**Determination of Physical and Mechanical
Properties of Copper-Clad Molybdenum Sheet**

**Report 34046
August 15, 1988**

P.J. Grobner

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ABSTRACT

Selected physical and mechanical properties of copper-clad molybdenum sheet have been determined. Among those properties determined were: room-temperature density, coefficient of thermal expansion in the temperature range -43 to 800 C, specific heat between -40 and +150 C, thermal conductivity from -50 to + 150 C, electrical resistivity in the same temperature range, magnetic susceptibility and modulus of elasticity both at room temperature. Materials with several different copper/molybdenum thickness ratios and composite thicknesses were evaluated.

INTRODUCTION

Climax Specialty Metals is producing copper-clad molybdenum sheet which is used in the electronic industry for thermal management. The copper-clad molybdenum sheet consists of roll-bonded laminates of OFHC copper on high purity (99.95%) molybdenum. Different copper thickness ratios are being produced, the most common being 13, 20, 25 and 33% per side, with total laminate thicknesses ranging from 0.13 to 13 mm (0.005 to 0.50 in).

Effective use of copper-clad molybdenum sheet in electronic applications requires the knowledge of various physical and mechanical properties of the material. The properties of interest include density, coefficient of thermal expansion, specific heat, thermal conductivity, electrical resistivity, magnetic susceptibility and the modulus of elasticity. The present report summarizes the results of determinations of these properties. Table I lists the laboratories involved in the project and the temperature ranges over which tests were conducted. The results of measurements obtained at the Thermophysical Properties Research Laboratory of Purdue Laboratory (TPRL) are reported in TPRL 716¹ and TPRL 716A².

EXPERIMENTAL PROCEDURES

MATERIAL

Samples of copper-clad molybdenum sheet, about 300 by 300 by 1 mm (12 by 12 by 0.04 in.), with nominally 13, 20, 25 and 33% Cu per side, were received for determining the physical properties. In addition, an unclad molybdenum sheet of similar size was included in the test program. The modulus of elasticity was measured on flat tensile specimens machined from a different set of sheets, with nominally 5, 13, 20, 25, 33 and 38% Cu per side. All materials were mill stress relieved at 800 C (1470 F).

The actual thickness of the cladding was measured metallographically at ten locations on each side and the average values and standard deviations were calculated. Similar measurements were done on the tensile specimens for Young's modulus. The results are given in Table II.

DENSITY

Two methods for determining the density were applied: by buoyancy and by measuring the weight and dimensions of the specimens. The determination by buoyancy was performed in duplicate according to the ASTM Standard Method C 693-74 by weighing the specimens, about 68 by 65 mm (2.7 by 2.2 in.), in air and in water. For the second method, slightly larger specimens, about 97 by 76 mm (3.8 by 3.0 in.) were weighed to the nearest 0.1 mg and their dimensions were measured to the nearest 0.01 mm at ten different locations to obtain a sufficiently accurate value of the volume. Each set of measurements was used to calculate the volume and the density, so that an average and a standard deviation could be evaluated.

COEFFICIENT OF THERMAL EXPANSION

The coefficient of thermal expansion (CTE) of copper clad molybdenum sheet as well as of unclad molybdenum sheet was measured at the Thermophysical Properties Research Laboratory (TPRL) of Purdue University in the X and Y direction, using a dual Push-Rod Dilatometer. CTE was determined over two temperature ranges, one being -43 C to +127 C and the other 25 to 800 C. Measurements in the high temperature range were requested by Climax Specialty Metals separately to obtain data useful for the production of ceramic coatings on the laminate. The specimens used were 50 mm (2 in.) long and 7 mm (0.28 in.) wide.

SPECIFIC HEAT

The specific heat was measured at TPRL using a standard Perkin-Elmer Model DSC-2 Differential Scanning Calorimeter with sapphire as a reference material. The standard and sample, both encapsulated in pans, were subjected to the same heat flux and the differential power required to heat the samples at the same rate was recorded. The specific heat of the sample was computed from the mass of the sapphire standard, pans, the differential power and the known specific heat of sapphire. The measurements were conducted in the temperature range -40 to +150 C (-40 to +302F).

THERMAL CONDUCTIVITY

The thermal conductivity was measured in the temperature range -40 to +150 C (-40 to + 302 F) at TPRL using the Kohl-rausch method which involves the determination of the product of thermal conductivity and electrical resistivity. Since the electrical resistivity is also measured at the same time, thermal conductivity can be calculated. The measurement was conducted by passing constant direct current through the specimen to heat it while the ends are kept at a constant temperature. Thermocouples also act as voltage probes. Radial heat losses are minimized by an external heater with a temperature profile matched with that of the specimen.

