, shown in Figure 9, indicated that the reaction started at about 580 °C and the peak temperature was about 1350 °C. The interval above 1000 °C was less than 1 minute. Despite the short period at high temperatures, it is believed that such exothermic reaction caused some deterioration of the diamond grits, such as the macrocracks shown in Figure 6. In addition, Figure 10 also shows that some graphitizations occurred



(*a*)

(*b*)

Fig. 6—The morphology of (*a*) SDA85+ and (*b*) SDB1100 diamond particles showing the presence of cracks in the SDA85+ particle.

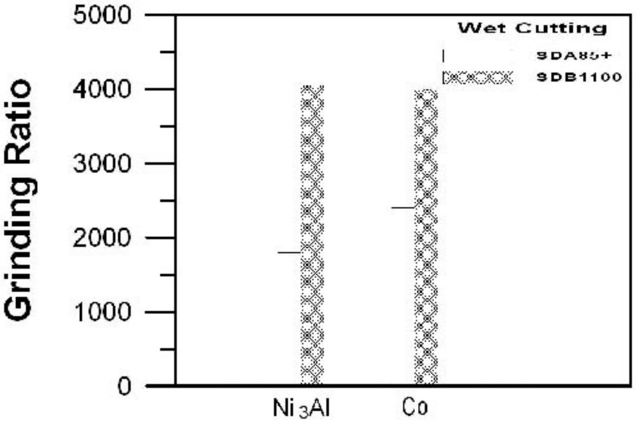


Fig. 7—The grinding ratio of diamond inserts with the Ni_3Al matrix is compatible to that with the Co matrix during wet cutting when SDB1100 diamond particles are used.

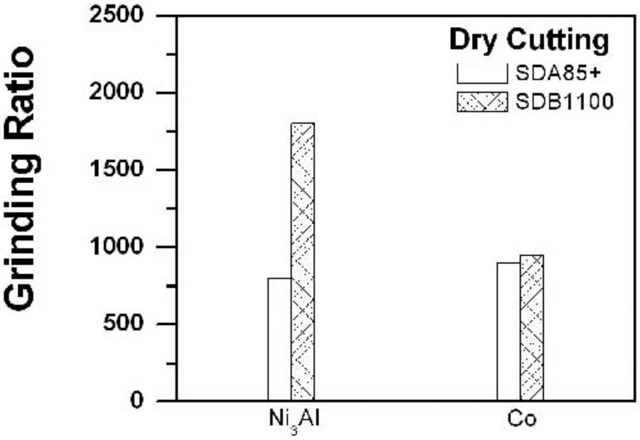


Fig. 8—The grinding ratio of diamond inserts with the Ni_3Al is superior to that with the Co matrix during dry cutting when SDB1100 diamond particles are used.

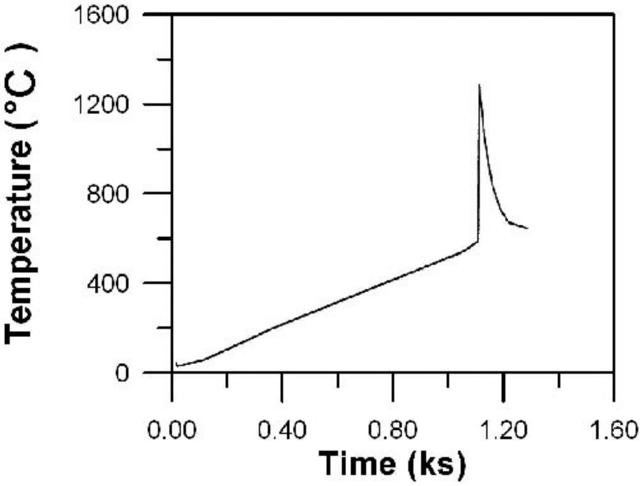


Fig. 9—The *in-situ* temperature reading indicating a sharp temperature rise during the exothermic reaction.

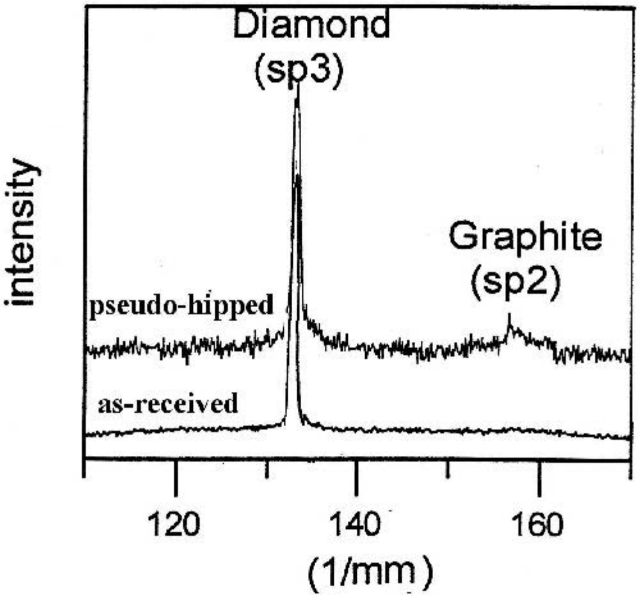


Fig. 10—The Raman spectrum of the extracted diamonds showing that slight graphitization occurred during the pseudo-hipping process.

during the processing, as evidenced by the small SP2 peak in the Raman spectrum. These results suggest that, for further improvements, a modification on the matrix composition is needed to reduce the peak reaction temperature or to shorten the reaction time.

Of the two diamonds evaluated, the SDB1100 is a better grade and can sustain the high reaction temperature, as indicated by the thermal strength index in Table II. To fully take advantage of the properties of the nickel aluminide at high temperatures, such as in the dry cutting conditions, the selection of the diamond grade is thus a prerequisite. The processing materials, particularly the type of the nickel, aluminum, and pressurizing media, are also critical. With the previous findings obtained by Bose *et al*.,[17] who showed that the heating rate and the particle size of aluminum are important factors in attaining optimum sintered properties of Ni_3Al, it is believed that the preliminary positive results presented here can be further improved.

V. CONCLUSIONS

With the unique high strength at high temperatures, boron-doped nickel aluminide (Ni_3Al) was used for the first time as a new matrix material for diamond cutting tools. The cutting inserts were prepared by reaction pseudo-hipping mixtures of elemental boron, nickel, and aluminum powders and the diamond grits. Densities greater than 99 pct can be attained due to the high exothermic heat released during the reaction sintering. The hardness, tensile strength, and elongation of the Ni_3Al matrix are similar to those of the cobalt. The temperature upsurges up to 1350 °C, however, deteriorate the properties of the diamond. This problem can be overcome by using diamond particles with high thermal strength, such as the SDB1100 grade used in this study.

The dry cutting results show that a 118 pct higher grinding ratio than that of using the Co matrix can be attained when the new matrix is used. This is mainly due to the improvement in the high-temperature properties by the boron-doped nickel aluminide.

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