Arc Resistance Rise using Powder Mixture of BN Powder and Silica-Sand during DC Interruption Process

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Abstract: An arc quenching in a direct current(DC) fuse requires an arc resistance(r_{arc}) rising due to evaporation of an arc quenching medium. This paper newly selected powder mixture of boron-nitride(BN) powder and SiO_2 powder as new DC arc quenching medium and applied for 1000 A DC arc interruption. As a result, r_{arc} was successfully increased with the BN powder admixing rate. This r_{arc} rise can be interpreted based on large collision integral of B and N atoms and electron density decay due to BN vapour admixing into the arc.

Keywords: DC arc interruption, Arc resistance, powder, Thermal plasma, Nitride material

1. Introduction

Direct current(DC) fuse is one of a protection device for DC system[1]. The DC fuse consists of copper(Cu) fuse element as current channel and a flattery silica-sand(low purity SiO_2 sand) as an arc quenching medium.

During a fault current interruption process in the DC fuse, a DC arc can be formed due to an evaporation of the Cu fuse-element and an ionization of a Cu vapour. Then, the flattery silica-sand can be decomposed due to the DC arc. This decomposition of the silica-sand quenches the DC arc, which increases an arc resistance r_{arc}. As a result of r_{arc} rise, the fault current can be reduced to zero ampere to achieve a DC arc quenching. Therefore, r_{arc} rise is necessary to increase an interruption capacity of the DC fuse. To further increase in r_{arc}, it is necessary to increase an electrical resistivity ρ of the arc due to decrease in an arc temperature or the admixing of the vapour of the arc quenching medium into the arc.

The authors have been studied about the DC fuse to increase r_{arc}[2-5]. As one of the researching results, the authors found that the admixing of the silica-sand vapour into the Cu arc decreased ρ of a Cu/silica-sand vapour mixture at temperature T below 10 kK[5]. This lowering ρ is arise from the low electron impact collision integral of O atom and the low ionization potential of Si atom. In addition, a thermal diffusivity α was also decayed due to the silica-sand vapour admixing into the Cu arc at T below 7 kK. The thermal diffusivity is important indicator of a conduction heat loss[6] of the arc and decaying α leads decreasing the conduction heat loss. Therefore, these lowering both ρ and α should be improved to further rise in r_{arc}. This issue requires development of new DC arc quenching medium which can improve both ρ and α with vapour admixing into the Cu arc.

This paper represents the DC arc quenching using new arc quenching medium with the flattery silica-sand (hereafter abbreviated as Silica-sand). In this paper, we selected powder mixture of a boron-nitride(BN) and the flattery silica-sand as new DC arc quenching medium. Firstly, we describe selection criteria of new DC arc quenching medium. Secondly, we represent gas properties of selected new DC arc quenching medium based on chemical compositions. Finally, we carried out the DC arc quenching experiment using powder mixture of BN and Silica-sand. Based on the experimental result and the calculation result of the chemical composition and electron density of the BN/Silica-sand vapour, we simply discuss the arc resistance rise by the utilization of the BN/Silica-sand powder mixture.

Table I Properties of arc quenching media in solid state

	Resistivity ρ [Ω/cm]	Thermal conductivity κ [W/(m K)]	Sublimation point [K]
Silica-sand	10^{15}	1.3-10	2503
h-BN	10^{14}	60-200	3246

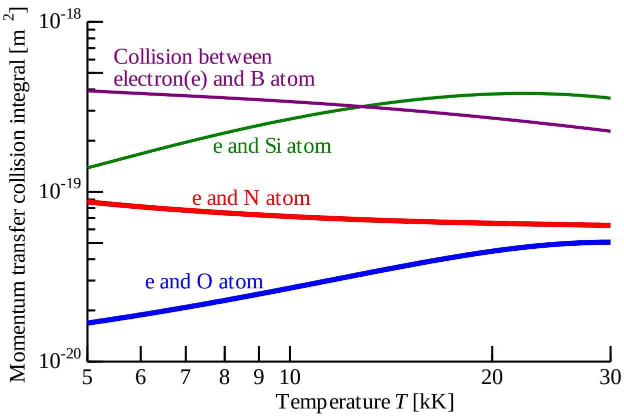


Fig.1 Electron impact collision integral of atoms

2. Selection criteria of new arc quenching medium

Based on our previous research, we determined selection criteria of new DC arc quenching medium as follows: (*a*) Insulation material in solid state as well as Silica-sand, (*b*) higher thermal conductivity in solid state compared with Silica-sand, and (*c*) containing chemical elements which have higher electron impact collision integral compared with Si and O atoms.

The criterion (*a*) is necessary from the point view of the steady-state operation of the DC fuse (i.e. operation under application of load current). The criterion (*b*) is also important to dissipate a thermal energy from a metal fuse-element during the steady-state operation. The criterion (*c*) is aiming to increase ρ of vapour mixture of the arc quenching medium and the arc.

