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TITLE: CRYOGENIC PROPERTIES OF ALUMINUM ALLOYS AND COMPOSITES

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CRYOGENIC PROPERTIES OF ALUMINUM ALLOYS AND COMPOSITES

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Several aluminum-based materials have been evaluated for possible application at cryogenic temperatures. These included the Al-Li alloy 2090, a high purity mechanically alloyed Al, SiC whisker reinforced Al 2124, and SiC particulate reinforced Al 6061. Mechanical properties, thermal properties and electrical properties were measured for these materials. Their performance in a radio frequency cavity was also determined.

INTRODUCTION

Lightweight structural materials have shown a great deal of promise for space-based accelerator applications (1). The BEAR project (Beam Experiment Aboard a Rocket) employed a copper coated 6061 aluminum accelerator. The aluminum alloy component weighed only 30% of a copper component with an equivalent volume. The specific strength and specific modulus of aluminum are also greater than those of copper. In this study four aluminum-base materials were chosen as possible candidate materials for a cryogenic space-based accelerator. These materials were subjected to a variety of mechanical, electrical, and thermal property tests, as a function of temperature, with emphasis on determining cryogenic behavior.

The Al-Li alloy 2090, from Alcoa, was included because of a ten percent density reduction compared to the aluminum alloys that had already been used for building accelerators. It was anticipated that its transport properties would be somewhat less desirable than those of some other aluminum alloys, but the weight reduction potential might compensate. The possibility of better thermal conductivity, without sacrificing strength, prompted the inclusion of Inco's me chanically alloyed pure aluminum, a dispersion strengthened unalloyed matrix, which should retain high conductivity. Both of these aluminum-based materials have the drawback of large thermal contraction on cooling to cryogenic temperatures.

A major concern in the design and fabrication of a cryogenic accelerator is the tuning of the machine and it is very well established that absolute dimensions of the cavity control this. A change from copper-based materials to aluminum-based materials would significantly aggravate this problem. However, if one adds SiC to aluminum as a reinforcement, the thermal contraction decreases and at the 20 volume percent level, it is similar to that of copper. For this reason ACM's 20v/o SiC whisker reinforced 2124 Al and 6061+20v/o SiC particulate from DWA were also chosen for the materials investigation.

EXPERIMENTAL METHODS

The method used to measure texture was the standard one of x-ray diffraction where for each d-spacing (e.g. that corresponding to {111} plane), the specimen is rotated in two directions to obtain a distribution of intensities. The texture plots or pole figures use a gray shading representation, the greater the concentration of poles in a given direction, the darker the plot is at that point. The gray scale given at the side of each plot shows how each intensity level is related to a random level, i.e. the intensity that would be obtained if no preferred orientation were present.

Elastic modulus, yield strength, percent elongation, and ultimate tensile strength were measured at room temperature for the four aluminum materials on an MTS 880 hydraulic testing machine with a 345 MPa load capacity. The test samples were taken parallel and perpendicular to the rolling or extrusion direction in the plate stock that was obtained for each material, with the exception of the Al SiC particulate. Only tensile samples parallel to the extrusion direction were available for this material. Samples were tested at a strain rate of 0.05 cm/min.

Mechanical testing at liquid helium temperatures (4°K) and liquid nitrogen temperatures (77°K) was done by the National Bureau of Standards in Boulder, Colorado. A 100 kN screw driven Instron machine was used to pull the threaded end tensile samples at a strain rate of 0.05 cm/min.

Thermal conductivity and electrical resistivity were tested from -150°C to 0°C at the Thermophysical Properties Laboratory at Purdue University using the Kohlrausch method (2). Thermal conductivity values are accurate to ±5% with the Kohlrausch method and the measured quantities are traceable to NBS standards.

For the study of electrical performance and resonant frequency shift as a function of temperature, a simple radio frequency cavity design was selected (3). Called a "pillbox", this component consists of three sections fastened together by two bolts. The center section incorporates a cylindrical cavity 1.9 cm in diameter and 1.3 cm in length. The design was chosen for our studies because of the ease of fabrication and conservation of the somewhat scarce developmental materials selected.

