Brazing Diamond Grits Onto Stainless Steel using Active Filler Metal and Porous Nickel as an Interlayer: Analysis of the Porous Nickel/Stainless Steel Interface

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Abstract. In this research, diamond grits were brazed to stainless steel successfully using active filler metal and porous nickel as an interlayer. Brazing was accomplished at three (3) brazing temperatures (880ºC, 920ºC and 960ºC) for 10 minutes. SEM-EDS and XRD analyses were adopted to facilitate the research process. However, the analyses were specifically focused on the porous nickel (Ni)/stainless steel interface. The interface near the bonding diamond did not seem strong enough for potential grinding tool applications. It is concluded in this research that 960ºC brazing temperature is the best for brazing because it causes less and discontinuous formation of the AgTi2 reaction layer in the brazed area. Otherwise, a continuously reacting layer would increase the small void formation in the area near the reaction layer, which could deteriorate the bonding joint.

1. Introduction
Demand for industrial diamonds is increasing due to the properties of diamond, which is the hardest material in nature. Diamond also has super abrasive ability for stock removal from various kinds of material surfaces. Therefore, several methods of diamond grit bonding have been investigated and patented [1, 2]. Common bonding methods used to attach diamond grits to tool matrix surfaces are sintering and electroplating. However, because of the mechanical burying of the diamond grits, it is difficult to achieve high bonding strength due to the uneven segregation of the diamond grits on the tool matrix surface [1]. The bonding process of diamond grits is important for enhancing tool performance. Hence, the technology of diamond brazing was introduced in the diamond tool industry in the 1990s to improve the bonding strength of diamond grits [3].

Significant brazing has been attained successfully using filler metals like Ni-Cr, Ag-Cu-Ti, etc. [4, 5]. Brazing is a promising method for manufacturing diamond abrasive tools. In general, diamond brazing can be performed at high temperatures (in the range of 930 - 1100ºC) but is also dependent on the type of brazing filler metal used [6]. It is interesting to note that it is difficult to braze diamond at brazing temperatures above 760ºC. This is due to diamond graphitization and oxidation that tend to occur from this temperature
onwards. Brazing of diamond can also be difficult to achieve on account of the high interfacial energy between the diamond and most metal alloy materials [7]. Therefore, it is suggested that more attempts should be made to improve brazing methods to achieve better bonding performance.

In this research, a preliminary attempt was made using porous Ni and commercial active filler metal (Ag-Cu-Ti) to join diamond grits with stainless steel AISI 304. Porous nickel (Ni) was inserted as an interlayer to increase the disperse-ability of the diamond grits onto stainless steel during brazing. Active filler metal was used due to its good wettability with the diamond surface. Due to the used of interlayer, there are two interfaces were important to analyze: (1) diamond/porous metal and (2) porous metal/metal. As part of the analysis, the aim was to investigate and determine only the brazing interface of the porous metal/metal side.

2. Methodology
In this research, industrial diamond grits acquired from Japan with average size of 0.4156 mm and coated with silver (Ag) were employed. Austenitic Cr-Ni stainless steel substrate (AISI 304) with dimensions of 20 mm x 20 mm x 3 mm served as the base metal. The brazing filler metal used in this work was a commercial active filler metal, Ag-Cu-Ti. This was manufactured by Wesgo Metals, USA, consists of 63Ag-35.25Cu-1.75Ti alloy (wt.%) and has solidus and liquidus temperatures of 775ºC and 795ºC, respectively. The filler metal with a thickness of 50 µm was then cut into 15 mm x 15 mm dimensions. The 50ppi porous nickel (Ni) with an average pore size of 0.2106 mm was prepared in 15 mm x 15 mm x 1 mm dimensions. The sample was arranged in a sandwich configuration on a special clamp with stainless steel as the base, followed by filler metal, porous Ni, filler metal and diamond grits on top. The diamond grits were 0.2g per sample.

Three brazing temperatures of 880ºC, 920ºC and 960ºC and 10 min brazing time were selected as the brazing parameters. The samples were brazed in a furnace with controlled atmosphere and argon gas at a flow rate of 5 L/min. The samples were heated and cooled at a rate of 10ºC/min, respectively. After brazing, all the samples were carefully ground using SiC grit paper and polished with diamond suspension for characterization.

The characterization machine used for analysis was a Scanning Electron Microscope (SEM) model Phenom Pro X Desktop equipped with an Electron Dispersive X-ray Spectroscope (EDS). An X-Ray Diffractometer (XRD) model PANalytical Empyrean was employed for testing, while analysis was done using HighScore software to identify the elements and compounds/phases.

3. Results and Discussion
Brazing diamond grits to stainless steel was successfully achieved with the addition of porous Ni as an interlayer and Ag-Cu-Ti active filler metal. However, the bonding of the diamond with filler metal and porous Ni (the first interface) appeared to not be strong enough for potential grinding tool applications. Therefore, the brazing method needs to be improved accordingly. Further analysis was conducted on the brazed porous Ni and stainless steel (Ni/stainless steel), the second interface.