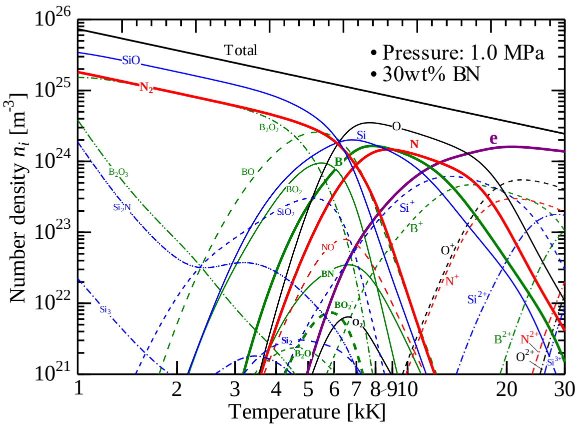


Fig.2 Number density of BN/Silica-sand vapour mixture under 30wt.% BN condition (Pressure: 1.0 MPa).

According to the above criteria, we selected h-BN powder as a component of new DC arc quenching medium. Table 1 compares physical properties of Silica-sand and BN powder in solid state[7,8]. The solid h-BN powder shows high ρ as same as Silica-sand and higher thermal conductivity κ and sublimation point compared with Silica-sand.

In addition, BN simply consists of B and N atoms. Fig. 1 shows calculation result of the electron impact momentum transfer collision integrals for B, N, Si, and O atoms. As clearly indicated in Fig.1, B and N atoms have much higher the electron impact collision integral compared with O atom. Especially for B atom, it has higher collision integral compared with Si atom at T below 10 kK.

According to the equation of the electrical resistivity on the Chapman-Enskog method[9,10], higher ρ can be obtained under condition of large value of product of the collision integral and the number density of corresponding chemical species. Therefore, both increasing ρ and r_{arc} can be expected when formations of B and N atoms with high density in the vapour mixture of the arc quenching medium with Cu arc.

3. Chemical composition of BN/SiO$_2$ vapour mixture

The previous section selected BN powder as component of new DC arc quenching medium. In the present experiment described in later section, we used powder mixture of BN/Silica-sand to investigate influence of BN admixing with conventional Silica-sand on r_{arc} rise. Before the experimental section, we theoretically calculated chemical composition of BN/Silica-sand vapour mixture to simply discuss about effect of BN vapour admixing into conventional Silica-sand vapour on ρ rise.

The chemical composition of BN/Silica-sand vapour mixture was calculated using the minimization of Gibbs free energy method[11]. A pressure of the vapour mixture was assumed as 1.0 MPa based on previous research and literatures[4,12]. The BN vapour concentration was changed to 0wt.%, 15wt.%, 30wt.%, and 50wt.%.

Fig.2 represents the equilibrium chemical composition of 30wt.%BN/70wt.%Silica-sand vapour mixture. At

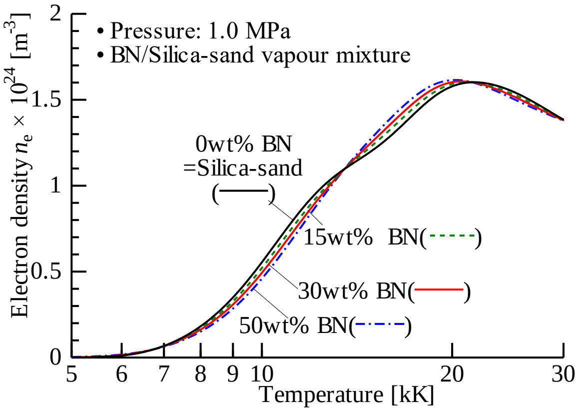


Fig.3 Electron density of BN/Silica-sand vapour mixture

temperature T above 20 kK, ionic chemical species forms as predominant species in the vapour mixture. Number densities of ionic chemical species decay with T decaying due to recombination reactions, and neutral atomic species such as N, B, Si, and O atoms are formed as predominant species at T between 5-15 kK. At T below 5 kK, many kinds of molecular species are generated. Under this condition, an ionization of Si atom generates electron from T=4 kK, while BO_2 attaches the electron to form BO_2^-. As a result, the electron density n_e increases from T=5 kK.

Figure 3 summarize n_e under each BN vapour concentration conditions. The electron density increases due to the BN vapour admixing into the Silica-sand vapour at high temperature region of T between 14-20 kK. On the other hand, the BN vapour admixing into the Silica-sand vapour decreases n_e at T below 14 kK. At T below 14 kK, large number of B and N atoms are formed as previously described. In addition, these atoms have much higher the electron impact momentum transfer collision integrals as suggested in Fig.1.

