Metal composite T-junction terminals for MW-class aerospace electric power distribution

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Abstract. There is a recent surge in activity to develop high power electric (or hybrid electric) aircraft. Part of this development effort is the creation of lightweight and small volume high-performance motors and airborne power transmission cables. As part of the power transmission of a distributed propulsion aircraft will be T-terminals to extract power to individual motors from a “main” power cable. In this research, a standard pressed plate high purity Cu T-terminal, with cylindrical high-temperature superconducting cables (main cable current of 20 kA, branch cable current of 2.5 kA), were investigated using Multiphysics simulations. Then, a more geometrically optimized high purity Al-Cu composite T-terminal was simulated under similar conditions. Discussed are the influence of T-junction geometry, operating temperature (30 to 50 K), contact resistance, and magnetoresistance on joule losses of terminals with different masses. It is shown the Al-Cu terminal can greatly reduce joule losses/mass of the T-terminal while also having an intrinsic clamping force from thermal expansion of the Al shell of the composite structure.

1. Introduction

Single aisle and twin aisle large commercial aircraft presently contribute approximately 1.9 to 2.3% of global CO₂ emissions [1]. While this appears to be a small portion, decreasing global greenhouse gas emissions will require a many pronged approach. Of the many initiatives and programs to develop remarkably high efficiency commercial aircraft by 2035 [2–5], a later generation NASA N+3 vehicle will require roughly 45 MW of electrical power [6]. At powers this high, nearly every electrical component will require significant breakthroughs in light-weighting and performance [7]. The transmission cables of the electrical wiring and interconnection system (EWIS) can start to weigh 1000s of kg [8], which is why alternate conductors including hyperconducting Al at 20 K, and high temperature superconducting (HTS) cables including MgB₂, barium strontium calcium copper oxide (BSSCO), and rare-earth barium copper oxide (REBCO) are possible options [9–12]. Many HTS cable options are available [13–15], and CORC® cables have advantages for mechanical flexibility and current density [16]. Hyper-conducting Al cables are options which can be extremely lightweight, however they still have resistive Joule losses which would have to be managed with cryocoolers or cryogenic liquids [10]. Saving weight of the transmission cables by using transmission voltages greater than 1 kV becomes...
more challenging due to the danger of dielectric breakdown, which is typically limited at fast switches and insulation interconnections [17].

Fully superconducting joints to connect HTS conductors, while desirable to eliminate Joule heating, are not easily achievable [18]. For this reason, non-superconducting terminals will likely be used in the EWIS in the N+3 vehicle even when HTS cables are used. “T-terminals”, i.e. terminals which distribute power from a main cable, if not properly engineered can contribute excess joule heating to the cryogenic system and excess mass. Standard terrestrial metal/metal or HTS/metal terminals utilize pressed high purity Cu plates, but for aerospace Al electrical conductors are desired due to their significantly higher mass specific conductivity which is equal to $\alpha / \rho_{\text{mass}}$ (electrical conductivity / mass density). Cu is still desirable due to the ease it can be soldered to itself and other materials. In this research, a standard terrestrial Cu T-terminal geometry was compared to a novel Al-Cu composite T-terminal. The Al-Cu terminal would utilize unique bonding techniques which have already been demonstrated in a similar geometry [19].

2. Details of simulations

T-terminal geometries were first created using Onshape® cloud-based computer-aided design software. The components were then imported and created into a three-dimensional assembly in COMSOL Multiphysics® version 5.3.0.223 with 64-bit Windows 10. The “Heat Transfer”, “AC/DC”, and “Structural Mechanics” modules were utilized along with the “Electromagnetic Heating”, “Magnetic Fields”, “Electric Currents”, and “Thermal Stress” interfaces [20–22]. All COMSOL simulations were steady-state solutions. A solid Cu pressed plate T-terminal (called TT-1), not necessarily requiring soldering in the T-terminal interfaces, was designed and scaled to handle the cylindrical terminals of an assumed Conductor On Round Core (CORC®) 20 kA main cable and 2.5 kA branch cable from Advanced Conductor Technologies (ACT) LLC [23]. The branch current was chosen as 2.5 kA so the main cable could support 8 separate superconducting motors for the aircraft. A contoured double ellipsoid Al-Cu T-terminal (called TT-2), requiring soldering in the T-terminal interfaces, was also designed and scaled to handle the terminals of an assumed CORC® 20 kA main cable and 2.5 kA branch cable from ACT LLC. The basic geometry of TT-1 and TT-2, and level of relative detail in the simulation mesh are shown in figures 1 and 2. All CORC® terminals were 200 mm long [24], extending slightly farther than the tapered CORC® cables. The main cable had a starting outer diameter of 7.6 mm and a terminal outer diameter of 12.6 mm. The branch cable had a starting outer diameter of 3.6 mm and a terminal outer diameter of 6.3 mm.

