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Nb_3Sn Conductors for ac Power Transmission: Electrical and Mechanical Characteristics

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I. Introduction

Although Nb_3Sn can now be fabricated with the low ac losses required for ac power transmission,(1-4) one is still left with the task of effectively incorporating this compound in a conductor to be wound in a coaxial cable. Conductor designs which incorporate a thin Nb tape (~20 μm thick) reacted to form Nb_3Sn layers on each side (~5 μm each) have been described in a recent review article.(1) The Nb_3Sn-Nb-Nb_3Sn composite is either clad symmetrically with ~30 μm of copper on each side or asymmetrically with ~50 μm copper on one side and ~20 μm stainless steel on the other. The copper is required for stabilization and the stainless steel provides additional strength which may be required during cable winding, handling and cooldown.

This paper describes materials choices and trade-offs associated with incorporating low-loss Nb_3Sn tapes into this type of composite. These include: 1) reducing the overall ac losses

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+On leave for 8 months from the Bulgarian Academy of Sciences, Sofia, Bulgaria.

arising from the Nb_3Sn, the unreacted Nb (or NbZr alloy) substrate and the copper/stainless steel laminates and (2) optimizing mechanical properties.

II. Choice of Substrate Material

The brittle nature of Nb_3Sn makes the substrate a requisite in the fabrication and handling of conductors incorporating this compound. Nb_3Sn tapes, therefore, consist of thin layers of Nb_3Sn on both sides (but not around the edges) of a substrate (see bottom of Fig. 1). This is the configuration of tape conductors when wide strips of Nb_3Sn are made by diffusion using a niobium substrate and then slit to the required width. It was shown earlier that, in helical windings, the presence of a substrate can lead to significant additional losses.(5) The current flow responsible for these losses is shown schematically in Fig. 1 for two helically wound layers of superconducting tape. The two layers shown, together with two underlying layers of normal conductor (not shown) similarly wound with opposite helicity, constitute the "inner conductor" of a coaxial pair. This design was adopted at BNL to avoid parasitic losses and voltages associated with axial fields.(6) The current pattern shown in Fig. 1 (top) assumes equal currents in both superconducting layers.(7) For the inner layer of tapes, current flow is entirely on the outer surface and along the tape axes; hence, no substrate loss results. For the outer layer, however, current flow on the top surface is along the cable axis and is antiparallel to the underlying layer on the back surface. This results in a component of current circulating around each tape of the upper layer, and hence crossing the substrate as shown schematically in Fig. 1. The component of field giving rise to these circulating currents is equal to $H_\theta \sin\varphi$ where H_θ is the azimuthal field at the surface of the inner coaxial conductor and φ is the lay angle of the tapes (see Fig. 1).(5) For H_θ between 400 and 500 rms A/cm and angles $30° < \varphi < 45°$ the axial field will be within the range 200 to 350 rms A/cm. Theoretical calculations of losses arising from these currents have been presented earlier for both normal and superconducting substrates.(5) For a normal substrate the loss per unit volume of substrate, p_n, is given by (MKS units):

$$p_n = (\mu_o^2 \omega^2 / 12\rho_n) b^2 H^2 \qquad (W/m^3) \qquad (1)$$

when $b/2 << \delta$, where ρ_n is the substrate resistivity, δ is the skin depth, b is the width of the tape, ω is angular frequency, and H is the rms value of the parallel field ($=H_\theta \sin\varphi$). For a superconducting substrate, assuming the critical current density, $J_c = \alpha/B$, the loss per unit volume of substrate is given by (MKS):

$$p_{sc} = \frac{\mu_o^2 \omega H^4}{\pi\alpha\sqrt{2}} [\tfrac{\pi}{2} + \sqrt{2} + \ell n(1+\sqrt{2})] [\tfrac{1}{b}] \qquad (W/m^3) \qquad (2)$$

provided the field does not penetrate to the center of the tape where α is a constant. For operation of an ac cable in the range of 6-8 K with a niobium (or Nb alloy) substrate, losses are reduced by increasing the critical current density J_c of the substrate. A gain in the maximum operating temperature of the cable can also be obtained by increasing the T_c of the substrate. As shown below both of these goals can be readily achieved by small additions of Zr to the Nb substrate. It is also shown that these additions do not seriously affect the loss behavior of the Nb_3Sn itself.