Therefore, these results simply imply that ρ can be increased due to the BN vapour admixing into the Silica-sand vapour especially at T below 14 kK region. Thus, it can be also expected that r_{arc} can be increased by utilization of the BN/Silica-sand powder mixture from the point view of the chemical composition of BN/Silica-sand vapour mixture.

4. Experimental

4.1 Experimental setup and conditions The previous section revealed that the BN vapour admixing into the Silica-sand vapour possible to increase ρ at T below 14 kK. Therefore, the present experiment used the powder mixture of BN and the Silica-sand.

The experimental procedure was follows. A Cu fuse-element was installed between current terminals in a fuse-box as represented in Fig.4. Then, the fuse-box was filled by the arc quenching medium. In the present experiment, following three arc quenching media were used: (1) Conventional Silica-sand (particle diameter d_p < 250 μm), (2) 15wt.%BN powder (d_p: few μm) admixing with the Silica-sand, and (3) 30wt.%BN powder admixing with the Silica-sand. The filling density of the arc quenching media

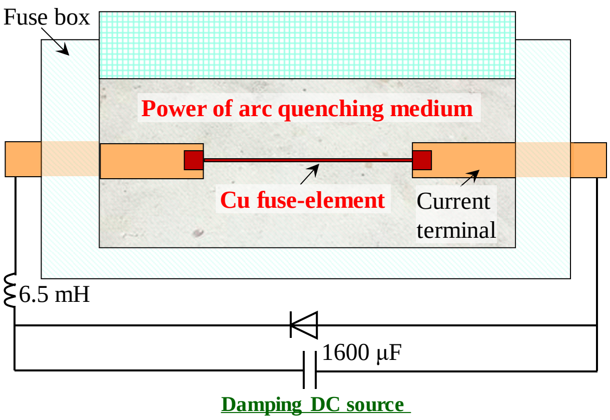


Fig. 4 Configuration of arc quenching chamber

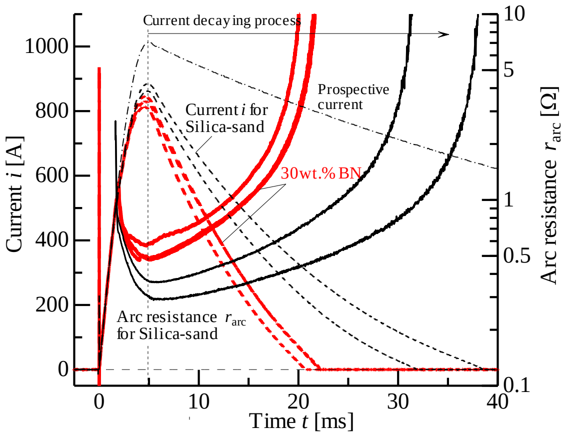
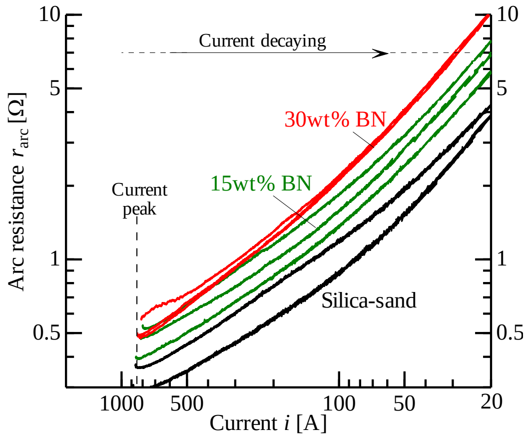
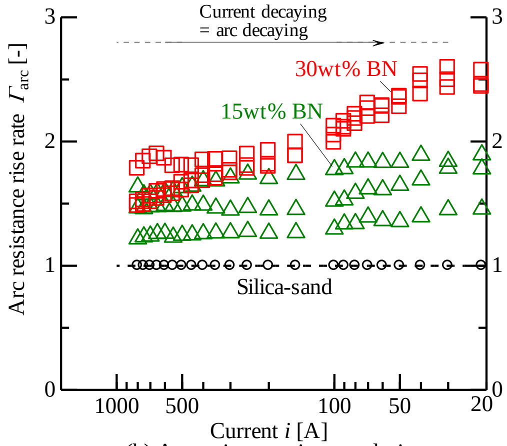


Fig.5 Current i and arc resistance r_{arc}



(a) Arc resistance during current decaying process



(b) Arc resistance rise rate during current decaying process

Fig.6 Arc resistance r_{arc} and arc resistance rise rate Γ_{arc}

in the fuse-box was fixed under each conditions. The fuse-box is connected to high damping DC supply circuit as illustrated in Fig.4. In the present experiment, a damping DC with a 1000 A prospective peak was energized to the Cu fuse-element to ignite the Cu DC arc. During the DC arc quenching process, current i and r_{arc} were measured.