A useful quantity describing the efficiency of a test cavity is the Q, a measure of the sharpness of resonance, defined as

$$Q = 2\pi \frac{\text{electromagnetic energy}}{\text{energy lost per cycle}}$$

In general, Q is roughly proportional to the volume divided by the surface area since stored energy depends upon the volume while losses occur at wall surfaces. The "pill box" is coupled to a radio frequency system thus losses not only occur at the walls, but also in the system, so energy loss is greater, and the Q less than for a totally enclosed cavity. (The Q for a totally enclosed cavity is called the unloaded Q and is only dependent upon wall losses, whereas the loaded Q takes into account wall and system losses.) Coupling is accomplished by two diametrically opposed holes in the cavity wall. The "pill box" is subjected to radio frequency signals at temperatures ranging from 12^{o}K to 298^{o}K The 'pill box' cavities are designed to resonate at 22 GHz.

RESULTS AND DISCUSSION

Texture results, shown in Figure 1, revealed the degree of preferred orientation in the four aluminum materials. The Al-Li 2090 alloy exhibited a strong rolling texture, and even here the anisotropy would be limited by the inherently high symmetry of the cubic crystal structure and the nearly isotropic nature of aluminum (single crystal) itself. A fiber texture was found in the mechanically alloyed aluminum. One very interesting result was that the SiC whisker reinforcement in the 2124 Al was more strongly textured than was the matrix. More work will be required on this point but it is possible that this texturing of the reinforcement might affect at least the elastic anisotropy of the composite. The SiC in the particulate reinforced aluminum displays a weak texture, although there is slight preference for alignment in the <111> direction with the rolling direction as in the whisker reinforced material.

Room temperature mechanical test results revealed that only the 2124 aluminum with 20% SiC whisker reinforcement showed significant directional dependence in terms of elastic modulus, 121 GPa in the extrusion direction and 100 GPa 90^{o} to the extrusion direction. The existence of a preferential alignment of the SiC whiskers was confirmed through texture measurements and metallography. The difference in yield strength for the two SiC reinforced materials was attributed to the difference in aluminum matrices, the whisker reinforced material had a 2124 Al matrix while the matrix for the particulate reinforced material was 6061 Al. The values for the other materials are consistent with the expected effect of lithium, which is to raise the elastic modulus of aluminum, and for pure aluminum, which is the matrix for the mechanically alloyed material. The reinforcing phases in this latter material clearly have no effect on the elastic modulus. Significant orientation effects were found in the Al-Li and the mechanically alloyed aluminum with regard to the ductility, measured as percent elongation. The percent elongation in the rolling direction of the Al-Li was 11.15 and 5.12 in the transverse direction. In the extrusion direction of the mechanically alloyed aluminum, the percent elongation was 7.14 and in the transverse direction, 3.36. Again these orientation effects were confirmed by texture measurements.

Cryogenic test results compare with those published in literature (4). Cryogenic tensile test results shown in Figure 2 for the four aluminum materials reveal that the ultimate strength increases with a decrease in temperature. The UTS more than doubles for the mechanically alloyed aluminum tested at 4°K as compared to room temperature (290°K). Yield strength values also increased as temperature decreased. Lattice defects producing significant stress fields extending over only a few atomic distances constitute the strong temperature dependent contribution to the strength of a material. These lattice defects include interstitials, vacancies, solute atoms, and dislocations perpendicular to the slip plane. The thermal contribution decreases as temperature is increased due to thermal activation, obstacles to deformation can be overcome with increased thermal energy.

The Al-Li fractures at room temperature and cryogenic temperatures are similar as they both exhibit ductile dimples. However, at cryogenic temperatures the Al-Li also displays evidence of brittle or flat fracture and delamination along the longitudinal direction. The appearance of gas bubbles was noted in the mechanically alloyed aluminum fractures. Fractures at both room and cryogenic temperatures exhibited ductile dimples. At cryogenic temperatures evidence of transgranular cracking was found in the mechanically alloyed aluminum. The fractures of the Al with 20% SiC whisker reinforcement showed some evidence of whisker pullout. The room and cryogenic samples displayed a tearing failure mode with some secondary cracking, the cracking was most apparent in the cryogenic sample. The aluminum with 20% SiC particulate, room and cryogenic samples, showed a combination of ductile dimples and tearing.