A number of Nb_3Sn tapes were prepared by solid state diffusion with Nb substrates containing 0%, 1%, 2% and 5% Zr. The bronze matrix (Cu-13 wt% Sn) was initially cast around the Nb[8] and the composites rolled to a final thickness of ~100 μm, the Nb or Nb alloy substrates being ~20 μm thick. The tapes were then reacted in vacuum at 725°C for times between 10 and 40 h. The tapes were then slit into 6 mm wide strips, the bronze removed, and substrate losses measured. For comparison losses were also measured on two commercial tapes made by liquid diffusion process (IGC 7617 and KB-15) using internally oxidized Nb-1% Zr substrates. Losses were measured by inducing currents across the 6 mm wide tapes mounted on a plate of natural quartz placed in low pressure (~1 mm) helium gas. Although losses are produced both in the Nb_3Sn and the substrate, the Nb_3Sn loss is usually much smaller and can be neglected. The details of the apparatus will be published elsewhere. Figure 2 shows losses of the Nb-1%Zr (BT-64) substrate versus temperature for surface fields of 150, 250 and 350 rms A/cm. The losses are expressed as volume losses x 10 μm and correspond to the additional loss per area of the inner coaxial pair for a substrate of 10 μm thickness. Note (Fig. 2) that losses increase very rapidly once a certain threshold temperature is exceeded, reach a maximum at a temperature T_m (temperature for maximum loss) and then decrease to a constant value as the critical temperature T_{cs} of the substrate is exceeded. The rapid rise in loss corresponds to the region described by Eq. (2). The flat region independent of temperature corresponds to a normal substrate (Eq. 1). Losses for the other substrate compositions showed essentially the same features as those of Fig. 2. Table I gives loss values for each of the substrates for fields of 250 and 350 rms A/cm at various temperatures including T_m and T_{cs}. The value of T_m is also given for each field. Losses are acceptable up to ~8.5 K for pure Nb and ~9 K for 2%Zr at typical values for the axial field (~250 rms A/cm for most cable designs). Losses of the Nb-5%Zr substrate reach a peak at a higher temperature than any other substrate but are rather high over the entire temperature range, making it less desirable than the 1% or 2% Zr substrates. At 350 rms A/cm the advantages of small additions of Zr to reduce losses are clearly visible. Table I also shows losses of the IGC and KB commercial samples which are seen to peak at lower temperatures than the Nb-1%Zr substrate of BT-64. Losses are acceptable up to ~8 K for the IGC sample and ~7 K for the KB sample. Losses in the normal state are within 20% of Eq. (1) for samples BT-62, BT-64 and KB-15 but are approximately twice the value of Eq. (1) for samples BT-65, BT-66 and IGC 7617. In the latter case extra losses are believed to arise from currents in the Nb_3Sn, especially at the Nb_3Sn/NbZr interface.

Substrate losses are therefore acceptable for most Nb substrates up to ~8 K. The addition of small amounts of Zr (1% or 2%) further reduces these losses to ~9 K. The addition of Zr to the substrate, however, will affect the loss characteristics of Nb_3Sn.[9] The Nb_3Sn loss was therefore measured at 4.2 K for each of the four solid state diffused tapes. For this measurement the tapes were reacted at 725°C for 40 h. Results are shown in Fig. 3 where it is seen that losses are somewhat increased with Zr content but remain below 3 $\mu W/cm^2$ at 500 rms A/cm even for the 5% Zr sample. The critical temperature T_c of Nb_3Sn was also found to decrease slightly with Zr content. The onset T_c values are respectively 17.7, 17.7, 17.6 and 17.3 K for Nb_3Sn containing 0%, 1%, 2% and 5% Zr. These effects are small and should have little influence on losses of the cable even at temperatures as high as 8.5 K.

Hence one can conclude that the addition of a few percent

Zr to the Nb substrate of Nb_3Sn produced by solid-state diffusion will allow a maximum operating temperature of ~9 K. The use of pure Nb or oxidized Nb-1%Zr substrates limits the temperature to less than 8.5 K. Additions of Zr are also desirable to increase the critical current density of diffused Nb_3Sn.[8]

III. Losses in Cladding Material

In an earlier study[10] it was shown that large parasitic losses often occur in the cladding materials of commercial tapes. These were associated with Pb-Sn solders and ferromagnetic nickel flashes used respectively for soldering and electroplating the cladding. Since then, Pb-Sn has been replaced by a nonsuperconducting Ag-Sn solder and nickel flashes are avoided whenever electroplating is necessary. The remaining sources of cladding losses are, therefore, eddy currents in copper and magnetic losses in stainless steels.

Eddy current losses in the copper depend on whether a Cu/Cu cladding or a SS/Cu cladding is used and are affected by the lay angle φ of the flexible cable. If we consider only the inner conductor of the coaxial pair (Fig. 1) three surfaces are exposed to magnetic fields, the top surface (field H_θ) and the two surfaces facing the region between layers (field $\frac{H_\theta}{2}$ sec φ). Eddy current losses of a thin layer of normal metal at the surface of a superconductor are approximately given by[10]

$$p \cong 2.1\times10^{-9}\ (d^3 f^2/\rho)H^2 \quad (W/m^2) \qquad (3)$$

where d is the normal metal thickness (m), ρ is its resistivity (Ω-m) and H is the surface field (rms A/m). As pointed out earlier[10] when the normal metal is bonded with solder d should include the total thickness of the copper and solder. For copper with resistivity ratio of 150 ($\rho=1.1\times10^{-10}$ Ω-m), a 30 μm copper layer exposed to a field H_θ=500 rms A/cm will give losses of ~4.6 μW/cm^2. For an angle of 40° the other surfaces will each contribute ~2 μW/cm^2 (assuming 30 μm copper for each) giving a total eddy current loss of ~8.5 μW/cm^2. Hence 30 μm copper is the approximate limit for a Cu/Cu clad tape. In a SS/Cu clad tape the stainless steel will be placed in the high field region and copper losses occur only for the bottom surface of the upper layer (Fig. 1). For a 40° angle and H_θ=500 rms A/cm a thickness of 50 μm copper (RR=150) will give rise to ~9 μW/cm^2. The other side of the tape should therefore be clad with ~20 μm of stainless steel to keep the neutral axis as close to the Nb_3Sn as possible for good bending characteristics.[11]