Figure 1 depicts the interface microstructure at three different brazing temperatures, at which various phases formed on the brazed interface. It is important to note that a piece of brazing filler metal was inserted between the porous Ni and stainless steel before brazing. After brazing, the brazing filler metal fully melted and diffused into the porous Ni and stainless steel. It is interesting to highlight that two colors were present in the porous Ni area, namely grey and white. Point analysis was done using EDS for all samples. Referring to Table 1, the grey area was dominated by Ni element and copper (Cu) that diffused from the brazing filler metal. It can be said that a Cu-Ni-Fe phase formed at point 2. Cu-Ni and CuNi 2 phases formed at points 5 and 7, while the white area indicates an Ag-rich region (point 6). At point 8, the Ag-rich area was also influenced by iron (Fe), Cu and a low concentration of Ni. The dark grey area in the brazing filler metal shows a highest percentage of titanium (Ti).
Figure 1. Microstructure of samples brazed for 10 minutes at different brazing temperatures: (a) 880°C, (b) 920°C and (c) 960°C.

As seen in Figure 1 (a) and point 4 (Table 1), this area shows a higher concentration of Ti than other areas with slightly higher concentrations of Fe, manganese (Mn) and chromium (Cr) that were influenced by the diffusion from stainless steel. The possible phases in this area were Fe-Ti/Fe-Cr/Fe-Mn. The possible phases of each point marked in Figure 1 (a) are listed in Table 1.

**Table 1.** EDS analysis (at.%) and possible phases according to SEM micrographs of the porous Ni/stainless steel interface marked in Figure 1 (a).

| Point      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Copper     | 53.27 | 73.69 | 18.50 | -   | 31.46 | 6.53 | 33.07 | 15.81 |
| Nickel     | 20.55 | 14.35 | 6.68 | -   | 60.47 | -   | 60.39 | 6.28  |
| Iron       | 15.78 | 7.41  | 7.58 | 32.59 | 4.85 | -   | 3.10 | 13.01 |
| Silver     | 3.67  | 4.55  | 67.24 | 13.83 | 3.22 | 93.47 | 3.43 | 64.90 |
| Sulfur     | 2.37  | -     | -    | 4.47 | -    | -    | -    | -    |
| Titanium   | -     | -     | -    | 26.28 | -    | -    | -    | -    |
| Chromium   | 4.36  | -     | -    | 9.36 | -    | -    | -    | -    |
| Carbon     | -     | -     | -    | -    | -    | -    | -    | -    |
| Manganese  | -     | -     | -    | 13.45 | -    | -    | -    | -    |
| Possible phase | Stainless steel + Cu-Ni | Cu-Ni-Fe | Ag-Cu | Fe-Ti/Fe-Cr/Fe-Mn | Cu-Ni | Ag | Cu-Ni | Ag-Cu-Fe + Ni |

Figure 2 presents the XRD analysis of the entire brazed surface of the sample. The XRD analysis clearly shows that all elements in the sample were detected. A few compounds/phases were also evidently present, such as Cu-Ni, Cu-Ni-Fe, Fe-Ti, Fe-Cr and Dideuterium Sulfide (D$_2$S$_2$). It is noted that the peak with the highest intensity was dominated by almost all elements and compounds/phases. This analysis confirms that most of the possible phases listed in Table 1 were present.
Figure 2. XRD analysis on the brazed joint.

Figure 1 indicates that the brazing layer grew with increasing brazing temperature due to the diffusion of the brazing filler metal into the stainless steel to form good bonding. During brazing, the Ag-rich liquid flowed easily and copper was depleted at high temperature. In this research, the brazing temperature of 960°C nearly reached the melting point of Ag (961.8°C). Figures 1 (a) and (b) show a continuous reaction layer crossing along the brazed layer. The reaction layer is obvious in the sample brazed at 920°C for 10 minutes (Figure 1 (b)). However, there was also a potential crack. In Figure 1 (c), the reaction layer shows discontinuity with lower thickness compared to the sample brazed at 920°C.

Therefore, the reaction layer was analyzed to identify the possible phases. Figure 3 displays a highly magnified micrograph of the sample brazed at 920°C with EDS analysis (at. %) and the list of possible phases.

Figure 3. SEM micrograph of the sample brazed at 920°C with EDS analysis and list of possible phases.

The reaction layer is marked at point 5. A possible phase in the reaction layer was Ag-Ti (AgTi₂) or Fe-Cr with carbon content. However, the EDS value for Fe-Cr was lower and less accurate compared with the EDS value for Ag-Ti. It is also important to highlight that the phase was not TiC in accordance to the peaks in the XRD that show no match for this phase as stated in literature [8]. It can also be said that almost the same phase was detected at point 3 (AgTi) with different stoichiometric elements. In line with literature, the Ag-Ti phase was not expected to be very brittle nor cause joint strength deterioration [9]. However, small
voids were observed in the Cu and Ag-rich phases near the reaction layer. Void formation is not good for bonding strength performance during servicing as crack failure could occur at this point. Hence, according to this analysis, the sample brazed at the highest temperature exhibited a good bonding interface due to the minimal and discontinuous AgTi$_2$ phase formation.

4. Conclusion
Good bonding was observed at the porous Ni/stainless steel interface. The results reveal that the filler metal and stainless steel diffused after brazing and a reaction layer of AgTi$_2$ formed and crossed along the brazing layer. The reaction layer appeared to form continuously at a low temperature (880°C). However, the reaction layer increased in thickness at 920°C brazing temperature and a crack was observed at low magnification due to the small void formation in the area near the reaction layer. At higher temperature (960°C), the reaction layer formed discontinuously due to the increasing Ag liquidity because the brazing temperature was close to the Ag melting point. The Ag-Ti phase formed was not expected to be very brittle nor cause joint strength deterioration. However, to improve the bonding performance, it is recommended to reduce the formation of this reaction layer. In this research, brazing at 960°C was more suitable for good bonding performance.

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