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PERFORMANCE EVALUATIONS OF DEMOUNTABLE ELECTRICAL
CONNECTIONS*

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PERFORMANCE EVALUATIONS OF DEMOUNTABLE ELECTRICAL CONNECTIONS

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ABSTRACT

Electrical conductors operating in cryogenic environments can require demountable connections along their lengths. The connections must have low resistance and high reliability and should allow ready assembly and disassembly. The performance of two types of connections has been evaluated. The first connection type is a clamped surface-to-surface joint. The second connection type is a screwed joint that incorporates male and female machine-thread components. The connections for copper conductors have been evaluated experimentally at 77 K. Experimental variables included thread surface treatment and assembly methods. The results of the evaluations are presented.

INTRODUCTION

Use of high-temperature superconductors (HTSs) for current leads to deliver power to devices at liquid helium temperature, now near commercial realization, has the potential to reduce refrigeration requirements and helium boil-off to values significantly lower than the theoretically best values achievable with conventional leads. Such leads are particularly advantageous for micro-SMES devices.^{1,2} Typically, these leads consist of a conventional upper stage and an HTS lower stage. Analyses of such binary leads^{3,4} show that considerable advantage is achieved by operating these leads with an intermediate-temperature heat sink, and a favorable location for the heat sink is at the junction between the upper and lower stage.

A superconducting magnet current lead employing HTS is being developed by the Argonne National Laboratory and Superconductivity Incorporated. The lead assembly incorporates a transition assembly to connect the conventional upper stage lead and the HTS lower stage lead elements. The transition assembly includes a connection to a cryocooler heat sink.

In order to facilitate lead fabrication and assembly, the lead stages' connections to the transition assembly are demountable in nature. The connections must be straightforward to affect, have low electrical resistance, and must have long term reliability. Connections incorporating clamped and screwed joint geometries were selected. The connection geometries are shown by Figure 1.

A measurement program was conducted to study the electrical performance of the selected demountable connections under different assembly conditions. The measurement program details and results are presented.

Figure 1. Current lead transition connections.

CLAMPED SURFACE-TO-SURFACE CONNECTION

Connection Details

The upper stage connection is a clamped surface-to-surface joint. The details of the connection are as given by Table 1.

Measurement Details

The test article details are as shown by Figure 2. Gold plating was employed to reduce the electrical contact resistance.^{5,6} The test article was instrumented with Type E (chromel-constantan) thermocouples and with voltage taps. The voltage taps were located to provide data on both the joint and the base material performance. The joint voltage taps were positioned at the two geometric ends of the joint in order to allow the determination of the resistance and apparent resistivity of the joint. The voltage taps were monitored by a Keithly Model 182 Digital Voltmeter through a Keithly Model 705 Scanner. The test article was connected at its ends to an external DC power supply. The test article was immersed in liquid nitrogen at 1 ATMA, i.e., 77 K, during the measurements. Measurement variables included joint gasket material, clamp screw torque and current.

Measurement Results

Since ohmic heating by the connection is the principal performance factor being evaluated, the measurement results are expressed in terms of resistance and/or resistivity of the connection

$$R = \frac{V}{I} \quad (1)$$

$$\rho = \frac{A}{L} \frac{V}{I} \quad (2)$$

where A = joint area [cm^2], L = joint length [cm], I = current [A], V = voltage [V], R = resistance [Ω], and ρ = resistivity [$\Omega\text{-cm}$].

The measurements were conducted with bare, gold plated joint surfaces and with an 0.038 cm indium foil gasket clamped between the joint surfaces.

The clamped joint without gasket and with indium gasket resistances vs. current and assembly torque are as shown by Figures 3 and 4 respectively. The following observations can be made relative to the data:

Table 1. Clamped surface-to-surface connection details.

Operating current	1500 A
Operating environment	
* Atmosphere	Gaseous helium @ 1 ATMA
* Temperature	60 K
Contact surface	
* Geometry	3.81 cm OD x 1.91 cm ID
* Area	8.54 cm ²
Contact materials	
* Joint halves	ETP copper
	1.9 μ m nickel plate
	1.3 μ m gold plate
* Joint gasket	Plain or 0.038 cm indium foil
Clamping method	
* Geometry	Central screw and mating insert with conical spring washers
* Material	304 stainless steel

Figure 2. Clamped joint test article. **Figure 3.** Clamped joint without gasket resistance vs. current and assembly torques. **Figure 4.** Clamped joint with indium gasket vs. current and assembly torque.