ELECTRICAL RESISTIVITY

Measurements in the temperature range -40 to +150 C (-40 to +302 F) were conducted at TPRL simultaneously when determining thermal conductivity.

MAGNETIC SUSCEPTIBILITY

Room temperature magnetic susceptibility was determined at the National Bureau of Standards, Electromagnetic Technology Division, in Boulder, Colorado. The measurements were made with a SQUID magnetometer at applied fields of 10, 20 and 50 Oe.

MODULUS OF ELASTICITY

The specimens were tensile tested at room temperature in the elastic portion of the stress-strain curve to determine the modulus of elasticity. Strain was measured using foil strain gages. Two strain gages were bonded to the opposite faces of the specimen with epoxy cement and the circuit designed as a self compensating bridge. Ten measurements were made on each specimen; the load was removed after each test; a new load was applied and the stress-strain curve registered. No permanent strains were detected, indicating that all measurements were performed in the elastic region. Young's modulus was evaluated from the slope of the stress-strain line.

RESULTS AND DISCUSSION

DENSITY

The results obtained at AMAX are given in Table III. They have good reproducibility and accuracy as indicated by the closeness of the results obtained by two independent methods and the low standard deviations which are in the range of 0.1 to 1.0% of the average value. A plot of the data against the copper ratio in Figure 1 shows a linear correlation corresponding to the equation

$$d = 10.22 - 1.27 x \quad (1)$$

where d is the density in g/cm^3 and x is the ratio of the total copper to the total thickness of the sheet. The theoretical density, calculated by weighed averages, can be expressed by the equation

$$d = 10.22 - 1.28 x \quad (2)$$

with a density of 10.22 g/cm^3 for molybdenum and 8.94 g/cm^3 for copper.³ The difference between the experimentally determined and theoretical equations is not statistically significant, so that the density of copper clad molybdenum sheet can be calculated when the actual copper thickness is known, using either equation.

It should be noted that density was also measured at TPRL as part of the determination of thermal conductivity. These results, reproduced in Table IV, (Table 6 of the Report TPRL 716) are systematically too low. It is inconceivable that the density of rolled molybdenum would be 9.97 g/cm^3 . A possible explanation for the error can be the small size of the specimens, which makes accurate measurement of dimensions difficult (relative effect of burrs, etc.).

COEFFICIENT OF THERMAL EXPANSION

The results of measurements in the temperature range of -43 to 127 C (-45 to 261 F) are given in Table V which shows the average CTE between room temperature and -43C (-45 F) and that between room temperature and 127 C (261 F). The data are plotted in Figure 2. The bar graph shows that the CTE generally increases with increasing copper ratios as expected. The testing direction has little effect on the test results. The only exceptions are the -43 C (-45 F) data of the 25 Cu samples, which are suspect, especially the measurement in the X direction, which seems too low. The effect of the temperature range is different in the unclad molybdenum and the copper-clad samples. The unclad molybdenum has a higher CTE at the higher temperature, which agrees with data published in the litera-

ture. In the copper-clad specimens, however, a lower CTE has been measured in the higher temperature range. This phenomenon can be explained by the effect of temperature on the strength of copper. Copper with its higher CTE tends to increase the CTE of the composite, but its influence will be stronger at low temperatures when it is stiffer and will diminish with increasing temperature as copper softens. The effect of temperature on the strength of molybdenum is negligible relative to its effect on that of copper.

Considering the small difference between the results obtained in the X and Y direction, the averages of the two were calculated for practical application with the exception of the suspect values of the 25 Cu material at low temperature. The data so obtained are plotted against the total copper ratio in Figure 3, showing a linear relation. This is probably an empirical observation without a strict theoretical basis, but it is useful to estimate the CTE of the 25 Cu laminate at the lower temperature by interpolation ($7.45 \times 10^{-6} \text{K}^{-1}$).

By averaging the results of the X and Y direction and estimating the CTE of the 25 Cu material at RT to -43C (RT to -45 F) by interpolation, a set of recommended data has been obtained and is summarized in the last column of Table V.

A second set of thermal expansion tests was conducted at TPRL between room temperature and 800 C (1470 F) and the results are presented in their Report TPRL 716 A³. The coefficients of thermal expansion calculated from the original experimental data (Table 1 in TPRL 716A) are given in Table VI. This table contains data obtained from the heating as well as the cooling paths. The difference between the results obtained in the X and Y direction is generally small enough that the average of the two values can serve as the single value. The exceptions are marked in the table. A comparison of the data obtained in Figure 4 shows several inconsistencies in CTE values of the copper clad specimens.