Electrical resistivity and thermal conductivity results are plotted as a function of tempera ture in figures 3 and 4, respectively. Of the four aluminum materials, all exhibited a decrease in electrical resistivity and thermal conductivity as the temperature decreased. The mechanically alloyed aluminum had the lowest electrical resistivity of the four materials and was one of the most thermally conductive, making it the most desirable of the four materials for an accelerator cavity material in terms of thermophysical properties.

The resonant frequency shift of the "pill box" cavity with temperature change is directly related to the cavity geometry. A plot of resonant frequency change as a function of temperature shown in figure 5 demonstrates the thermal coefficient of expansion of the cavity materials. Of the four aluminum materials tested, only the mechanically alloyed aluminum and 6061 Al with SiC particulate had a lower coefficient of thermal expansion than the copper. The coefficient for thermal expansion of the copper as compared with the SiC reinforced aluminum differs over the temperature range from 20^{o}K to 290^{o}K. These materials were chosen for their match in thermal expansion with that of copper.

"Q" values were measured for OFE copper and the various aluminum materials. Results are shown in Figure 6. As anticipated "Q" values were greatest for the OFE copper. A somewhat disturbing result is that the "Q" values associated with the aluminum cavities were only a little less than half of the OFE copper. If any of these materials is to be used for an accelerator cavity, it will first have to be copper plated to take advantage of the electrical properties associated with copper.

CONCLUSIONS

The four aluminum materials were characterized in terms of mechanical, electrical, and thermal properties. The following conclusions were derived from this study

1 The anisotropy of room temperature mechanical properties data was confirmed by the use of texture measurements

2. Yield strengths and tensile strengths increased with decreasing temperature.

3. Of the four materials examined, the mechanically alloyed aluminum had the best thermo-physical properties in terms of cryogenic accelerator applications (high thermal conductivity, low electrical resistivity, and small coefficient of thermal expansion).

4. "Q" values were less than half that of copper. These materials should be copper plated if chosen for use in an accelerator cavity.

5. Resonant frequency results revealed a deviation in coefficient of thermal expansion for the copper and Al-SiC reinforced materials.

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Figure 1. Texture results in the 111 plane for a) Al-Li alloy 2090, b) mechanically alloyed aluminum, (c) Al 2124 in Al-SiC, and d) SiC whiskers in Al-SiC .