The stainless steel should be carefully selected because many common stainless steels are unstable with respect to martensitic transformation under stress or at low temperatures, and become magnetic[12] resulting in appreciable loss. A number of stainless steels were obtained in strip form and the losses measured at 4.2 K. The strips, obtained in the "soft" (or annealed) condition ranged in thickness between 50 μm and 250 μm. Results are shown in Fig. 4. Losses are normalized to a 20 μm thickness which is the approximate thickness to be used in a SS/Cu clad Nb_3Sn tape. Note that steels such as 304, 310 and Hastelloy B exhibit losses in excess of 10 $\mu W/cm^2$ at 500 rms A/cm and are therefore unacceptable. The steel Carpenter 10 CR (not shown) had a loss behavior very similar to type 310 SS. Steels such as 302, 305, 316, 21-6-9 and 316L, 22-13-5 (not shown) were found to be only weakly magnetic and have acceptable losses. The steel 21-6-9, which is stabilized with nitrogen, showed no sign of magnetic hysteresis in the loss waveform and the loss displayed in Fig. 4 is probably the limit of accuracy of the apparatus. The magnetic behavior of this steel was also unaffected after stressing it to failure at room temperature. The high strength of this steel at low temperatures and its stability against martensitic transformation make it desirable for ac conductor applications. However, because of difficulty of soldering or other problems, other steels such as 302, 305, 316, 316L, and 22-13-5 are adequate provided samples of the melt are tested for ac losses before they are used.

IV. Mechanical Behavior

As mentioned earlier, an important consideration is the design of Nb_3Sn conductors is adequate mechanical characteristics. The behavior during bending and under tensile stress is compared below for a tape clad or both sides with copper and a tape clad with stainless steel and copper. Both tapes were obtained from Intermagnetics General Corp. (IGC). The Nb_3Sn/Nb substrate was prepared by liquid diffusion followed by an etching process to reduce ac losses.[3] The copper and stainless steel cladding were bonded by soldering with a Ag-Sn eutectic. The thickness of the copper was 24 μm for the Cu/Cu clad tape and 48 μm for the SS/Cu clad tape. The stainless steel was 26 μm thick. Specimens were machined by electrical discharge in the shape of standard sheet tensile coupons having a reduced area gauge section of 3.2 mm x 55 mm. The bending characteristics were determined by measuring the critical current at 4.0T and 4.2 K with the specimen on a holder of the desired radius. The effect of room temperature tensile stress was determined by applying a load to the reduced section tensile specimens held straight in the grips of an Instron Universal Testing machine at room temperature. The samples were then mounted on 2.5 cm radius holder and the critical current measured at 4.2 K in a 4.0T field. Separate samples were used for each radius and tensile load because of possible damage from handling. The critical current of the SS/Cu clad tape gave consistent and reproducible results. The Cu/Cu clad tape, however, gave variations of up to 30% for different tapes possibly because of its greater fragility. Bending and tensile test results are shown respectively in Figs. 5 and 6. The bending test results of Fig. 5 show that the SS/Cu clad tape is not completely balanced, the minimum bending radius being smaller with the SS on the outside. The first signs of critical current decrease for the SS/Cu clad tape occur at 0.8 cm with the SS on the outside and 1.5 cm with the SS inside. For the Cu/Cu clad tape the decrease starts at a radius of ~1.2 cm. The effect of a tensile load applied at room temperature is shown in Fig. 6. An average load of 22 kg/cm produces fracture of the Cu/Cu clad tape whereas a load of up to 35 kg/cm produces no damage in the Cu/SS clad tape.

In conclusion, the Cu/Cu and SS/Cu clad tapes differ most significantly in their behavior under a tensile load, the SS/Cu clad tape being able to sustain approximately twice the load of the Cu/Cu clad tape before showing any degradation.

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Table I

Characteristics and ac Losses of Nb Substrates

Sample	Substrate Composition	Substrate Critical Temp. T_{cs}(K)(1)	ρ_n ($\mu\Omega$-cm)	Substrate Thickness a (μm)	250 rms A/cm						350 rms A/cm					
					T_m (K)	Loss (μW/cm^2)(2)					T_m (K)	Loss (μW/cm^2)(2)				
						8.0K	8.5K	9.0K	T_m	T_{cs}		8.0K	8.5K	9.0K	T_m	T_{cs}
BT-62	Nb	9.3	0.8	14	8.8	*	2.3	106	239	59	3.6	1.7	362	186	457	116
BT-64	Nb-1%Zr	9.6	1.4	16	9.1	*	*	119	225	34	8.9	1.5	5.7	338	462	72
BT-66	Nb-2%Zr	9.7	2.8	19	9.4	*	*	4.9	197	25	9.3	1.3	4.4	38	353	55
BT-65	Nb-5%Zr	10.0	5.6	17	9.65	1.4	2.2	9.4	109	21	9.6	4.8	9.9	53	223	50
IGC 7617	Nb-1%Zr (Oxidized)	9.4	5.1	10.5	8.8	1.8	12	31	162	23						
KB-15	Nb-1%Zr (Oxidized)	8.5	4.3	7	8.0	124	9.6	9.6	110	9.6						

(1)midpoint, $\Delta T_c \sim 0.2$ K

(2)(loss/volume) x 10 μm for 6 mm wide tapes; *indicates losses smaller than 1 μW/cm^2

Figure Captions

Fig. 1. Schematic of current flow in the superconducting layers of the inner conductor of a coaxial pair (top) and across the unreacted Nb substrate (bottom).