The CTE of unclad molybdenum increases with increasing temperature, and there is little difference between results obtained during the heating and cooling period. The data for 200 C (390 F) are in reasonable agreement with those obtained between room temperature and 127 C (260 F), see Table V. The effect of the copper ratio is rather irregular. Little effect is observed in the 13%, 20% and 25% Cu laminates and only the 33% Cu has a higher CTE. Similarly, the effect of the temperature range seems to be random with the possible tendency of an increase of CTE with increasing temperature. Striking are the many cases with a large difference between the results obtained during the heating and the cooling cycle. In most of these the data from the cooling cycle are lower than the corresponding data from the heating cycle. A possible reason for this

behavior was found when examining the tested specimens, which all show a distinct oxide layer. The growing oxide will simulate a higher expansion during the heating cycle, but retard the contraction during the cooling cycle.

The data obtained on copper clad molybdenum sheet in this set of tests seem questionable and the tests should be repeated under conditions preventing oxidation of the specimens.

SPECIFIC HEAT

The results of measurements at TPRL are shown in Table VII and Figure 5. The data are quite consistent with the expected effect of the copper ratio according to the rule of mixtures. The specific heats at 21 C (70 F) are plotted against the copper ratio in Figure 6. The effect of the copper ratio x on the specific heat can be expressed by the equation:

$$c = \frac{x (d_{Cu} c_{Cu} - d_{Mo} c_{Mo}) + d_{Mo} c_{Mo}}{x (d_{Cu} - d_{Mo}) + d_{Mo}} \quad (1)$$

where x is the copper ratio

d_{Cu} is the density of copper

d_{Mo} is the density of molybdenum

c_{Cu} is the specific heat of copper

c_{Mo} is the specific heat of molybdenum

The room temperature density of copper is 8.94 g/cm³ and that of molybdenum is 10.22 g/cm³. The specific heats of molybdenum and copper at 21 C (70 F) are 0.387 and 0.247 W_s/gK respectively according to data in Reference 4. When using these values in equation (1) the following formula is obtained.

$$c = \frac{0.935 x + 2.524}{-1.280 x + 10.22}$$

The corresponding curve is plotted in Figure 6 and the diagram shows an excellent agreement between the experimental data and the theoretical plot.

THERMAL CONDUCTIVITY

The results of the in-place (X and Y direction) thermal conductivity (TC) measurements at TPRL are presented in Table VIII and are plotted against testing temperature in Figure 7. The diagram indicates that temperature has little systematic effect on thermal conductivity in the range tested, although it is known⁴ that the TC of copper as well as of molybdenum decreases with increasing temperature. The effect of tempera-

ture was tested statistically by calculating the slope "a" of the linear regression equation

$$TC = at + b$$

where t is the temperature in centigrade. The results are presented in Table IX. Some of the data are negative (as expected), but some are positive and their values don't exceed 2.22×10^{-4} , which indicates that there is no statistically significant effect of temperature in this range. An average TC for the temperature range of -50 to 150 C (-58 to 300 F) can therefore be assumed.

Figure 7 also shows little difference between the data points obtained in the X and the Y direction. An exception is the 33% Cu material, where the results are slightly, yet systematically lower in the Y direction than in the X direction. But even in this case the difference in the means is within one standard deviation, so that the two sets of data can be considered as one for practical purposes and an average can be established. The calculated values and the corresponding standard deviations are given in the last row of Table VIII. These data are plotted against the copper ratio in Figure 8, showing a linear correlation. The unexpectedly low value for the 20% Cu material can not be explained.

Results of thermal conductivity measurements at TPRL in the Z direction (through thickness) are reproduced in Table X. The effect of temperature is consistent in the 0% Cu, 13% Cu and 25% Cu material (TC drops with temperature) while the 20 and 33% Cu results show irregularities. The room-temperature TC increases with the copper ratio between 0 and 25% Cu, but the 33% Cu result is almost identical with that of the 25% Cu material. This anomaly may be due to poor thermal contact between the layers.

ELECTRICAL RESISTIVITY

Electrical resistivity was measured at TPRL in the temperature range of - 50 to 150 C (-58 to 300 F) as part of the thermal conductivity determination. The results obtained are given in Table XI. A plot of the data against temperature in Figure 9 shows that the temperature dependence is linear and that the difference between the X and Y data is practically negligible. There is practically no difference between the electrical resistivity observed in the 13% Cu and 20% Cu, which is difficult to explain. It could be related to the large scatter of the copper ratio in the 20% Cu product (see Table 2).