1. At low torque, the resistance without gasket is 100 times greater than that with gasket.
2. At high torque, the resistance without gasket is 4 times greater than that with gasket.
3. Resistance is essentially independent of current. The variation shown in the indium gasket case at low current is due to the unfavorable signal-to-noise ratio.

The clamped joint without and with gasket resistances vs. assembly torque at 500 A are as shown by Figure 5. The gasket provides maximum advantage at low torques while the resistance is weakly dependent on torque at moderate to high torques.

The apparent resistivities for the clamped joint test article with gasket vs. assembly torque at 500 A are as shown by Figure 6. The following observations can be made relative to the data:

1. The base material apparent resistivities are constant relative to assembly torque and of a magnitude that is equal to that for the material at 77 K. This correlation provides a check on the validity of the measurement.
2. At moderate to high assembly torques, the apparent resistivity of the gasketed joint is 1.8 greater than that of the base material.

SCREWED CONNECTION

Connection Details

The lower stage element connections are machine screw joints. The details of the connections are as given by Table 2.

Measurement Details

The test article details are as shown by Figure 7. The initial test article incorporated three joints:

1. Gold plated threads on gold plated threads ("uncoated threads").
2. Soft soldered threads.
3. Indium tinned gold plated male thread on gold plated female thread ("coated threads").

Figure 5. Clamped joint without and with gasket vs. assembly torque at 500 A.

Figure 6. Clamped joint apparent resistivities vs. assembly torque at 500 A.

Table 2. Screwed connections details.

Operating current (A)	250 A
Operating environment	
* Atmosphere	Gaseous helium @ 1 ATMA
* Temperature	60 K
Contact surface	
* Geometry	7/16-20 NC x 0.95 cm long thread 1.59 cm OD x 1.11 cm ID flat
* Area	3.99 cm ² thread 1.01 cm ² flat
Contact materials	
* Joint halves	ETP copper 1.9 μm nickel plate 1.3 μm gold plate
* Thread coating	Plain or indium tinned
* Joint gasket	Plain or 0.038 cm indium foil
Clamping method	Machine screw

Figure 7. Screw joint test article.

The initial test article was employed for the evaluations to high assembly torques, i.e., to 43.8 N-m. Subsequent test articles employed for the evaluation of low assembly torques, i.e., less than 11.3 N-m, incorporated only a single screwed joint. The threaded connections allowed evaluation without and with gaskets in the annular flat area. Four gasket configurations were employed:

1. No gasket, i.e., gold-plated copper on gold-plated copper.
2. 0.013 cm Kapton
3. 0.051 cm G10
4. 0.038 cm indium

The insulating gaskets, i.e., Kapton and G10, were employed to evaluate the relationship of screw thread and face conductances.

The test instrumentation was identical to the clamped joint measurements.

Measurement variables included joint gasket material, assembly torque and current.

Measurement Results

Uncoated threads. The results for the low and high assembly torque evaluations were in close agreement at their common torque point, i.e., ≈ 10 N-m and were thus merged to provide a continuous zero to high torque performance representation.

The screw joint with indium gasket resistances vs. current and assembly torque are as shown by Figure 8 for the low torque evaluations. The resistance is essentially independent of current. The variations with the indium gasket at low current are due to the unfavorable signal to noise ratio. The corresponding relationships of resistance to current for the gasket-less, Kapton and G10 gaskets are flat.

The uncoated screw joint resistances vs. assembly torque and gasket material are as shown by Figure 9.

- At low torques the resistances are dominated by the gasket resistance as the contact pressure between the mating screw thread surfaces is low.
- As torque is increased, thread contact pressure increases, thread resistance decreases and dominates the overall conductance. At torques above 10 N-m, the choice of gasket is essentially irrelevant and the resistance is essentially flat with torque.

The uncoated screw joint resistivity vs. assembly torque and gasket material for low torque evaluations are as shown by Figure 10.

- The base material resistivity is constant relative to torque and of a magnitude that is equal to that for the material at 77 K.
- At moderate assembly torques, the apparent resistivity of the indium gasketed joint is 2.0 greater than that of the base material.

Figure 8. Uncoated screw joint with indium gasket resistance vs. current and assembly torque (low torque evaluations).

Figure 9. Uncoated screw joint resistance vs. assembly torque and gasket material.

Figure 10. Uncoated screw joint resistivity vs. assembly torque and gasket material (low torque evaluations).

Figure 11. Coated screw joint with indium gasket resistance vs. current and assembly torque (low torque evaluations).