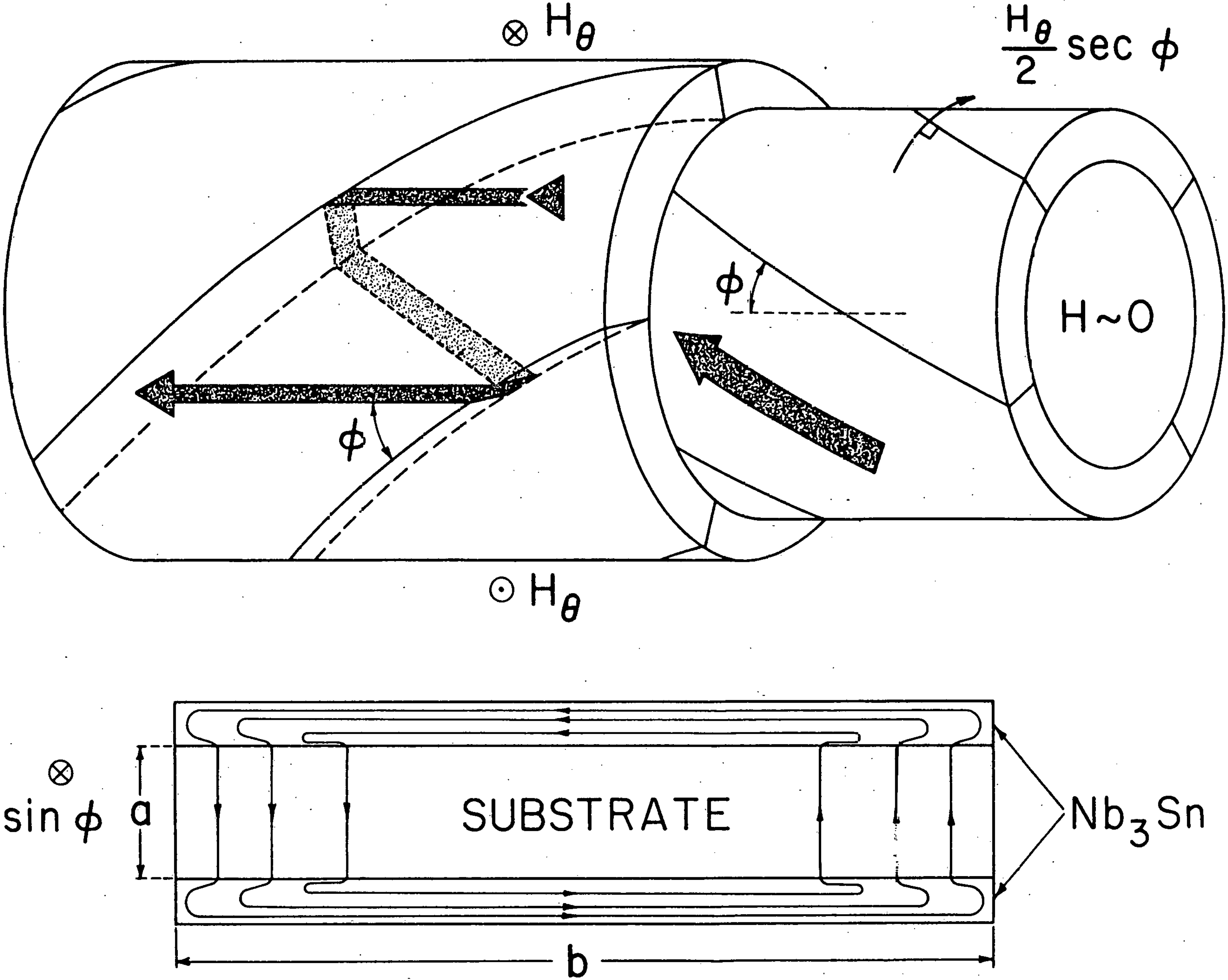
Fig. 2. Losses of a 6 mm wide Nb-1%Zr substrate versus temperature.

Fig. 3. Effect of zirconium additions on ac losses of Nb_3Sn at 4.2 K.

Fig. 4. 60 Hz magnetic losses of stainless steels at 4.2 K.

Fig. 5. Effect of bending radius on the critical current of a Cu/Cu and a SS/Cu clad tape. The Cu/Cu points are averages of three measurements.

Fig. 6. Effect of room temperature tensile stress on critical current of Cu/Cu and SS/Cu clad tapes. The Cu/Cu points are averages of three measurements.



