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2002 J. Phys.: Condens. Matter 14 11291

(http://iopscience.iop.org/0953-8984/14/44/469)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **14** (2002) 11291–11296 PII: S0953-8984(02)39356-1

Material properties of Ni–Cr–Al alloy and design of a 4 GPa class non-magnetic high-pressure cell

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Received 1 June 2002
Published 25 October 2002
Online at stacks.iop.org/JPhysCM/14/11291

Abstract
The Ni–Cr–Al Russian alloy was prepared. Its magnetic and mechanical properties were better than those of MP35N alloy. We fabricated the a piston–cylinder-type hybrid high-pressure cell using the Ni–Cr–Al alloy. It has been found that the maximum working pressure can be repeatedly raised to 3.5 GPa at $T = 2$ K without any difficulties.

1. Introduction

Undoubtedly, the study of physical properties at high pressure, high magnetic field and low temperature is one of the important problems in achieving an understanding of highly correlated electron systems, in which attractive pressure-induced phenomena such as superconductivity and magnetically ordered non-Fermi liquids have been observed. Until now, many scientists have designed non-magnetic piston–cylinder-type high-pressure cells made of non-magnetic Cu–Be alloy [1]. Unfortunately, the pressure limit is only 20 kbar due to the limited tensile strength of Cu–Be alloy. Recently, however, new high-pressure cells made of Ni–Cr–Al alloy (Russian alloy) and Co–Ni–Cr–Mo alloy (MP35N) have been tested successfully up to pressures of 31.5 and 35 kbar, respectively. These strong non-magnetic materials, Ni–Cr–Al and MP35N, were introduced by Eremets *et al* [2] and Walker [3]. For the field of the solid-state physics at low temperature, the mechanical and magnetic properties of Ni–Cr–Al alloy seem to be better suited than those of MP35N alloy. But, the main disadvantage of this alloy is that it is unavailable outside the Russian Federation. We attempted to produce this alloy and the attempt went well. In the present paper, the details of the material properties of the Ni–Cr–Al alloy (Russian alloy) and the design of the cell are presented. For example, the electrical resistivity at low temperature of $YbInCu_4$ has been measured practically using the Ni–Cr–Al pressure cell.

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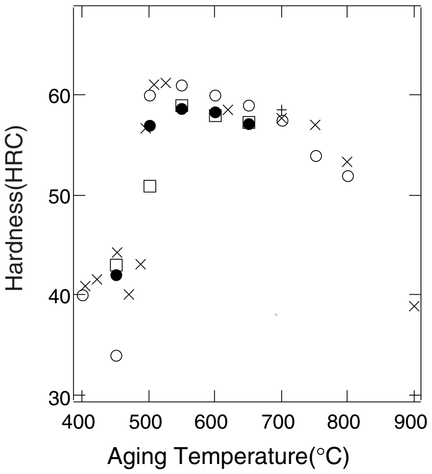

Figure 1. The ageing temperature dependence of the hardness. The ageing time varied between 90 and 120 min. Data were measured at various institutes. Different symbols indicate different institutes.

2. Experimental details

The alloy was melted from weighed amounts of Ni (99.9%), Cr (99%) and Al (99.999%) by an induction furnace and cast under an Ar atmosphere. The contents of the constituents were 56.5 wt% Ni, 40.0 wt% Cr and 3.5 wt% Al. We modified the Russian alloy a little by the addition of about 50 ppm B to improve the forging process. An ingot of about 7 kg was hot worked to rods with various sizes at 1200 °C. The reduction in area was estimated to be 90–95% from the change between the cross-sections before and after the hot working.

2.1. Hardness and mechanical properties

Ni–Cr–Al alloy rods were annealed at 1200 °C for one hour; this was followed by water quenching. After machining, samples with disc shape were were aged in the temperature range from 400 °C to 900 °C. The ageing temperature dependence of the hardness is shown in figure 1. The hardness of the alloys suddenly increases around 500 °C to the maximum hardness about 60 HRC, and then the hardness decreases with increasing ageing temperature. The results on hardness are almost the same as the previous ones [4]. For the optimum mechanical properties, which were obtained at the ageing condition of 700 °C for 2 h, the hardness became about 57 HRC.

A tensile test was carried out at room temperature for tensile samples with a gauge section of 3.5 mm diameter × 25 mm length after ageing. Figure 2 shows the stress–strain curves for samples aged at 700 and 750 °C. The alloy showed ultimate tensile strengths of over 2 GPa, which is almost the same as that of MP35N alloy [3], and a true strain of about 2%.