The linear regression coefficients of the temperature dependence were calculated by the least square method and are

listed in Table XII together with the coefficients of correlation and the calculated values of electrical resistivity for 25 C (77 F). These data are plotted against the total copper thickness ratio in Figure 10, which shows, with the exception of the 20% Cu value, a good agreement with the theoretical curve. This curve was derived from the general formula for electrical resistance for parallel resistors.

$$1/R = 1/R_1 + 1/R_2 + \dots \quad (2)$$

which leads to the equation

$$ER = \frac{ER_{Mo}}{x (ER_{Mo}/ER_{Cu} - 1) + 1}$$

where ER_{Mo} and ER_{Cu} are the electrical resistivities of molybdenum and copper and x is the total copper ratio in the laminate. Using $ER_{Mo} = 5.7 \mu\Omega\text{cm}$ according to Reference 3, Equation (3) becomes

$$ER = \frac{5.7}{2.365x + 1} \quad (4)$$

The curve in Figure 10 corresponds to this equation.

MAGNETIC SUSCEPTIBILITY

Room-temperature magnetic susceptibility was measured at the National Bureau of Standards in Boulder, Colorado. The results are given in Table XIII and are plotted in Figure 11 against the copper thickness ratio. The plot shows that magnetic susceptibility decreases linearly with the copper ratio.

MODULUS OF ELASTICITY

The results of the mechanical tests to determine Young's modulus are given in Table XIV. They have good reproducibility as indicated by their low standard deviations which are systematically below 2% of the average. Young's modulus of the unclad molybdenum sheet is well within the values reported in the literature. Smithells and Brandes⁵, for example, give a value of 324.8 GPa (47.1×10^6 psi), while an older edition of the Metals Handbook (1958) quotes 344.7 GPa (50.0×10^6 psi).

A plot of the data against the copper ratio in Figure 12 shows a non-linear correlation, corresponding to a quadratic equation

$$y = a + bx + cx^2 \quad (1)$$

The curve in Figure 12 was calculated from the experimental data using the least square regression of this formula, leading to the equation for Young's modulus in GPa

$$E = 336.8 - 93.795 x - 108.011 x^2$$

where x is the ratio of total copper to the total thickness of the specimen. The cause of the non-linear correlation is most probably internal stress in the copper layer which changes with its thickness. The internal stress is generated in the copper during cooling from the stress relieving temperature of 800°C (1470° F) when the much stiffer molybdenum core shrinks less (coefficient of expansion = $5.1 \times 10^{-6}/K$) than the copper cladding, (coefficient of expansion of $17.0 \times 10^{-6}/K$). When extrapolating the curve to a copper ratio of 1 according to Equation 2, a hypothetical modulus of elasticity of 135.0 GPa (19.6×10^6 psi) is obtained. This value is only slightly higher than 129.8 GPa (18.8×10^6 psi) found in handbooks for copper.

AMAX Research & Development Center

Paul J. Grobner

REFERENCES

1. R.E. Taylor, H. Groot and J. Larimore, "Thermophysical Properties of Copper and Aluminum Clad Molybdenum", Report to TPRL 716, Thermophysical Properties Research Laboratory, Purdue University, West Lafayette, IN, April, 1988.
2. R.E. Taylor, "Thermal Expansion of Cu/Mo/Cu", Report TPRL 716A, Thermophysical Properties Research Laboratory, Purdue University, West Lafayette, IN, March, 1988.
3. C.J. Smithells and E.A. Brandes, "Metals Reference Book", Butterworths, London, UK, 1987.
4. J.H. Perry, "Chemical Engineer's Handbook", 4th edition, McGraw-Hill, New York, NY, 1963.
5. "Metals Handbook", Vol. 2, 9th Edition, Amer. Soc. for Metals, Metals Park, OH, 1979

Table I. Tests Performed

<u>Property</u>	<u>Laboratory</u>	<u>Temperature</u>
Density	AMAX R&D Center	Room Temperature
Coefficient of Thermal Expansion	Purdue University	-43 C to + 127 C
Coefficient of Thermal Expansion	Purdue University	25 to 800 C
Specific Heat	Purdue University	-40 C to +150 C
Thermal Conductivity	Purdue University	-50 C to +150 C
Electrical Resistivity	Purdue University	-50 C to +150 C
Magnetic Susceptibility	National Bureau of Standards	Room Temperature
Modulus of Elasticity	AMAX R&D Center	Room Temperature