⊗ H_θ
$\frac{H_\theta}{2} \sec \phi$
ϕ
ϕ
H ~ O
⊙ H_θ
⊗
$H_\theta \sin \phi$
a
SUBSTRATE
Nb_3Sn
b

Fig. 1

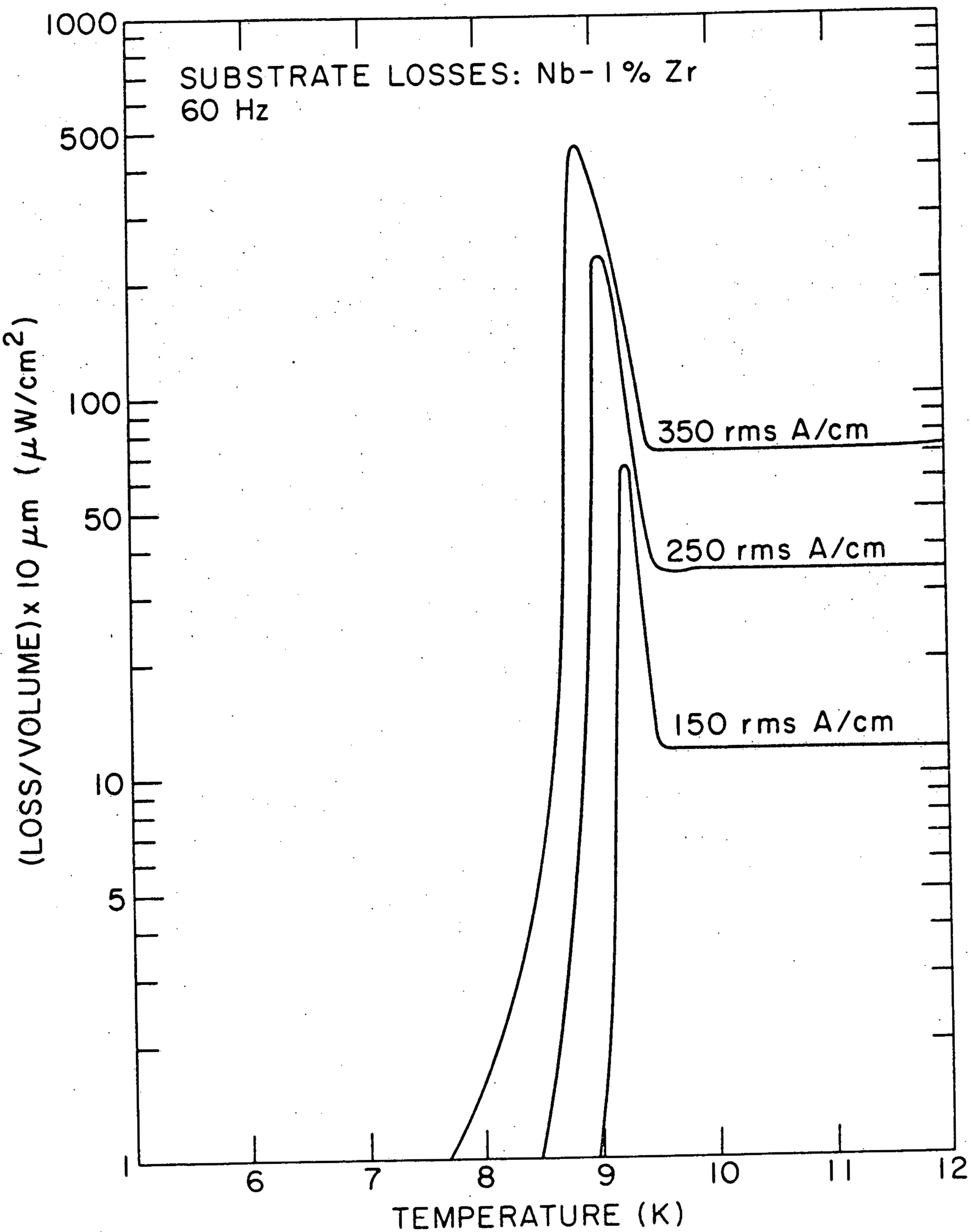

SUBSTRATE LOSSES: Nb-1% Zr
60 Hz
350 rms A/cm
250 rms A/cm
150 rms A/cm
1000
500
100
50
10
5
1
6
7
8
9
10
11
12
(LOSS/VOLUME) x 10 μm (μW/cm²)
TEMPERATURE (K)