![Figure 1](image_url)

*Figure 1. (Left) Cu pressed plate T-terminal TT-1, bolt holes not included to reduce computational requirements. The top Cu plate and a Cu CORC® are partially transparent to reveal the internal geometry and conical tapering of the CORC® cable. (Right) The fine level of meshing used during simulations (shown is TT-2).*
Figure 2. Al-Cu composite T-terminals TT-2, 1x, 0.66x, and 0.34x volumetric size of Al in top left, top right, and bottom left, respectively. The bottom right image is a zoom image showing the CORC® cable, CORC® cable Cu terminal, TT-2 thin Cu layer for soldering purposes, and TT-2 Al bulk.

The Cu material included was alloy 10100 high purity (99.999 %wt) Cu (RRR_{4.2/273} K = 300) with electrical conductivity calculated using equations from the National Institute of Standards and Technology [25]. The Al material included was very high purity (greater than 99.9999 %wt) hyper-conducting Al with a zero-field RRR_{4.2/273} K of 3000 [26]. An isotropic magnetoresistance was assumed for Cu and Al materials utilizing perpendicular field data. The magnetoresistance of Cu was extracted from a Kohler plot in reference [27] using RRR_{4.2/273} K = 300. The magnetoresistance of Al is more complicated, and was taken from reference [27], assuming RRR_{4.2/273} K = 2100 and operation at 19.6 K. The anomalously large magnetoresistance which can occur in high purity aluminium-metal composites was ignored in these simulations [28]. Thermal conductivity, which was taken from [25] and [29] for Cu and Al respectively, was not magnetically dependent. See figure 3 showing the used electrical properties of the metals.

Figure 3. Electrical properties of cryogenic (left) Cu and (right) Al [25–27] used in simulations.

The solder used for TT-2 was assumed a very thin layer of 63/37 Sn-Pb with a negligible resistance such that, similar to TT-1, only contact resistance was included in determining current sharing between the CORC® cables and T-terminal [24]. Mechanical deformation was assumed to be purely elastic and
the cryogenic coefficient of thermal expansion (CTE), Young’s modulus, and Poisson’s ratio of the Cu and Al was taken from references [30], [25], and [31]. The effect of mechanical deformation on electrical conductivity, such as those described in reference [32], was ignored. The Young’s modulus and CTE of the soldered CORC® cable was assumed to be dominated by the Cu core. Both TT-1 and TT-2 were mechanically fixed at the CORC® to T-terminal interfaces. Both TT-1 and TT-2 were mechanically anchored at the exposed end of the branch CORC® cable. The zero-strain reference temperature for CTE simulations was chosen as 293.15 K. See figures 4 and 5 showing the mechanical properties of the metals used in the simulations.

For modelling purposes, a highly non-linear CORC® cable temperature dependent electrical conductivity (see equations 1–3) was modified from an equation in reference [33] to contain an “if” statement when describing pre-current sharing temperatures and assumed full current sharing with the copper stabilizer above the superconducting transition temperature, $T_c$. The self-field contribution to the magnetic dependence of critical current density, $J_c$, was not included at this time. The CORC® cable inside of the T-terminals was trimmed and staged for enhanced current injection/extraction [34], and this was modelled by the cable forming a conical taper as shown in figure 1.
\[
J_c(T) = J_{c0} \left( \frac{T}{T_0} \right)^{1.65} \left( \frac{T}{T_0} \right)^{1.65} \text{[A/m}^2\text{]} \\
\sigma_{Cu}(T) = \left( \left( 3 \times 10^{-9} \right) \left( 1 + \alpha_{Cu}(T-T_c) \right) \right)^{-1} \text{[S/m]} \\
\sigma_{CORC}(T) = \begin{cases} 
\frac{J_c}{\|E\|} \left( \frac{\|E\|}{E_c} \right)^{0.8} + \sigma_{Cu} & \text{if } T < T_c \\
\sigma_{Cu} & \text{if } T \geq T_c 
\end{cases} \text{[S/m]}
\]

In equation 1, \( T_0 \) and \( J_{c0} \) are a reference temperature and the critical current density at that reference temperature, respectively. In equation 2, \( \alpha_{Cu} \) is the temperature coefficient of resistivity. In equation 3, \( \|E\| \) and \( E_c \) are the magnitude of the electric field and an electric field criterion at which \( J_c \) is described, respectively.