Table II. Measured Cladding Thickness of Samples Tested

Type of Sample	Nominal Cu Thickness per Side, %	Total Thickness of Sample, mm Average (Standard Deviation)	Total Copper Ratio Average (Standard Deviation)
Sheet for Physical Properties	0	1.016 (0.016)	0
	13	1.004 (0.003)	0.298 (0.045)
	20	1.025 (0.003)	0.358 (0.148)
	25	1.022 (0.017)	0.493 (0.083)
	33	0.990 (0.005)	0.672 (0.055)
Tensile Specimens	0	1.004 (0.010)	0
	5	1.075 (0.006)	0.094 (0.009)
	13	1.606 (0.009)	0.293 (0.009)
	20	1.605 (0.014)	0.410 (0.008)
	25	1.001 (0.007)	0.502 (0.007)
	33	1.259 (0.002)	0.668 (0.015)
	38	1.025 (0.004)	0.762 (0.029)

Table III. Density of Copper Clad Molybdenum Sheet

Nominal Cu Ratio Per Side, %	Measured Total Cu Ratio	Density, g/cm ³		
		Buoyancy Method ^a	Dimension Measure- ment Method	Average of Both Methods
0	0	10.22	10.22 ± 0.05 ^b	10.22
13	0.298	9.85	9.83 ± 0.02	9.84
20	0.358	9.80	9.76 ± 0.01	9.78
25	0.493	9.59	9.58 ± 0.10	9.59
33	0.672	9.38	9.35 ± 0.02	9.37

a Average of two specimens

b Standard Deviation

Table IV. Sample Geometries, Masses and Bulk Density Values*

Sample Designation	Thick (in)	Width (in)	Width (in)	Mass (gms)	Density (gms cm ⁻³)
Mo	0.0400	0.4867	0.482	1.5337	9.974
13%	0.0408	0.4860	0.485	1.5024	9.533
20%	0.0405	0.4855	0.487	1.5063	9.599
25%	0.0424	0.486	0.486	1.5354	9.356
33%	0.0405	0.486	0.489	1.4435	9.152

* From Report TPRL716

Table V. Coefficients of Thermal Expansion (CTE)
Between RT to -43C and RT to 127C

Nominal Cu Ratio, %	Temperature Range, C (F)	CTE, 10^{-6} K^{-1} in the		Average CTE, 10^{-6} K^{-1}
		X Direction	Y Direction	
0	RT to -43 (RT to -45) RT to 127 (RT to 261)	5.00 5.32	4.97 5.25	4.99 5.29
13	RT to -43 (RT to -45) RT to 127 (RT to 261)	5.66 5.70	6.14 5.52	5.90 5.61
20	RT to -43 (RT to -45) RT to 127 (RT to 261)	6.26 5.91	6.45 5.97	6.36 5.94
25	RT to -43 (RT to -45) RT to 127 (RT to 261)	5.89 6.67	7.97 7.07	7.43* 6.87
33	RT to -43 (RT to -45) RT to 127 (RT to 261)	8.88 7.96	8.82 8.07	8.85 8.02

* Interpolated value

Table VI. Coefficients of Thermal Expansion Between
Room Temperature and 800C (1470F)

Cu atio, %	Temperature Range, RT to C (F)	Cycle	CTE, 10 ⁻⁶ K ⁻¹		X-Y Average CTE 10 ⁻⁶ K ⁻¹	H-C Average CTE 10 ⁻⁶ K ⁻¹
			X Direc- tion	Y Direc- tion		
0	200 (390)	H	5.19	5.31	5.25	5.26
		C	5.21	5.32	5.27	
	400 (750)	H	5.49	5.35	5.42	5.39
		C	5.37	5.35	5.36	
	600 (1110)	H	5.54	5.49	5.52	5.52
		C	5.54	5.50	5.52	
	800 (1470)	H	5.69	5.66	5.68	5.68
		C	5.68	5.67	5.68	
13	200 (390)	H	5.69	5.98	5.84	5.55 ^a
		C	5.38	5.14	5.26	
	400 (750)	H	5.60	5.70	5.65	5.60
		C	5.57	5.51	5.54	
	600 (1110)	H	5.32	5.73	5.53	5.45
		C	5.68	5.06	5.37 ^a	
	800 (1470)	H	5.87	5.91	5.89	5.61 ^a
		C	5.79	4.84	5.32 ^a	
20	200 (390)	H	5.73	6.15	5.94	5.73 ^a
		C	5.44	5.57	5.51	
	400 (750)	H	5.63	5.61	5.62	5.65
		C	5.62	5.71	5.67	
	600 (1110)	H	5.44	5.40	5.42	5.61
		C	5.74	5.83	5.79	
	800 (1470)	H	6.15	5.91	6.03	5.95
		C	5.77	5.96	5.87	
25	200 (390)	H	6.39	7.59	6.99 ^a	5.59 ^a
		C	5.02	5.22	5.19	
	400 (750)	H	5.63	6.40	6.02	5.72 ^a
		C	5.50	5.31	5.41	
	600 (1110)	H	5.17	5.71	5.44	5.52
		C	5.73	5.47	5.60	
	800 (1470)	H	5.49	6.08	5.79	5.69
		C	6.01	5.16	5.59 ^a	
33	200 (390)	H	8.13	6.55	7.34 ^a	6.59 ^a
		C	5.62	5.62	5.64	
	400 (750)	H	6.54	5.93	6.24	6.04 ^a
		C	5.81	5.84	5.83	
	600 (1100)	H	6.05	5.74	5.90	5.96
		C	5.93	6.09	6.01	
	800 (1470)	H	6.22	5.85	6.04	6.18
		C	6.26	6.39	6.33	