2.2. Magnetic properties

We have analysed the magnetic properties of samples of aged Ni–Cr–Al alloy, MP35N and Cu–Be alloy using a SQUID magnetometer (Quantum Design). Figure 3 shows the temperature dependence of the magnetic susceptibility of aged Ni–Cr–Al alloy, MP35N and Cu–Be alloy. The magnetic susceptibility of Ni–Cr–Al alloy is almost ten times lager than that of Cu–Be

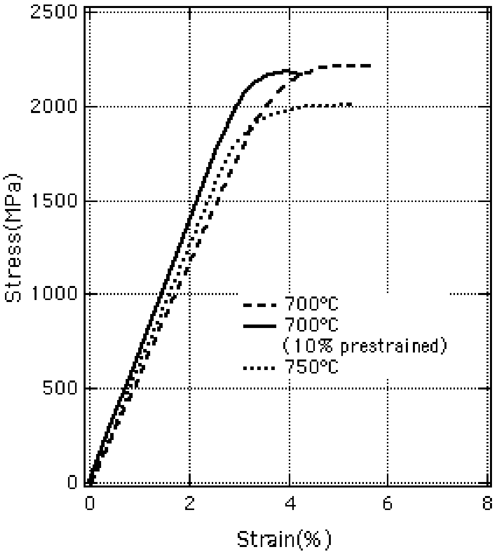

Figure 2. The stress–strain curves for samples aged at 700 and 750 °C.

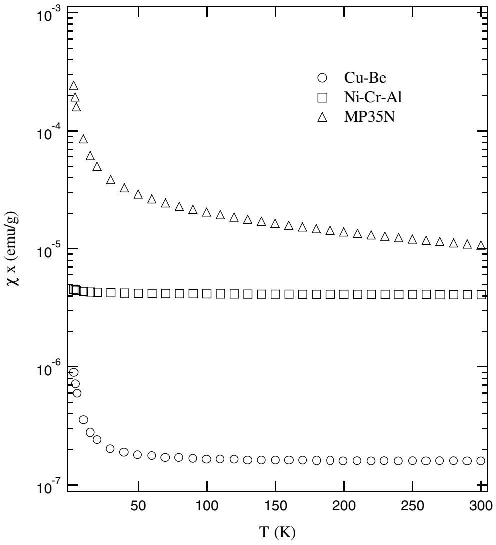

Figure 3. The temperature-dependent susceptibility of MP35N alloy, Ni–Cr–Al alloy and Cu–Be alloy.

alloy. While the susceptibility of Ni–Cr–Al shows no temperature dependence, that of MP35N has a strong temperature dependence. Ni–Cr–Al seems to be a better material for high-pressure cell use at high magnetic field and low temperature. These materials are not ferromagnetic, at least down to 2 K.

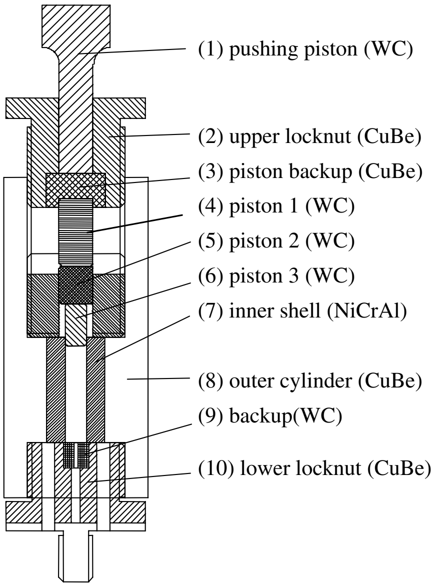

Figure 4. A cross-sectional view of the hybrid high-pressure cell.

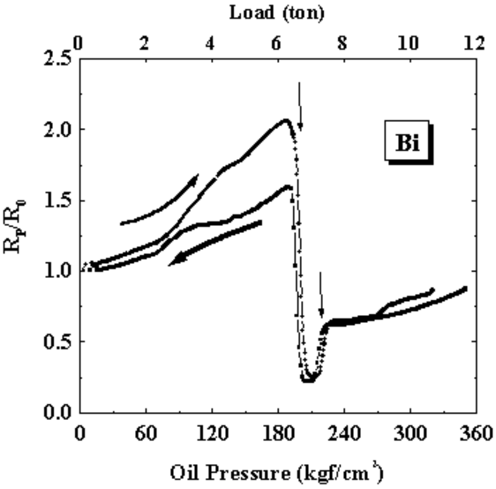

Figure 5. The applied-force-dependent resistivity of Bi at room temperature.