4.2 Experimental results Figure 5 shows transient behaviours of current i (broken lines) and arc resistance r_{arc} (solid lines) during the DC arc quenching process under the conditions of the Silica-sand (thin black lines) and 30wt.%BN (bold red lines).

The current is energized from time t = 0 ms, and it increases with time elapse. At t around 1.6 ms, the DC arc was ignited under the both conditions. Then, i reaches peak current at t around 5 ms. In the condition of the Silica-sand, the peak current is about 880 A. After the current peak, i decreases with time elapse. At an arc quenching time t_q, i is completely reduced to 0 A.

After the arc ignition, the interelectrodes resistance means r_{arc}. Under the condition of the Silica-sand, r_{arc} is sharply decreased after the arc ignition until the current peak. On the other hand, this drastic decreasing of r_{arc} is relaxed under the 30wt.%BN condition. Furthermore, r_{arc} is rapidly increases with time elapse after the current peak compared with r_{arc} under the Silica-sand condition. Therefore, r_{arc} is successfully increased by the utilization of the BN powder with the Silica-sand. As a result, current is further reduced compared with that under the Silica-sand condition. For instance, the current peak is further reduced to about 820 A and t_q is further shortened to about 21 ms under the 30wt.%BN condition.

4.3 Arc resistance rise during arc decaying process

Figure 6(a) quantitatively compares r_{arc} at i during the current decaying process after the current peak. As indicated in Fig.6(a), r_{arc} is increased with the rise in the BN powder mixture rate in the BN/Silica-sand powder mixture. For instance, at i =100 A, r_{arc} is about 2.1 Ω under the 30wt.%BN condition, which is higher than that of 1.3-1.8 Ω for the 15wt.%BN condition and 0.8-1.2 Ω for the Silica-sand condition.

In order to quantitatively evaluate r_{arc} rising due to the utilization of the BN powder, we defined an arc resistance rise rate Γ_{arc} with respect to r_{arc} under the Silica-sand condition as following simple equation.

$$\Gamma_{arc}(i) = \frac{r_{arc}(i)}{\overline{r_{arc}(i)} \text{ for Silica} - \text{sand condition}} \quad (1)$$

where $\overline{r_{arc}(i)}$ in the denominator shows simple average of r_{arc} at i under the Silica-sand condition and results are plotted in Fig.6(b) as function of i.

As indicated in Fig.6(b), Γ_{arc} is increased with decay in current i. Especially at low current region where i below 100 A, Γ_{arc} drastically increases compared with that at high current region over i > 100 A. For instance, Γ_{arc} is about 1.5 under both 15wt.%BN and 30wt.%BN condition at i=800 A, while it increases until about 1.8 under 15wt.%BN condition and 2.5 under 30wt.%BN condition at i=20 A.

According to our previous work about the arc temperature measurement during the Cu DC arc quenching using the Silica-sand, the temperature T of the DC arc can be decayed about 7000-10000 K at i = few hundreds ampere[4]. As discussed in Sec.3, the electron density was decreased as the BN vapour admixing into the Silica-sand vapour at T around 7000-10000 K. Furthermore, the predominant chemical species in this T region were B and N atoms which have high collision integrals.

Therefore, formation of large amount of B and N atoms with large collision integrals and electron density decay could increase ρ of the BN/Silica-sand vapour mixture especially at low current region where i below 100 A. As a result, r_{arc} was significantly increased due to the BN powder utilization.

Further deep discussion for r_{arc} rise requires detail data of the gas properties such as the electrical resistivity, thermal conductivity, a specific heat, and so on for the BN/Silica-sand vapour mixture.

5. Conclusion

An arc quenching in a direct current(DC) fuse requires an arc resistance(r_{arc}) rising due to evaporation of an arc quenching medium filled in a fuse. Conventionally, a flattery silica-sand(low purity SiO_2 sand) have been used as the arc quenching medium. In order to increase r_{arc} more, new DC arc quenching medium should be developed.

This paper newly selected powder mixture of boron-nitride(BN) powder and the flattery silica-sand as promising new DC arc quenching medium. This material was selected based on the properties in the solid state, electron impact collision integrals of constituting elements of materials, and high temperature chemical composition of vapour mixture of the BN and the silica-sand.

As the DC arc quenching experiment, the powder mixture of the BN powder and the flattery silica-sand was filled inside the fuse box. Then, a damping DC with a 1000 A prospective peak was energized. As a result, r_{arc} was successfully increased with admixing rate of the BN powder. This r_{arc} rise can be interpreted based on large collision integral of B and N atoms and electron density decay due to BN vapour admixing into the flattery silica-sand vapour.

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