^a These averages are taken from two widely different values and are therefore suspect.

Table VII. Specific Heats of Copper-Clad Molybdenum Sheet

Temperature		Specific Heat of Sheets of the Nominal Copper Ratio Indicated, Ws/gK				
C	(F)	0	13	20	25	33
-40	(-40)	0.237	0.269	0.274	0.297	0.319
-30	(-22)	0.239	0.272	0.277	0.299	0.321
-20	(- 4)	0.242	0.274	0.281	0.302	0.323
-10	(14)	0.244	0.277	0.283	0.304	0.325
0	(32)	0.246	0.280	0.286	0.306	0.328
11	(52)	0.248	0.282	0.288	0.309	0.330
21	(70)	0.250	0.285	0.291	0.312	0.332
31	(88)	0.252	0.287	0.294	0.314	0.334
41	(106)	0.254	0.289	0.296	0.316	0.336
51	(124)	0.255	0.291	0.298	0.318	0.339
61	(142)	0.255	0.293	0.300	0.320	0.341
71	(160)	0.258	0.295	0.303	0.322	0.343
81	(178)	0.258	0.297	0.304	0.324	0.345
91	(196)	0.260	0.298	0.306	0.325	0.346
101	(214)	0.261	0.299	0.307	0.326	0.348
111	(232)	0.262	0.300	0.308	0.328	0.349
121	(250)	0.263	0.301	0.310	0.329	0.350
125	(257)	0.264	0.301	0.310	0.329	0.350
150	(302)	0.266	0.304	0.313	0.332	0.354

Table VIII. Thermal Conductivity (TC) in the X and Y Direction (In-Plane)

Cu Ratio	0% Cu		13% Cu		20% Cu		25% Cu		33% Cu	
	Temp, C	TC $\text{Wcm}^{-1}\text{K}^{-1}$	Temp, C	TC $\text{Wcm}^{-1}\text{K}^{-1}$	Temp, C	TC $\text{Wcm}^{-1}\text{K}^{-1}$	Temp, C	TC $\text{Wcm}^{-1}\text{K}^{-1}$	Temp, C	TC $\text{Wcm}^{-1}\text{K}^{-1}$
X	-46	1.298	-48	2.100	-46	1.995	-45	2.627	-51	3.025
	-31	1.317	-37	2.102	-33	2.016	-31	2.674	-33	3.009
	-14	1.314	-26	2.134	-22	2.027	-14	2.667	-18	3.011
	29	1.343	-11	2.105	26	2.006	26	2.656	28	3.027
	50	1.325	28	2.068	48	1.980	49	2.630	52	3.025
	72	1.302	50	2.082	72	1.955	72	2.593	72	2.999
	103	1.293	72	2.073	97	1.946	97	2.588	96	2.997
	122	1.303	101	2.067	121	1.973	122	2.620	120	3.040
	148	1.313	125	2.102	149	2.003	150	2.651	149	3.086
			153	2.109						
Y	-48	1.324	-47	2.100	-44	2.000	-52	2.606	-42	2.956
	-32	1.343	-32	2.133	-31	2.014	-41	2.649	-29	2.996
	-19	1.347	-20	2.144	-20	2.024	-27	2.666	-16	2.984
	31	1.285	26	2.112	30	1.992	-15	2.662	26	2.948
	51	1.303	49	2.143	48	2.001	24	2.579	50	2.957
	71	1.292	74	2.116	74	1.981	53	2.603	73	2.937
	97	1.287	96	2.109	99	1.982	75	2.577	95	2.928
	121	1.297	122	2.144	122	2.008	97	2.573	125	2.980
	150	1.309	152	2.159	151	2.034	120	2.608	147	3.013
							152	2.642		
Average Standard Deviation		1.311		2.111		1.997		2.625		2.995
		0.019		0.027		0.024		0.034		0.040

