Thermal conductivity improvement of Al alloy with Nb nanopowder using SPS for transmission conductor

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Abstract. Aluminium 1000 alloy has high purity and good electrical conductivity required for high power transmission conductors but lacks adequate thermal conductivity which induces sagging in service. To augment this deficiency, Nb nanopowder was incorporated into it as a reinforcement and consolidated with spark plasma sintering (SPS). The SPS was conducted with pre-optimized processing parameters of 630 °C, 30 MPa, 10 min and 200 °C/min. The sintering was conducted in a vacuum with graphite die of 20 mm in diameter. Thereafter, the sintered samples were metallographically prepared and subjected to thermal conductivity testing. A laser flash analyzer was used to generate the thermal diffusivity of the samples. Then their thermal conductivities were computed. Results obtained showed that Al-4Nb had the highest thermal conductivity of 115.95 ± 6.9 W/mK which represented 42% improvement. So, it follows that Al-Nb composite is a better replacement for monolithic Aluminium 1000 alloy in power transmission conductors with a potential property of low sag.

Key words: Thermal conductivity; Al alloy; Niobium; High transmission conductor; Laser flash analysis.

1. Introduction

Aluminium 1000 alloy is widely used in power transmission conductors due to its high purity, high electrical conductivity, good passivation property and low density. Nevertheless, it has high coefficient of thermal expansion (CTE) due to its poor thermal conductivity. Consequently, it sags excessively when high load is transmitted across it. Meanwhile, researchers have discovered that this challenge can be redeemed by reinforcing it with suitably selected metals, non metals or fibers [1-3]. Pietrak and Wisniewski [4] observed that interfacial thermal resistance (ITR) is one of the major causes of drop in thermal conductivity of metal matrix composites (MMCs). This situation arises when matrix/reinforcement interface is loosely bonded; such that flow of electrons are hampered resulting in conductivity drop. Studies have also shown that thermal conductivity of Al matrix composites (AMCs) is dependent on the nature of its reinforcement since it relies on the amount of crystals present in the solid solution as the Guinier Preston (GP) zones/age-hardening precipitates [5]. And that is why Tritt [6] rightly pointed out that solid solution creates the greatest electron and phonon scattering spots on the MMCs. Meanwhile, high power transmission conductors must possess high thermal conductivity
so as to contain the expansion and contraction of the conductor during the peak and off-peak hours respectively. So, it is imperative to develop a conductor material with a good thermal behaviour. Interestingly, it has been shown that Nb reinforcement induces the formation of Nb_2O_5 which enhances compression strength on materials [8]. This attribute will control its sag level. Several researchers have used spark plasma sintering (SPS) to compact Al with one or more additives in order to enhance its properties. Guo et al. [5] used CNTs, Wang et al. [6] worked with TiAl-based alloy, Yilmaz [7] utilized Al_2O_3 and SiC while Ujah et al. [8] reinforced with CNTs/Nb. The authors achieved various improvements which were attributed to the SPS technique as well as the properties of the reinforcements used. However, SPS is a non-conventional sintering technique that consolidates powders using pulsed direct current applied concurrently with pressure. It improves the properties of composites, conserves energy, saves time and money, generates cohesive boundaries with refined grains, vaporizes impurities and enhances the dispersion of reinforcements [9, 10]. Likewise, Nb nanopowder is a grain refiner, a toughening and strengthening material and a superconductor; hence, its choice. The excellent characteristics of SPS and Nb manifested in Ujah et al. [3] where the electrical conductivity, microhardness and microstructure of Al alloy were improved considerably. Works aimed at improving the properties of Al alloy with several additives abound in the literature. But little has been discussed on using Nb nanopowder as reinforcement and SPS as fabrication technique to improve the thermal conductivity of Al alloy despite the good characteristics of the material and technique. Therefore, this work was aimed at improving the thermal conductivity of Al using Nb reinforcement and SPS technique with the primary objective of reducing Al alloy’s CTE which will subsequently reduce its sagging so as to perform creditably in high transmission conductor.

2. Experimental Procedure

2.1 Materials and method.

The materials (Al 1000 alloy nanopowder and Nb nano powder), the composition, purity and supplier have been reported elsewhere [8]. Accordingly, the powders were mixed vigorously with tubular mixer for 10 hours to ensure homogenous dispersion of reinforcement in the matrix. The appropriate masses were weighed out before the mixing. The masses included that which would produce the following samples, pure Al, Al-1wt.%Nb, Al-4wt.%Nb, Al-8wt.%Nb, Al-12wt.%Nb with the dimensions of 20 mm diameter and 5 mm thickness as shown in Fig. 1b. The blended powders were then weighed into a graphite die and covered with punches as shown in Fig. 1a and placed into the sintering chamber of the SPS. The sintering was performed with SPS machine using optimized parameters of Ujah et al. [9] in a vacuum pressure of 0.605 mbar. Thereafter, the sintered samples where cut into 10 mm x 10 mm x 4 mm dimensions and polished for thermal conductivity testing.

![Graphite die and punches assembly](image1.png)

**Figure 1. (a) graphite die and punches assembly. (b) Sintered sample**

2.2. Microstructural characterization.

As-received powders were analyzed with Transmission electron microscopy (TEM, JEM-2400F), while the sintered samples were studied with scanning electron microscopy connected to electron dispersion spectroscopy (SEM/EDS, FE-SEM, TESCAN).
2.3. Thermal conductivity testing.

