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Anisotropic Magnetic and Superconducting Properties of $DyNi_2B_2C$ Aligned Powder†

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Magnetic susceptibility on basal-plane aligned $DyNi_2B_2C$ powder reveals a strong anisotropic magnetic and superconducting properties for this magnetic superconductor. The intrinsic room temperature normal-state magnetic anisotropy supplies the preferred tetragonal basal-plane alignment. The observed antiferromagnetic Néel temperature $T_N(Dy)$ of 12.9 K is higher than 10-10.8 K observed for the bulk sample. Since the normal state magnetic susceptibility is very small for both applied field directions near superconducting T_c onset of 4.2 K, the observed superconducting anisotropy can be attributed to the anisotropic supercurrent distribution due to the anisotropic geometric shape of aligned microcrystalline powder.

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Recently, relatively high superconducting transition temperatures T_c up to 23 K have been reported for the quaternary borocarbides RT_2B_2C (R = Sc, Y, Th, U, or a rare earth; T = Ni, Pd or Pt) [1-5]. For Ni-based system containing non-magnetic rare earth elements R = Sc, Y, Lu, La or Th, T_c has a simple relationship with the Ni-Ni in-plane distance which is closely related to the Fermi-level density of states $N(E_F)$ [2]. For magnetic rare earth compounds, lower superconducting transitions were reported for R = Dy, Ho, Er or Tm due to the magnetic pair-breaking effect [1,4,5]. Among them, the $DyNi_2B_2C$ compound shows a bulk T_c of 3.8 K with high onset of 5.2 K below the antiferromagnetic Néel temperature T_N around 10-11 K and no reentrant behavior was observed down to 0.3 K indicating a perfect coexistence between superconductivity and antiferromagnetism below T_c [4]. As part of the effort to study this interesting magnetic superconductor with $T_N > T_c$, we report here the results of anisotropic magnetic and superconducting properties of $DyNi_2B_2C$ by magnetically aligning fine powder sample.

The $DyNi_2B_2C$ bulk samples were prepared from high-purity elements (Dy: 99.9%: Ni foil: 99.99%, B: 99.9995% and C: 99.995%) with stoichiometric starting composition (1:2:2:1) under an argon atmosphere in a Zr-gettered arc furnace. The starting ingredients were wrapped in the Ni foil and slowly arc-melted several times in order to ensure negligible weight loss and sample homogeneity. Except for small amounts of Ni_2B impurities, the

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x-ray diffraction pattern of the $DyNi_2B_2C$ sample can be well indexed with the body-centered-tetragonal $LuNi_2B_2C$-type structure with the lattice parameters $a = 3.532(3)$ Å, c = 10.488(5) Å and an unit cell volume $V = 130.8(1)$ Å^3 [4]. For powder alignment, bulk samples were first ground to fine powders with an average microcrystalline grain size of 1-10 μm then mixed with SPAR 5-minute epoxy/hardener in an 8-mm quartz holder wjth a typical powder-epoxy weight ratio of 1:7, and finally aligned in a 9.4 tesla high magnetic field under flowing inert nitrogen gas at room temperature. The block diagram of the alignment setup is shown in Fig. 1.

Because of the intrinsic room temperature normal-state magnetic anisotropy with preferred easy tetragonal basal-plane alignment, the 'x-ray diffraction pattern of aligned powder in epoxy as shown in Fig. 2 indicates a prevailing tetragonal (hk0) lines. The degree of tetragonal basal plane alignment is close to 90% under the present 9.4 tesla alignment field at room temperature, as verified by the very low (hkl) line intensity and the intensity ratio of the strongest (200) line to the normally strongest (112) line in randomly-oriented powder diffraction pattern [4]. Small amounts of Ni_2B impurities were also observed in the pattern.

This intrinsic normal-state magnetic anisotropy can be readily verified through the magnetic susceptibility measurement on aligned powder. The magnetic susceptibility data were taken using a p-metal shielded Quantum Design $MPMS_2$ superconducting quantum interference device (SQUID) magnetometer from 2 K to 300 K. Using a 5 kG field applied parallel and perpendicular to the aligned basal plane, the temperature dependence of magnetic susceptibility M/H of $DyNi_2B_2C$ aligned powder is shown in Fig. 3, with inset presenting the inverse magnetic susceptibility H/M. The magnetic anisotropy between two applied field directions is observed for all temperatures. The inverse magnetic susceptibilities clearly show lower H/M values for field applied parallel to the basal-plane indicating that the easy magnetization direction is indeed along the basal plane at room temperature alignment procedure.

The antiferromagnetic Néel temperature T_N of 12.9 K observed for aligned powder sample is somewhat higher than IO-IO.8 K reported for bulk sample [4]. Since the antiferromagnetic ordering is associated with the long range Dy^{3+} magnetic ordering through the RKKY indirect exchange interaction, the magnetic anisotropy below T_N indicates that the ordered Dy^{3+} moments are aligned antiferromagnetically along the basal plane. This magnetic structure is verifed by the recent low temperature neutron diffraction measurement where the moments are aligned ferromagnetically in each Dy-C layer perpendicular to the c-axis with the magnetic moments of two consecutive layers aligned in opposite directions [6].