Table IX. Slopes of the Linear Regression Equation

$$TC = at + b$$

Nominal Cu Ratio, %	Testing Direction	Slope "a"
0	X	-4.22×10^{-5}
	Y	-2.22×10^{-4}
13	X	-8.99×10^{-5}
	Y	$+1.19 \times 10^{-4}$
20	X	-2.16×10^{-4}
	Y	$+2.56 \times 10^{-6}$
25	X	-1.99×10^{-4}
	Y	-1.79×10^{-4}
33	X	$+1.89 \times 10^{-4}$
	Y	$+2.79 \times 10^{-5}$

Table X. Thermal Conductivity in the Z Direction
(Through Thickness)

Nominal Cu Ratio %	Testing Temperature		TC W cm ⁻¹ K ⁻¹
	C	(F)	
0	-40	(-40)	1.37
	0	(32)	1.35
	23	(73)	1.34
	50	(122)	1.32
	100	(212)	1.30
13	-40	(-40)	1.68
	0	(32)	1.66
	23	(73)	1.65
	50	(122)	1.63
	100	(212)	1.62
20	-40	(-40)	1.73
	0	(32)	1.74
	23	(73)	1.76
	50	(122)	1.73
	100	(212)	1.68
25	-40	(-40)	1.99
	0	(32)	1.97
	23	(73)	1.96
	50	(122)	1.95
	100	(212)	1.90
33	-40	(-40)	1.99
	0	(32)	1.98
	23	(73)	1.97
	50	(122)	1.98
	100	(212)	2.05

Table XI. Electrical Resistivity (ER) of Copper Clad Molybdenum Sheet

Cu Ratio	0%		13%		20%		25%		33%	
	Temp, C	ER, $\mu\Omega\text{cm}$	Temp, C	ER, $\mu\Omega\text{cm}$	Temp, C	ER, $\mu\Omega\text{cm}$	Temp, C	ER, $\mu\Omega\text{cm}$	Temp, C	ER, $\mu\Omega\text{cm}$
X	-46	4.087	-48	2.417	-46	2.499	-45	1.977	-51	1.687
	-31	4.442	-37	2.559	-33	2.677	-31	2.116	-33	1.846
	-14	4.841	-26	2.712	-22	2.824	-14	2.298	-18	1.975
	29	5.869	-11	2.904	26	3.473	26	2.700	28	2.365
	50	6.401	28	3.407	48	3.774	49	2.947	52	2.585
	72	6.936	50	3.708	72	4.107	72	3.200	72	2.764
	103	7.686	72	3.999	97	4.453	97	3.454	96	2.974
	122	8.164	101	4.389	121	4.793	122	3.719	120	3.191
	148	8.849	125	4.709	149	5.190	150	4.023	149	3.369
			153	5.097						
Y	-48	3.933	-47	2.414	-44	2.418	-52	1.865	-42	1.729
	-32	4.301	-32	2.599	-31	2.597	-41	1.977	-29	1.844
	-19	4.599	-20	2.768	-20	2.745	-27	2.122	-16	1.958
	31	5.762	26	3.404	30	3.451	-15	2.242	26	2.322
	51	6.246	49	3.710	48	3.696	24	2.638	50	2.545
	71	6.705	74	4.045	74	4.034	53	2.944	73	2.752
	97	7.332	96	4.338	99	4.375	75	3.171	95	2.952
	121	7.899	122	4.702	122	4.689	97	3.394	125	3.220
	150	8.632	152	5.117	151	5.094	120	3.634	147	3.426
							152	3.971		

Table XII. Temperature Dependence of Electrical Resistivity (ER)

Nominal Copper Ratio	Equation ER = at + b (t = temp. in C)	Coefficient of Correlation r	ER at 25 C $\mu\Omega\text{cm}$
0	0.02405 t + 5.118	0.998	5.72
13	0.01344 t + 3.047	0.999	3.38
20	0.01382 t + 3.065	0.998	3.41
25	0.01042 t + 2.417	0.999	2.68
33	0.00877 t + 2.117	0.999	2.34

Table XIII. Magnetic Susceptibility of Copper-Clad Molybdenum Sheet at Room Temperature