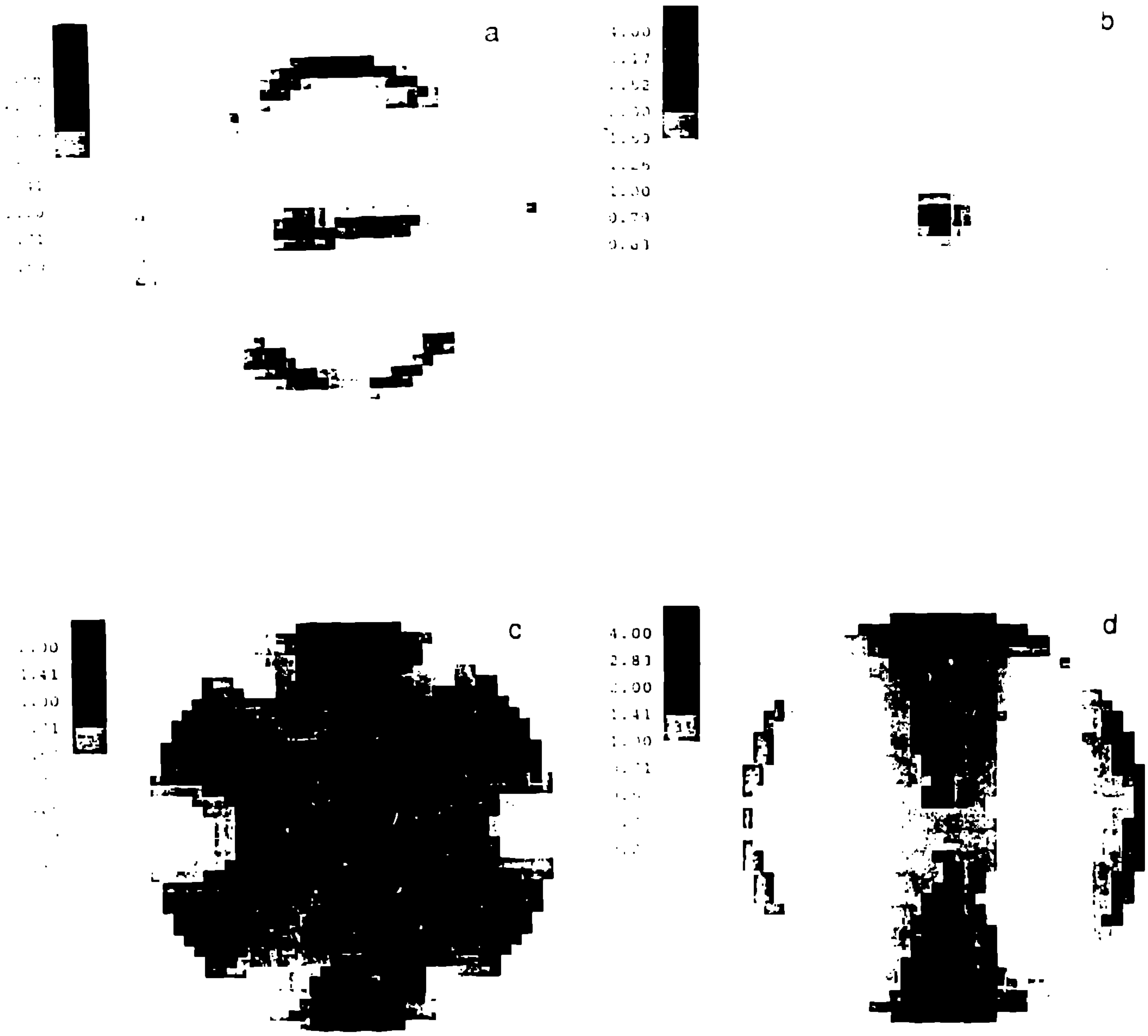
Figure 2. The ultimate tensile strength as a function of temperature for the four aluminum materials.

Figure 3. Electrical resistivity as a function of temperature

Figure 4. Thermal conductivity as a function of temperature.

Figure 5. "Q" values as a function of temperature compared with OFE copper.