Fig. 2

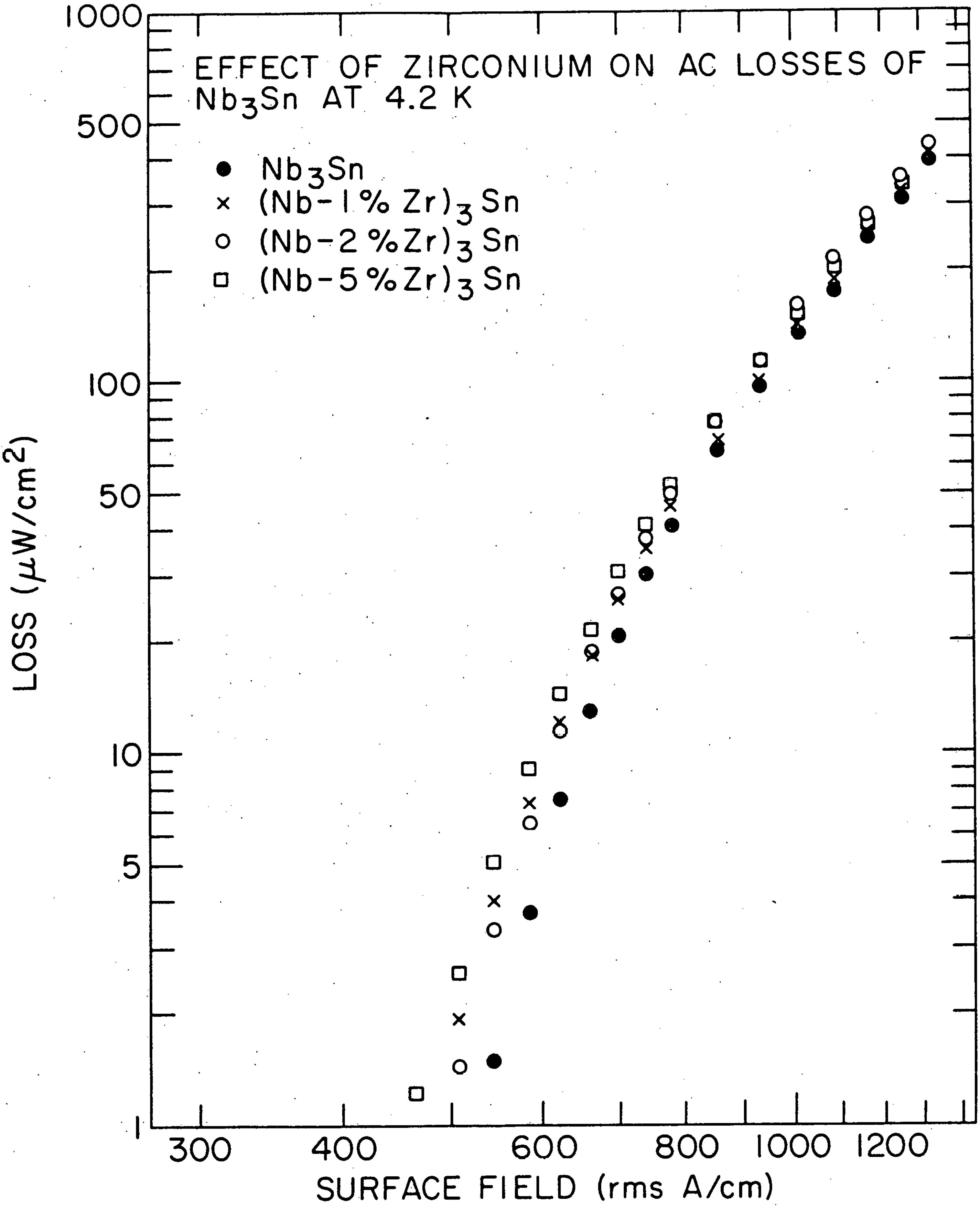

EFFECT OF ZIRCONIUM ON AC LOSSES OF Nb_3Sn AT 4.2 K
● Nb_3Sn
× $(Nb-1\% Zr)_3Sn$
○ $(Nb-2\% Zr)_3Sn$
□ $(Nb-5\% Zr)_3Sn$
LOSS ($\mu W/cm^2$)
1000
500
100
50
10
5
1
300
400
600
800
1000
1200
SURFACE FIELD (rms A/cm)