Out of the options in literature, the main and branch cables were chosen such that (assuming a lift factor of 4.4 from self-field 77 K to self-field 50 K [35]) the main cable would operate near 75% \( I_c \) and the branch cable near 60% \( I_c \) at 50 K [23]. Contact resistances were assumed to occur only at the interfaces located between the CORC®, cable, CORC® cable terminals, and the T-terminals.

Overall, three values of background temperature (30, 40, 50 K), three relevant values of contact resistivity (0, 20, and 200 nΩ•cm² [24]), and three different relative volumes of T-shaped terminal (1x, 0.63x, and 0.34x) were compared. The cooling of the system was governed by a heat transfer coefficient equal to 20 kW/m²K [36]. The total Joule heating and masses of the simulated systems were calculated using volumetric integrals which included all the simulated material.

3. Results from simulations

The 1x TT-1 T-terminal had generally ~2.8x joule losses compared to 1x TT-2, even though these were of near identical masses (9.99 kg versus 9.44 kg respectively), see figure 6. The non-negligible influence of contact resistivity on joule losses is shown for TT-1 and compared to the negligible influence for TT-2 at 50 K in figure 6. Shown in figure 7 is that the influence of magnetoresistivity on joule losses was negligible for the fully Cu TT-1 but was non-negligible for the Al-Cu TT-2. The maximum magnetic fields experienced for both TT-1 and TT-2 was slightly above 1.1 T, which was located near the surface of the tapered CORC® main cable.

The joule losses were dependent on size and temperature, as shown for TT-2 with a fixed contact resistivity of 20 nΩ•cm², in figure 7. Thermal expansion did not play a role in TT-1 because the thermal expansion coefficient was equal for all materials. For 1x TT-2, the thermal expansion mismatch of Al and Cu within TT-2 did result in radially compressive stresses of approximately 90 MPa on the CORC® cable and terminal.

Across all geometries, the temperature within all of the materials never deviated from the exterior temperature by more than 0.1 K. The standard Cu pressed plate geometry of TT-1 had significantly higher current density current crowding near the intersection, even when compared to 0.3x TT-2.
4. Discussion of results
The lack of temperature deviations from the exterior temperature is due to the fact that the thermal conductivity of Al and Cu at these temperatures is high and the joule losses from the terminals was small compared to the heat transfer coefficient taken from [36]. The joule losses in all versions of TT-1 and TT-2 appears small, but there will need to be at least thirty-two T-terminals in the proposed aircraft (sixteen input and sixteen return T-terminals) and in terms of an entire EWIS, every component must have the losses minimized to reduce the thermal load on any proposed cryogenic system.

The radially compressive stresses generated on the CORC® cable in TT-2 are not enough to degrade the superconducting properties [37], and therefore would only go towards possibly reducing contact resistivity. The simulations were performed in the purely elastic regime and high purity Al is likely to plastically deform near 60 MPa [38], further reducing the stress on the CORC cable. The difference in TT-1 and TT-2 geometry played a clear role in determining the joule heating. It was shown to be a good
mass saving measure to maximize T-terminal thickness near the intersection point and reduce the thickness away from the intersection point. The final design of a T-terminal will likely have a different geometry than that here, but the benefits of a non-constant cross-section are apparent.

The use of high purity Al clearly benefited the joule heating/mass ratio. Even the smallest Al-Cu TT-2 examined (3.7 kg) at 50 K had half the joule losses of a standard Cu pressed plate terminal TT-1 (9.99 kg) at 50 K. The magnetoresistivity of Al is more of an issue than Cu at low fields and should be considered during any designs. The anomalous magnetoresistivity of Al-Cu composites [28] was not taken into account, and this may play a small role in determining joule losses and should be examined before deploying a Al-Cu composite T-terminal into the field. The expected range of contact resistivity did play a role in determining the joule losses, but the operation temperatures and mass reductions examined played a larger role. While construction of a TT-2 terminal design may be complicated due to the need of bonding Cu to the Al bulk in such a geometry [19], aerospace cable T-terminals would greatly benefit from this advancement.

5. Conclusion
Significant light-weighting is possible using cryogenic hydrogen gas cooled Al-Cu composites throughout the power distribution network of a proposed NASA N+3 aircraft. Along with elementary geometrical modifications to partially account for current crowding effects, a novel Al-Cu composite T-terminal was designed which generated one-third the amount of joule heating for a comparable mass of a standard Cu pressed plate T-terminal under similar conditions. The self-fields generated near HTS cables are enough to increase joule heating within T-terminals due to magnetoresistive effects, and these effects should be considered. When using Al-Cu composites, it will be important to keep thermal expansion in mind to prevent Ic-degradation to the HTS cables.

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