The applied field of 5 kG in Fig. 3 is specifically chosen to suppress the superconductivity at low temperature with upper critical field $H_{c2}(0)$ of 3 kG [4]. To study the anisotropic superconducting properties, a 10 G low field magnetic susceptibility measurement is performed with the zero-field-cooled (ZFC) mode on $DyNi_2B_2C$ aligned powder. As shown in Fig. 4, the data for both applied field directions show a T_N of 12.9 K and a superconducting T_c onset around 4.2 K with diamagnetic signal onset of 3.4 K for the perpendicular direction and 3.1 K for the parallel direction. Since the normal state magnetic susceptibility is very small near T_c for both directions, the superconducting anisotropy can be attributed mainly to the anisotropic supercurrent distribution which is related to the

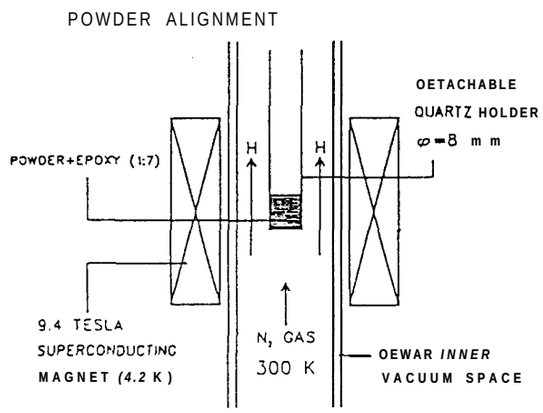

FIG. 1. Block diagram of $DyNi_2B_2C$ powder alignment setup

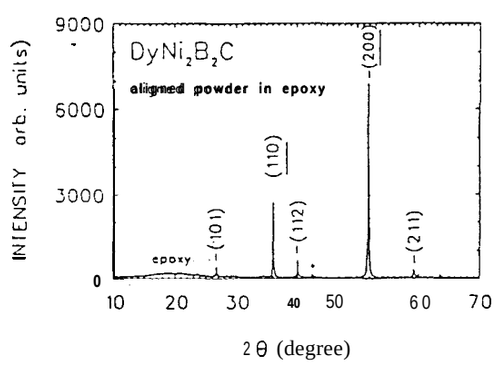

FIG. 2. X-ray diffraction pattern for the almost-basal-plane-aligned $DyNi_2B_2C$ powder in epoxy. The Ni_2B impurity line is indicated by asterisk.

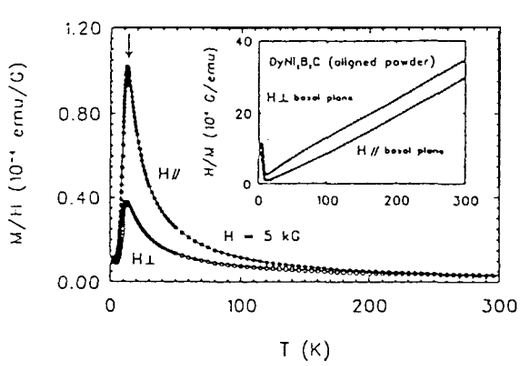

FIG. 3. Temperature dependence of magnetic susceptibility M/H of $DyNi_2B_2C$ aligned powder with 5 kG field applied parallel and perpendicular to the tetragonal basal plane. Inset shows the inverse magnetic susceptibility H/M.

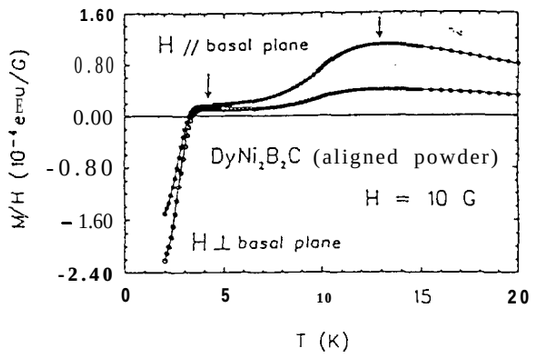

FIG. 4. Low field (10 G), zero-field-cooled (ZFC) magnetic susceptibility of $DyNi_2B_2C$ aligned powder for both applied field directions.

anisotropic geometric shape of the aligned microcrystalline powder.

In conclusion, magnetic susceptibility on basal-plane aligned $DyNi_2B_2C$ powder reveals a strong anisotropic magnetic and superconducting properties for this magnetic superconductor. The intrinsic room temperature normal-state magnetic anisotropy supplies the preferred tetragonal basal-plane alignment. The observed antiferromagnetic Néel temperature $T_N(Dy)$ of 12.9 K is higher than 10-10.8 K observed for the bulk sample. Since the normal state magnetic susceptibility is very small for both applied field directions near superconducting T_c onset of 4.2 K, the observed superconducting anisotropy can be attributed to the anisotropic supercurrent distribution due to the anisotropic geometric shape of aligned microcrystalline powder.

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