A Laser Flash Analyzer (LFA 427) connected to (NETZSCH Proteus software) was used in this test. The samples were cut to 10 mm by 10 mm dimensions, with a thickness of 4 mm. The samples were polished and coated with graphite to enhance its thermal diffusivity and absorptivity. The test was run in an argon atmosphere, with laser voltage of 450 V and laser pulse width of 0.8 ms. The thermal diffusivity of each sample was measured by sending a laser (energy pulse) to the surface of a sample and generating the time taken for the energy to reach the other side of the sample. Then thermal conductivity was computed with the relationship shown in Eq. 1 as follows:

\[ \lambda = \alpha \rho C_p \]  

Where \( \lambda \) is the thermal conductivity (W/mK), \( \alpha \) is the thermal diffusivity (m\(^2\)/s), \( \rho \) is the density of the sintered material (kg/m\(^3\)), \( C_p \) is the specific heat capacity of the material (J/KgK).

3. Results and Discussion

3.1. Microstructure.

Fig. 2 shows the TEM micrographs of as-received powders. The grains of Al in Fig. 2a are spherical in shape with tiny particles surrounding large ones. Fig. 2b shows the grains of Nb made of large spherical grains surrounded by smaller particles which form feather-like structure which may aid in bonding to the adjacent grains. Fig. 3 displays SEM micrographs of sintered samples. From the EDS results there in and elsewhere [8], it could be seen that the white patches are Nb grains. In Fig. 3a, the white particles were not seen because it was a sample of pure Al which equally confirms that assertion. Al-1Nb SEM micrograph shown in Fig. 3b has the white grains of Nb dispersed scantily in the microstructure. This shows that 1 wt. % was not enough in microstructure. However, in Fig. 3c, the percentage of Nb was 4 wt. % and could be seen to have dispersed evenly to the entire surface. Also, it could be seen in Fig. 3d (Al-8Nb) that there was a very high concentration of Nb as depicted by the white reflective particles. More so, in Fig. 3e (Al-12Nb), the white particles became so much pronounced on the surface. In general, the grains of the sintered samples (Fig. 3) can be seen to be more refined, spherical and closely packed which were as a result of the sintering [10] and this shows that the SPS consolidation enhanced densification and grain refinement in Al-Nb composites. There were no pores and the microstructure was devoid of impurities as was reported by Xie et al. [10], and there was homogenous dispersion of reinforcements. The grain boundaries were tightly bonded, and this was also observed by Ujah et al. [9].

3.2 Thermal conductivity

Fig. 4 shows the thermal conductivity plot of sintered samples. In Fig. 4a, it could be seen that the thermal conductivity decreased with increase in temperature. This would be attributed to the thermal conductivity drop induced by electron and phonon scattering phenomenon when heat flow is increased in a system as reported by Baudouy and Four [11]. However, the addition of 1 wt. % Nb increased the average thermal conductivity of pure Al from 81.55 ± 9.0 W/mK to 108.05 ± 7.6 W/mK as can be seen in Fig. 4b. Again, when the percentage weight of Nb was increased to 4, the thermal conductivity increased to 115.95 ± 6.9 W/mK. But when the increase got to 8 wt.%Nb, the thermal conductivity...
decreased to 99.13 ± 8.0 W/mK. At 12 wt. % Nb, the thermal conductivity decreased even lower than the pure Al, it became 74.38 ± 8.0 W/mK. The improvement was effective when the Nb content was within the range of 1 to 4 wt.%. The improvement could be attributed to grain refining property of Nb with its superconductivity and the exploits of SPS technique which impacted excellent microstructure on the composites as observed in Al-1Nb and Al-4Nb samples. Also their microstructures attested to their superior properties because Fig. 3b and 3c show microstructure without pores, with refined grains and compact interface. Hence, the samples had cohesively bonded grain boundaries which induced free flow of electrons and enhance thermal conductivity which is usually absent in weakly bonded matrix/reinforcement interface as observed by Krishna et al. [12]. Meanwhile, the decline in thermal conductivity in Al-8Nb and Al-12Nb nanocomposites would be attributed to the fact that the weight fractions of Nb seemed to have exceeded optimal concentration required for thorough wetting out. For this reason, they got agglomerated in the grain boundaries as can be seen in Fig. 3e which rather induced thermal resistivity. Therefore, 4 wt.% Nb was the optimum concentration that gave the highest thermal conductivity of 42% improvement.

**Figure 4. (a) Thermal conductivity of sintered samples. (b) Average thermal conductivities**

### 4. Conclusion

The study aimed at enhancing the thermal conductivity of Al 1000 alloy was successfully conducted and the results obtained showed that Al-4Nb composite got improved in thermal conductivity by 42%. This was attributed to the enhanced properties of the developed sample with microstructure devoid of pores, and exhibited high grain refinement with cohesively bonded boundaries. And all these attributes were impacted by the SPS fabrication technique and the grain refining property Nb reinforcement. However, Al-12Nb sample had poor wetting out of the reinforcement which resulted in its agglomeration in the boundaries and a subsequent drop in the thermal conductivity of the sample. Therefore, it could be said that the optimum weight percentage of Nb adequate to improve the thermal conductivity of Al is 4 wt.%. So, it can be concluded that Al-4Nb nanocomposite would perform much better than monolithic Al alloy in terms of thermal conductivity in power transmission conductors.

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