Figure 6. Percent change in resonant frequency as a function of temperature.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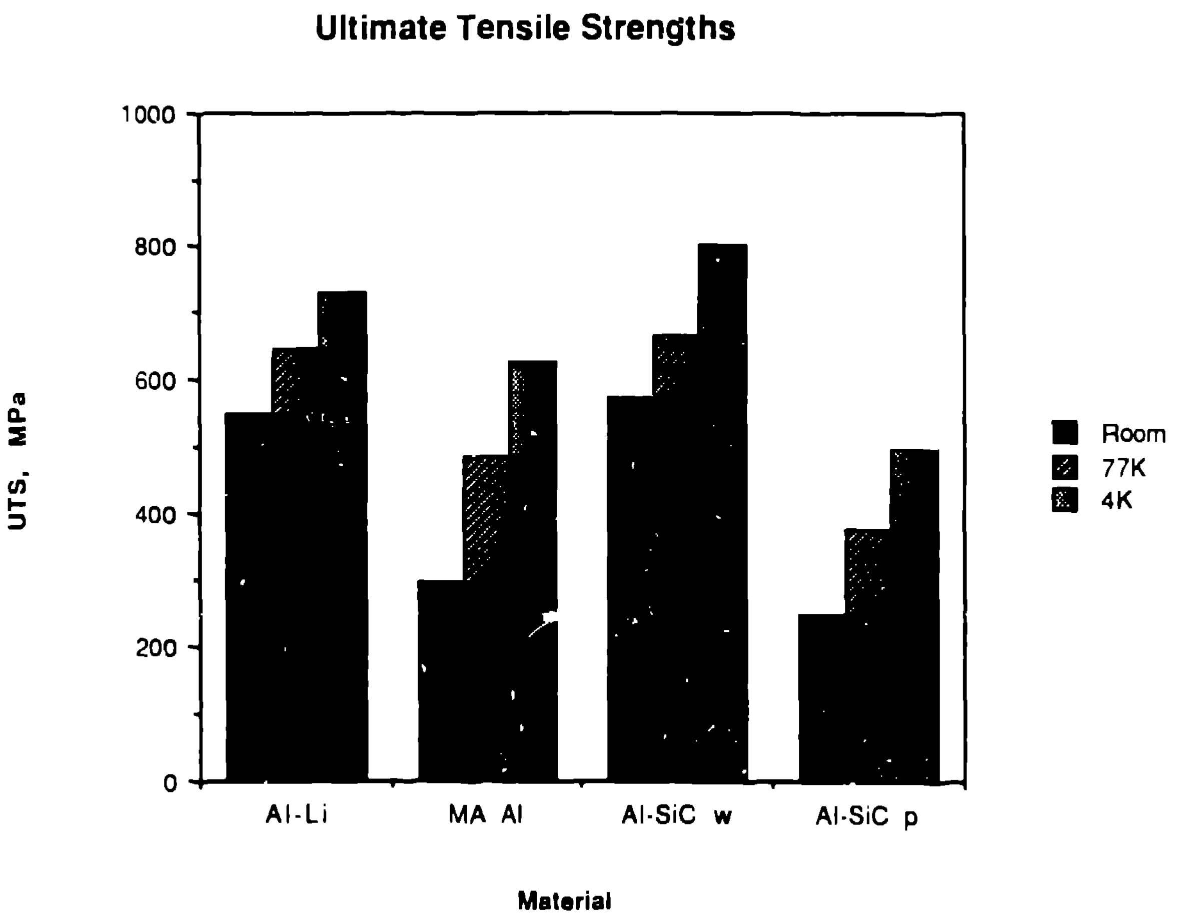
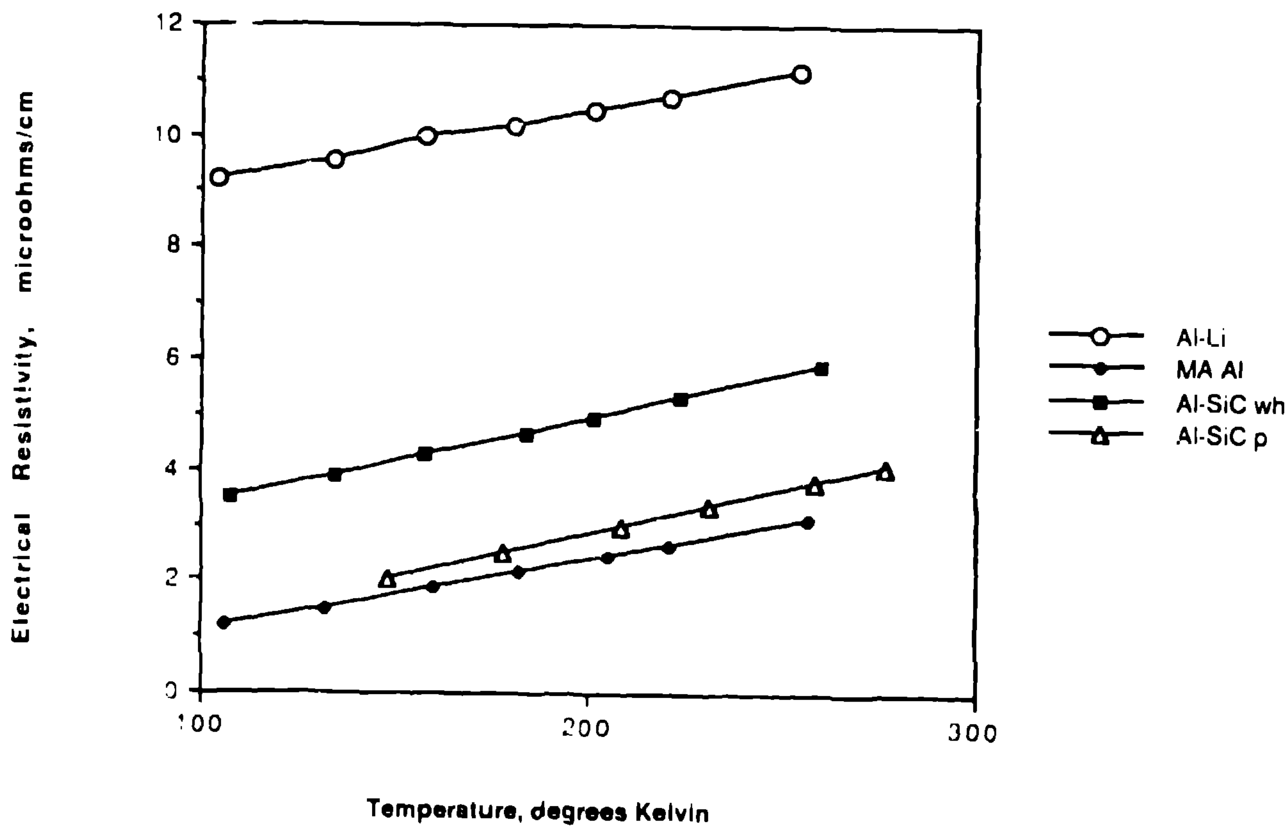
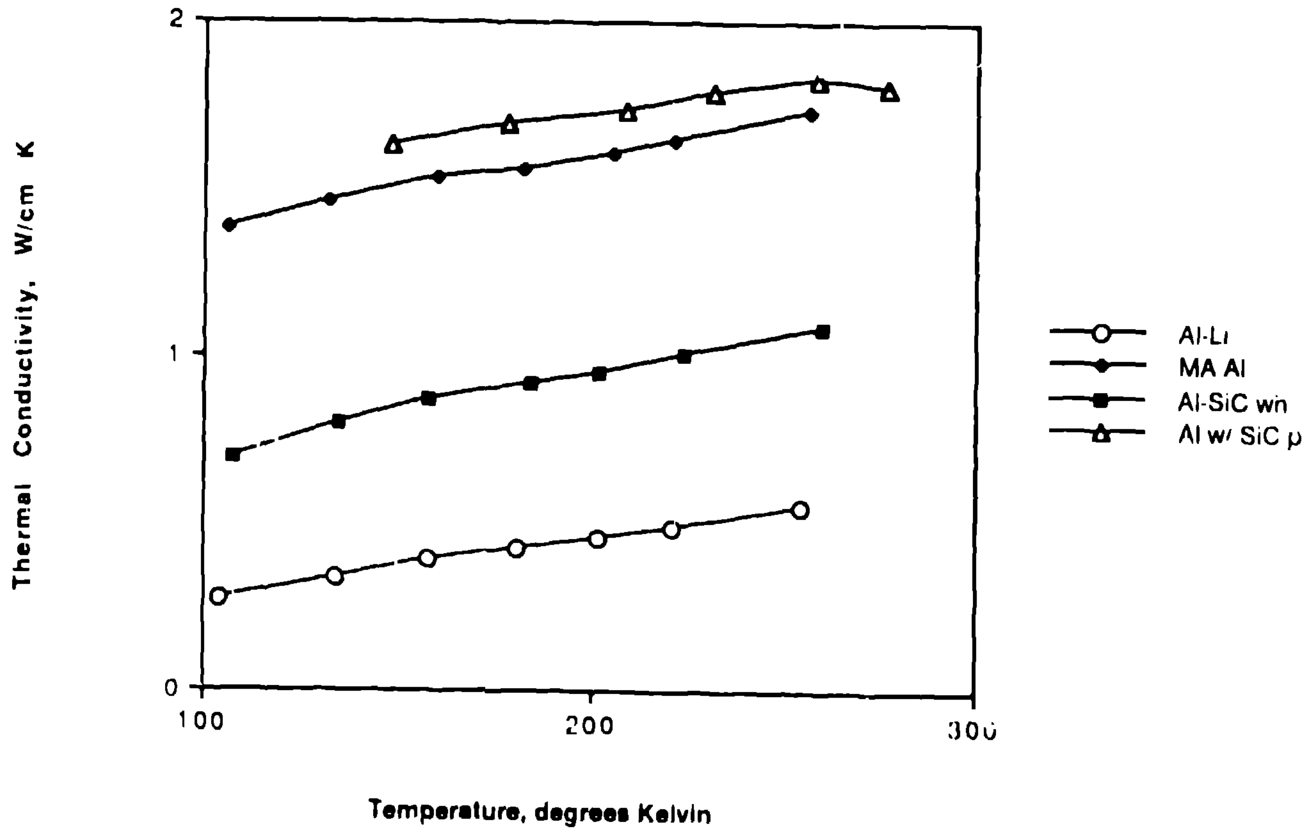