Coated Threads. The results for the low and high assembly torque evaluations were in close agreement at their common torque point, i.e., ≈ 10 N-m and were thus merged to provide a continuous zero to high torque performance representation.

The coated threads screw joint with indium gasket resistances vs. current and assembly torque are as shown by Figure 11 for the low torque evaluations. The resistance is essentially independent of current. The variations with the indium gasket at low current are due to the unfavorable signal to noise ratio. The corresponding relationships of resistance to current for the gasketless, Kapton and G10 gaskets are flat.

The coated screw joint resistances vs. assembly torque and gasket material are as shown by Figure 12.

- At low torques the resistances are dominated by the gasket resistance as the contact pressure between the mating screw thread surfaces is low.
- As torque is increased, thread contact pressure increases, thread resistance decreases, and dominates the overall conductance. At torques above 10 N-m, the choice of gasket is essentially irrelevant and the resistance is essentially flat with torque.

The coated screw joint resistivity vs. assembly torque and gasket material for low torque evaluations are as shown by Figure 13.

- The base material resistivity is constant relative to torque and of a magnitude that is equal to that for the material at 77 K.

Figure 12. Coated screw joint resistance vs. assembly torque and gasket material.

Figure 13. Coated screw joint resistivity vs. assembly torque and gasket material (low torque evaluations).

- At moderate assembly torques, the apparent resistivity of the indium gasketed joint is ≈ 2.0 greater than that of the base material.

APPLICATIONS

The experience gained in the measurement program was applied to the design of the connections of the abovementioned HTS current lead transition assembly.

Upper Stage Connections

The geometry and materials are the same as the clamped measurement joint.

The assembly torque is ≈ 55 N-m.

The clamped joint ohmic heating has been estimated. Based on the evaluations, at high currents, i.e., $I > 100$ A, that the resistance is independent of current. Thus, the resistance without gasket is $0.12 \mu\Omega$ and with indium gasket is $0.084 \mu\Omega$. For two leads operating at 1500 A, the ohmic heating without gasket is 0.27 W and with indium gasket is 0.19 W. Both heat inputs are small in comparison to the capacity of the heat intercept cryocooler to be employed.

Lower Stage Connections

The geometry and materials are the same as the screwed measurement joint.

The assembly torque selection was based on screw elastic considerations and joint resistance. It was required that the screwed connection remain elastic. Torque to yield measurements for indium coated threads with an indium gasket resulted in a yielding of the thread undercut region at 12 N-m. An assembly torque of 8 N-m was selected.

The resistance with indium coated threads and without the gasket is $0.41 \mu\Omega$, and with the indium gasket is $0.29 \mu\Omega$. For two leads consisting of six HTS elements each, the ohmic heating without the gasket is 0.31 W and with indium gasket is 0.22 W. Both heat inputs are small in comparison to the capacity of the cryocooler to be employed. The indium gasket is not employed.

CONCLUSIONS

- Low resistance, demountable electrical connections can be readily made with clamped and screwed joint geometries.

- Clamped surface-to-surface connections that employ an indium gasket between two gold plated ETP copper surfaces can yield an apparent joint resistivity of $0.35 \mu\Omega\text{-cm}$ at 77 K. This resistivity is 1.5 greater than that of the base material at 77 K. The resistivity without the gasket is four times that with the gasket. The resistance is independent of current level. The resistance is dependent on torque at low torque levels.
- Screwed connections that employ indium coated threads and an indium gasket between a gold plated ETP copper machine screw assembly can yield an apparent joint resistivity of $0.40 \mu\Omega\text{-cm}$ at 77 K. This resistivity is 2.0 greater than that of the base material. The resistivity with uncoated threads and without an indium gasket is 1.5 times that with coated threads and gasket. The resistance is independent of current level. The resistance is dependent on torque at low torque levels.
- Clamped and screwed connections are being applied to a transition assembly to connect the conventional upper stage and the HTS lower stage of a superconducting magnet current lead assembly. The upper stage connection employs a clamped surface-to-surface connection with an indium washer. The estimated ohmic heating at 77 K for two lead assemblies, i.e., two connections, operating at 1500 A is 0.19 W. The lower stage connection employs screwed connections with indium coated threads to connect each of the six HTS elements to the transition. The estimated ohmic heating at 77 K for two lead assemblies, i.e., twelve connections, operating at 1500 A is 0.31 W. Both heating rates are small compared to the capacity of the cryocooler employed for heat intercept and the heat conducted down through the conventional upper stage copper leads.

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