2.3. Design of the high-pressure cell

We have designed a conventional piston–cylinder cell, which consists of non-magnetic WC and the Ni–Cr–Al inner cylinder inserted into a Cu–Be outer sleeve. A schematic diagram of the hydrostatic cell is shown in figure 4. The dimensions of cylinder are 25, 28 and 5 mm, in length, outer diameter and inner diameter. The basic idea of the cell is similar to that of former hybrid cells [2, 3].

The high-pressure sample space was sealed by the Teflon cell technique [5]. As a pressure-transmitting fluid a mixture of Fluorinert FC70:FC77 1:1 is used. The pressures at room temperature and liquid helium temperature were determined from the values for the phase

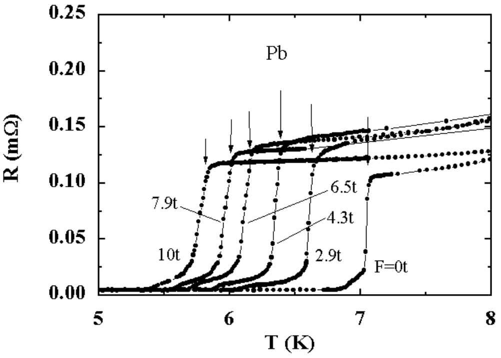

Figure 6. The temperature-dependent resistivity of Pb for several applied forces.

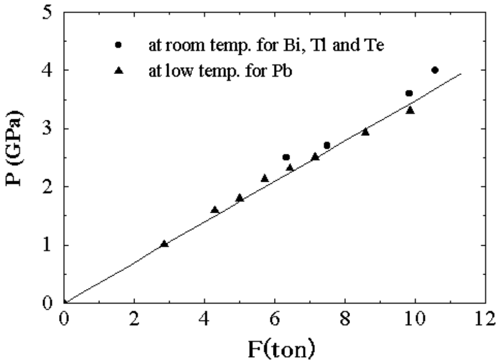

Figure 7. Pressure versus applied force.

transitions, $P_t(F)$, for Bi, Tl and Te and the superconducting transition temperature, $T_C(P)$, for Pb which have well known pressure dependences. The applied-force-dependent resistivity of Bi is shown in figure 5 at room temperature, and the temperature-dependent resistivity of Pb is shown in figure 6 for several applied forces. An estimate of the pressure can be derived from the transition curves, as seen in figures 5 and 6. From the data measured in this study, at room and low temperatures, pressure is shown as a function of applied force in figure 7. There is a linear variation at room and low temperature up to 4 GPa. As a final result, it has been found that a maximum working pressure of 3.5 GPa could be reached repeatedly at $T = 2$ K without any problems arising.

3. Resistivity measurements of $YbInCu_4$

As an example of the application, the electrical resistivity of single-crystalline $YbInCu_4$ has been measured as a function of temperature under hydrostatic pressure ($0 < P < 3.5$ GPa), as seen in figure 8 [5]. The valence phase transition temperature T_V decreases linearly at a rate of -2.0 K GPa^{-1} with increasing pressure up to 1.0 GPa. Many other groups have reported similar values for the pressure dependence of T_V. At above 1.0 GPa, however, T_V decreases more gradually and is depressed to temperature below 1.5 K at 2.5 GPa, as seen in figure 9.

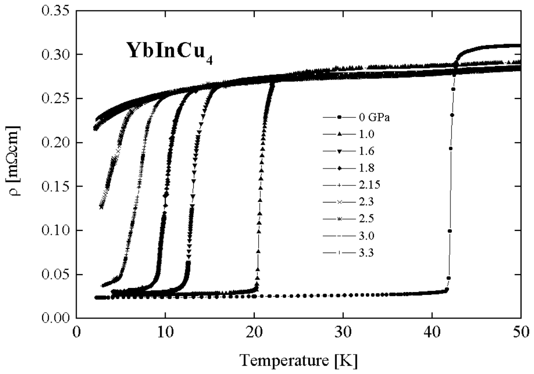

Figure 8. The temperature-dependent resistivity at various pressure for YbInCu$_4$ single crystal.

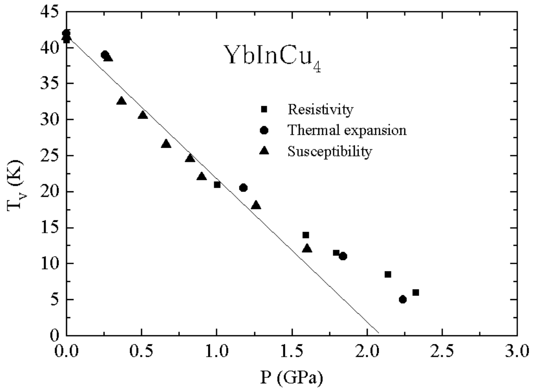

Figure 9. The transition temperature of YbInCu$_4$ versus pressure.

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