Ultimate Tensile Strengths
1000
800
600
400
200
0
UTS, MPa
Al-Li
MA Al
Al-SiC w
Al-SiC p
Material
Room
77K
4K

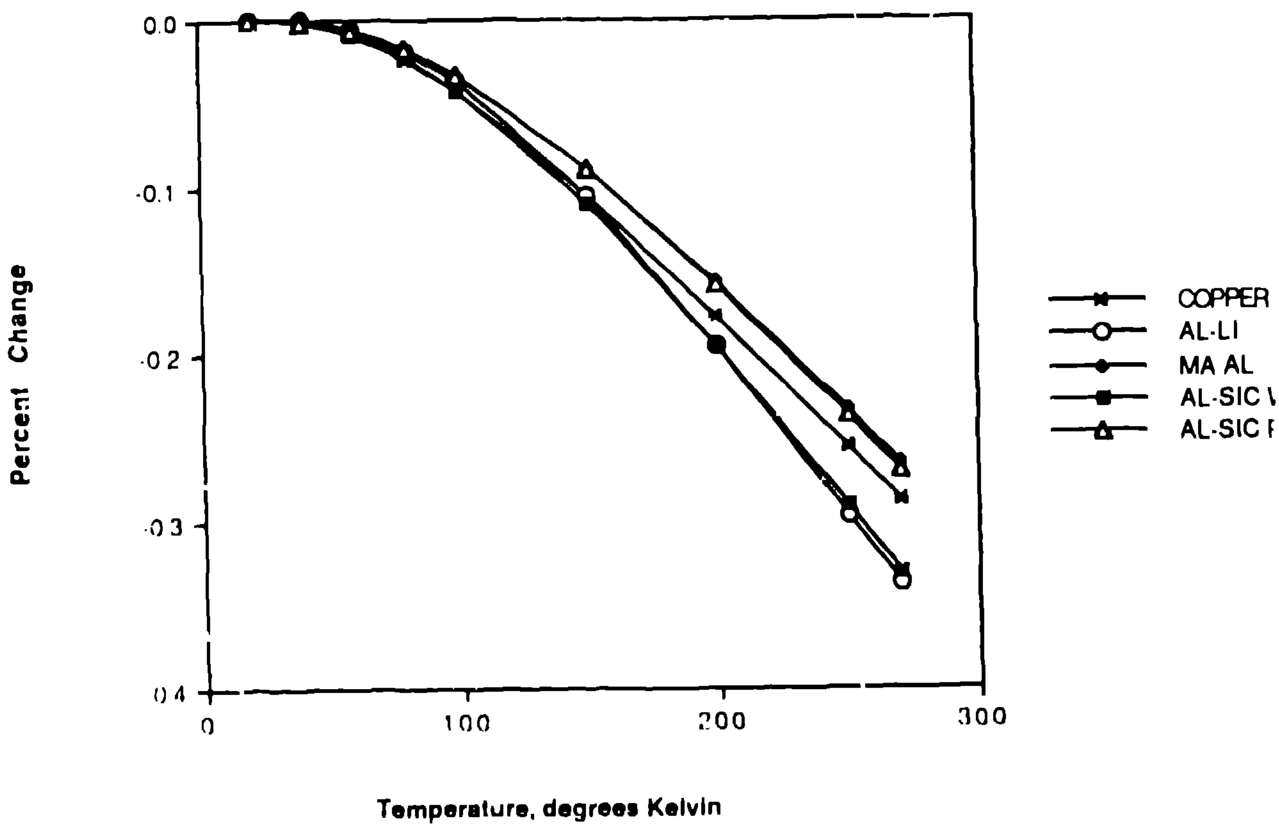
Electrical Resistivity as a Function of Temperature



Thermal Conductivity as a Function of Temperature



Resonant Frequency as a Function of Temperature



Unloaded "Q" as a Function of Temperature