Fig. 3

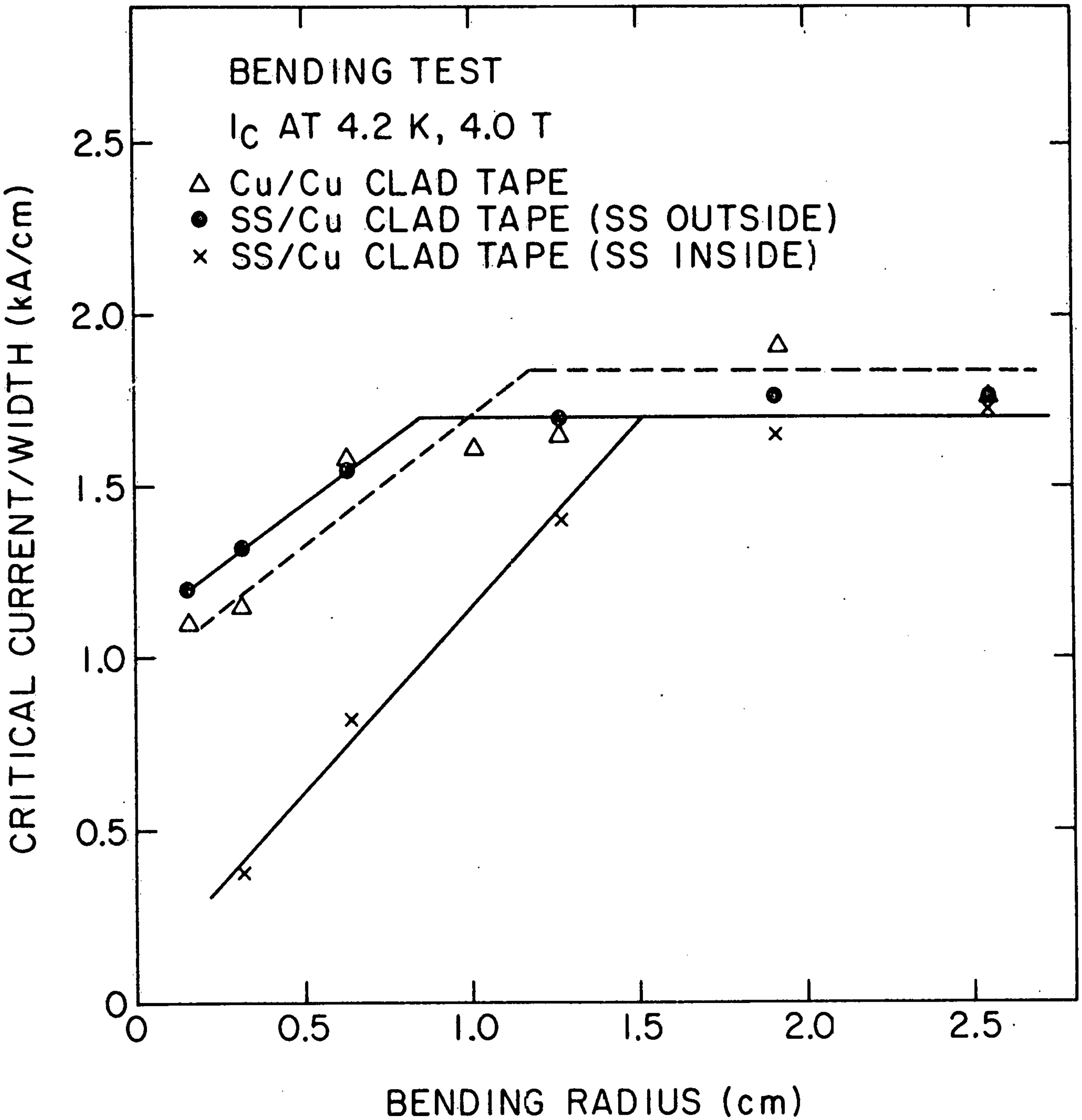
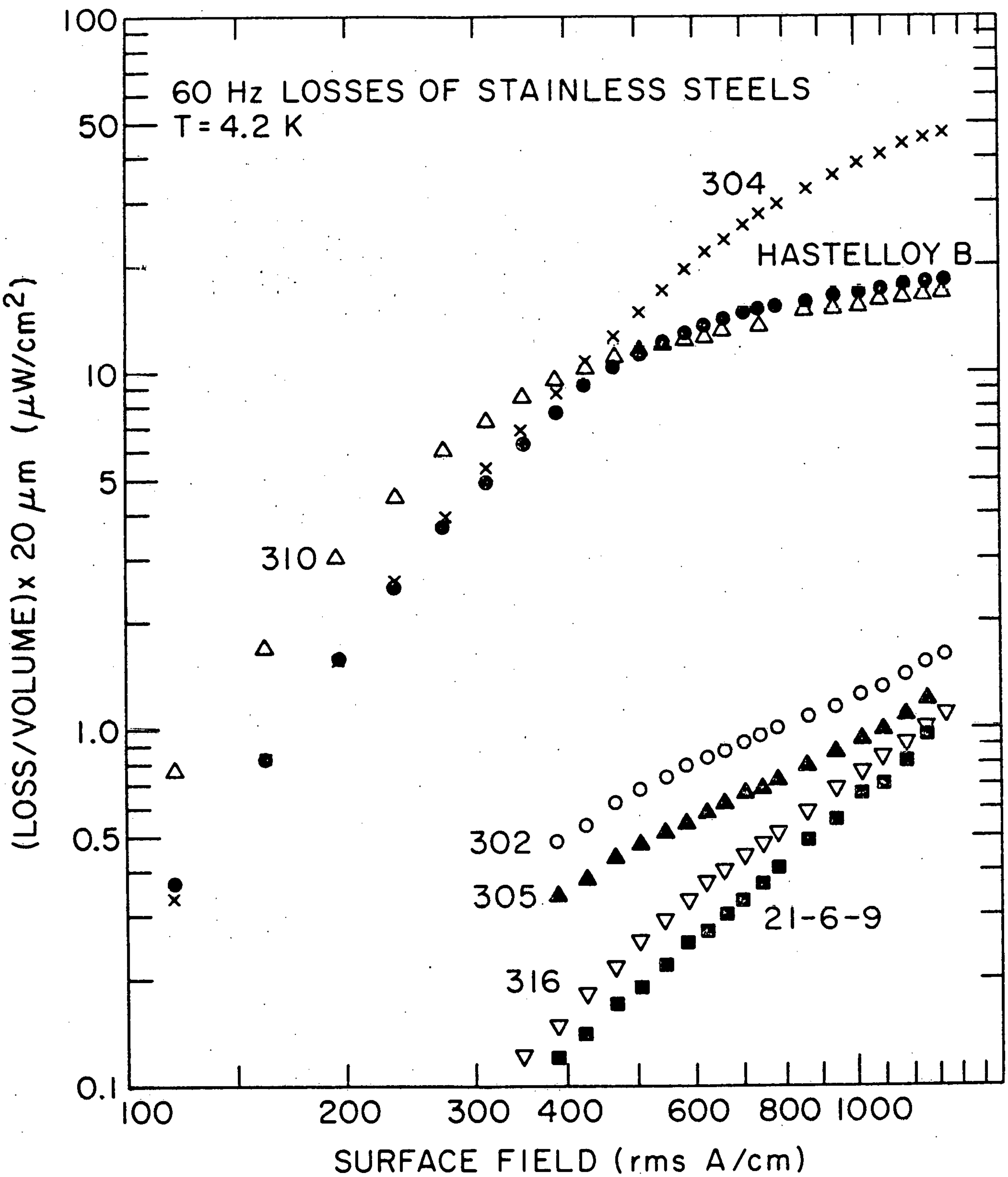