Nominal Cu Ratio, %	Magnetic Susceptibility, $\frac{\text{emu}}{\text{cm}^3} \text{ Oe}$
0	$(8.2 \pm 0.1) \times 10^{-6}$
13	$(5.2 \pm 0.1) \times 10^{-6}$
20	$(5.1 \pm 0.1) \times 10^{-6}$
25	$(3.7 \pm 0.1) \times 10^{-6}$
33	$(2.4 \pm 0.1) \times 10^{-6}$

Table XIV. Results of Measurements of Modulus of Elasticity

Nominal Cu Ratio Per Side %	Speci- men No.	Measured Total Cu Ratio, %	Average Total Cu Ratio, %	Modulus of Elasticity				
				Average of 10 Measurements GPa (10 ⁶ psi)	Standard Deviation GPa (10 ⁶ psi)	Average of Specimens Tested GPa (10 ⁶ psi)	Standard Deviation GPa (10 ⁻⁶ psi)	
0	M1	0		--	--	--	--	
	M2	0	0	342.6 (49.69)	2.3 (0.33)	341.7 (49.56)	1.3 (0.19)	
	M3	0		340.7 (49.41)	2.1 (0.30)			
5	C1	9.4		321.5 (46.63)	0.8 (0.12)	--	--	
	C2	9.6	9.5	318.4 (46.18)	1.1 (0.16)	319.5 (46.34)	1.8 (0.26)	
	C3	9.4		318.5 (46.19)	1.2 (0.18)	--	--	
13	13A	--	--	--	--	--	--	
	13B	--	29.2	--	--	300.8 (43.63)	3.4 (0.49)	
	13C	29.2	--	300.8 (43.63)	3.4 (0.49)	--	--	
20	20A	41.0	--	283.2 (41.07)	1.5 (0.22)	--	--	
	20B	41.8	41.1	283.9 (41.18)	1.5 (0.22)	283.5 (41.12)	1.5 (0.22)	
	20C	40.6	--	283.4 (41.10)	1.4 (0.20)	--	--	
25	25B	50.4	--	262.1 (38.02)	3.0 (0.43)	--	--	
	25C	50.0	50.1	264.8 (38.41)	3.1 (0.45)	262.2 (38.04)	2.6 (0.37)	
	25D	50.0	--	259.8 (37.68)	1.4 (0.20)	--	--	
33	33A	66.4	--	223.7 (32.44)	1.0 (0.14)	--	--	
	33B	67.2	67.1	225.3 (32.67)	1.7 (0.24)	224.9 (32.62)	1.1 (0.16)	
	33C	67.6	--	225.7 (32.74)	1.5 (0.22)	--	--	
38	38B	77.2	--	199.6 (28.95)	1.6 (0.23)	--	--	
	38C	76.6	76.3	205.9 (29.86)	1.8 (0.26)	202.0 (29.29)	3.4 (0.49)	
	38D	75.0	--	200.4 (29.07)	1.8 (0.26)	--	--

Figure 1. Effect of Copper Ratio on the Density of Copper-Clad Molybdenum Sheet

Figure 2. Effect of Nominal Copper Ratio, Temperature Range and Testing Direction on the Coefficient of Thermal Expansion.

Figure 3. Effect of Copper Ratio on the Average CTE in the Temperature Ranges Indicated.

Figure 4. Coefficients of Thermal Expansion Between Room Temperature and 200, 400, 600 and 800 C, as Measured During the Heating (H) and Cooling (C) Period. Bars with x indicate suspect data.

Figure 5. Specific Heat

Figure 6. Effect of the Copper Ratio on the Specific Heat of Copper Clad Molybdenum Sheet at 21C (70F).

Figure 7. Effect of Temperature on In-Plane Thermal Conductivity of Copper-Clad Molybdenum Sheet. Open symbols: Tests in the X direction. Full symbol: Tests in the Y direction.

Figure 8. Effect of Copper Ratio on In-Plane Thermal Conductivity of Copper-Clad Molybdenum Sheet.

Figure 9. Effect of Temperature on Electrical Resistivity. Open Symbols: Tests in the X direction. Full symbols: Tests in the Y direction.

Figure 10. Effect of Copper Ratio on Room-Temperature Electrical Resistivity of Copper Clad Molybdenum Sheet

Figure 11. Effect of Copper Ratio on Room-Temperature Magnetic Susceptibility of Copper-Clad Molybdenum Sheet.

Figure 12. Effect of the Copper Ratio on Young's Modulus of Copper Clad Molybdenum Sheet

END

**DATE
FILMED**

9 / 4 / 92