BENDING TEST
I_C AT 4.2 K, 4.0 T
△ Cu/Cu CLAD TAPE
● SS/Cu CLAD TAPE (SS OUTSIDE)
× SS/Cu CLAD TAPE (SS INSIDE)
CRITICAL CURRENT/WIDTH (kA/cm)
0
0.5
1.0
1.5
2.0
2.5
BENDING RADIUS (cm)

Fig. 5



60 Hz LOSSES OF STAINLESS STEELS
T = 4.2 K
304
HASTELLOY B
310
302
305
316
21-6-9
(LOSS/VOLUME) x 20 μm (μW/cm²)
100
50
10
5
1.0
0.5
0.1
100
200
300
400
600
800
1000
SURFACE FIELD (rms A/cm)

Fig. 4

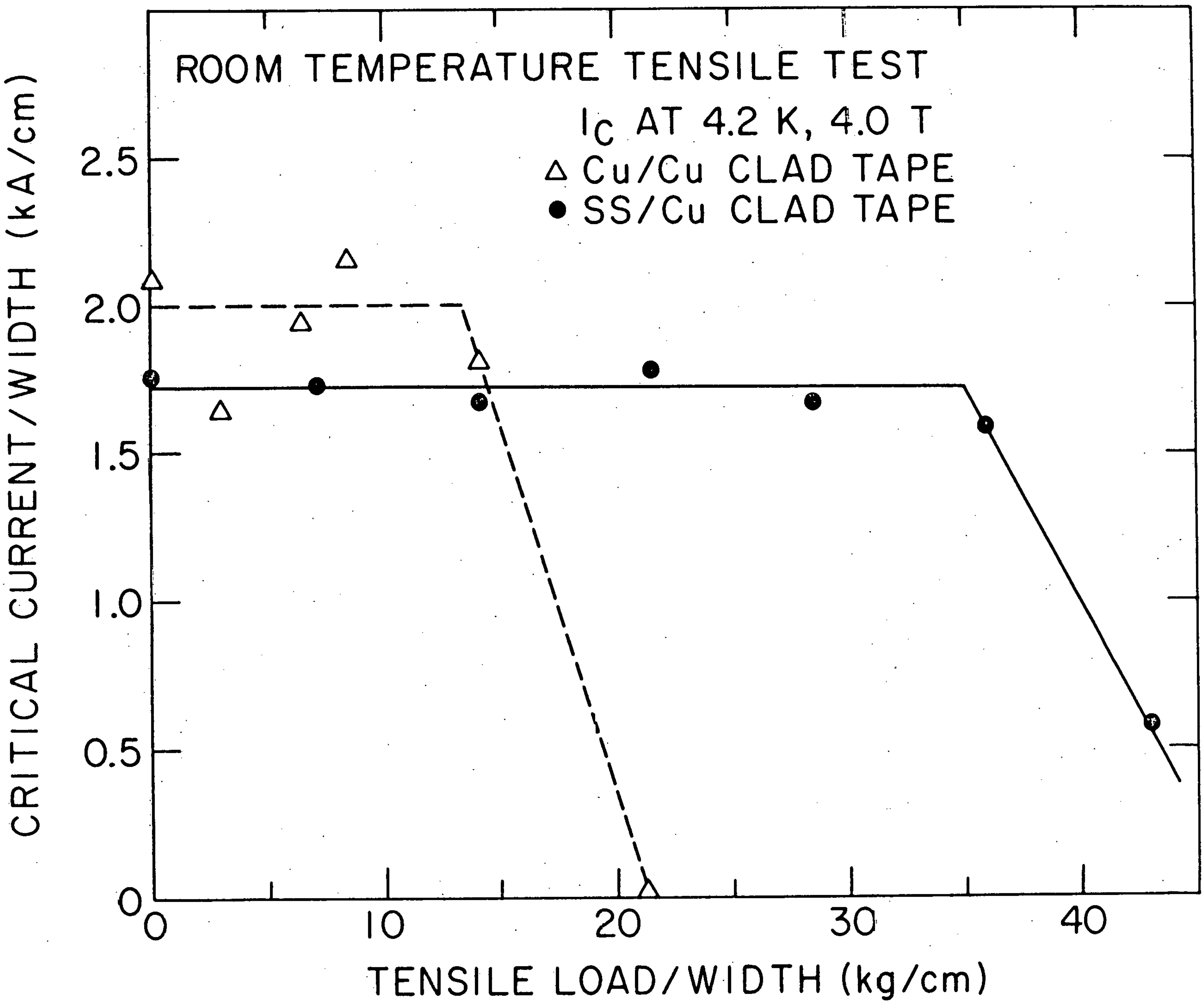

ROOM TEMPERATURE TENSILE TEST
I_C AT 4.2 K, 4.0 T
△ Cu/Cu CLAD TAPE
● SS/Cu CLAD TAPE
CRITICAL CURRENT/WIDTH (kA/cm)
TENSILE LOAD/WIDTH (kg/cm)
2.5
2.0
1.5
1.0
0.5
0
0
10
20
30
40

Fig. 6