Similarity between the effects of pressure and electron concentration on the magnetic behaviour of a $Cr_{99.7}Ru_{0.3}$ alloy

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LETTER TO THE EDITOR

Similarity between the effects of pressure and electron concentration on the magnetic behaviour of a $Cr_{99.7}Ru_{0.3}$ alloy

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Abstract. Measurements are reported of the magnetic phase transition temperatures of a $Cr_{99.7}Ru_{0.3}$ alloy doped with V to decrease the electron concentration, and with Mn to increase it. A similarity is found between the pressure–temperature and electron concentration–temperature magnetic phase diagrams of this system by using a scaling factor of 4.4 GPa per 1% change in the electron concentration per atom.

Empirical correspondence is found for some dilute Cr alloys between the effects of the application of pressure, and the effects of changing the electron concentration per atom, e_A, on the magnetic phase diagram [1]. In alloys like Cr–V and Cr–Ta the effect of applied pressure on the Néel point, T_N, is equivalent to reducing the electron concentration [2]. In fact, reasonably good correspondence can be obtained [2] between the dependence of T_N of these alloys on pressure, p, and its dependence on e_A, by using a scaling factor of 2.8 GPa per 1% change in e_A on alloying. These two alloy systems exhibit an incommensurate spin density wave (ISDW) antiferromagnetic state at all temperatures $T < T_N$. Some other Cr alloy systems, like Cr–Ge, Cr–Ru, Cr–Ir and Cr–Mn, have more complex magnetic phase diagrams [1]. For them the composition–temperature, $(x–T)$, magnetic phase diagram contains three magnetic phases, the ISDW phase, the commensurate (C) SDW phase and the paramagnetic phase. There exists a triple point on the $(x–T)$ phase diagram where these three phases coexist. The pressure–temperature, $(p–T)$, magnetic phase diagrams of the above alloys also contain a similar triple point [1]. For Cr–Mn alloys there is a striking similarity between the $(x–T)$ and $(p–T)$ magnetic phase diagrams [1]. Applied pressure drives this system towards the triple point on the $(p–T)$ phase diagram in the same direction as is done by a decrease in x on the $(x–T)$ diagram. The similarity goes further. The slopes of all three, the CSDW–paramagnetic, ISDW–paramagnetic and ISDW–CSDW, phase lines in the $(x–T)$ plane have opposite signs to that of the slopes of the corresponding phase lines in the $(p–T)$ plane. In this sense there is thus also a similarity between increasing p and decreasing x. There is furthermore reasonable agreement between the absolute values of the slopes of corresponding phase lines in both phase planes for Cr–Mn. For some other Cr alloy systems with a triple point on their magnetic phase diagrams, the similarity between the $(x–T)$ and $(p–T)$ phase diagrams is not complete. It holds only for some, but not for all, of the phase lines [1].

The antiferromagnetism of Cr and its alloys, and therefore also the magnetic phase transition temperatures, is closely related to nesting of the electron and hole sheets of the

Fermi surface [3]. One expects [2] that the Fermi surface will respond quite differently to applied hydrostatic pressure than to changes in electron concentration, e_A, caused by changes in the dopant concentration, x. In a hypothetical compensated metal, applied hydrostatic pressure will change both Fermi surface sheets by the same amount, thereby leaving the nesting vector unchanged [2]. On the other hand, an increase in e_A enlarges the electron Fermi surface sheet and simultaneously shrinks the hole sheet, thereby changing the nesting vector. Quite different effects are therefore expected on the magnetic phase diagram for changes in p and changes in e_A. The similarity observed between (p–T) and (x–T) magnetic phase diagrams of some dilute Cr alloys is presently not understood theoretically [1] and there is renewed interest in this similarity.

The complete (p–T) magnetic phase diagram for a Cr–Ru alloy was determined for the first time only recently [4]. In previous studies [5] on Cr–Ru the ISDW–CSDW phase line could not be determined. The latest work [4] was done on a $Cr_{99.7}Ru_{0.3}$ alloy and shows that all the phase lines are straight lines near the triple point in the (p–T) phase plane. It should be of interest to search for a similarity between the (p–T) and (e_A–T) magnetic phase diagrams of a Cr–Ru alloy of this concentration. In this letter we report such a study. The approach that is followed is somewhat different from that previously used in other Cr alloys to analyse the similarity. In previous studies [1, 2] the starting point was Cr ($e_A = 6$) which is in the ISDW phase at all $T < T_N$. It was then alloyed into binary alloys to either increase e_A or to decrease it. In the present study the starting point is a $Cr_{99.7}Ru_{0.3}$ alloy that exhibits both ISDW and CSDW phases at $T < T_N$. e_A for this alloy is then increased by alloying with Mn ($e_A = 7$) or decreased by alloying with V ($e_A = 5$). Ternary Cr–Mn–Ru and Cr–V–Ru alloys were therefore used for this study. The results should give further information on how general the similarity in Cr alloy systems is and should lead to a better understanding of this phenomenon.

It was decided to prepare Cr–Mn–Ru and Cr–V–Ru alloy series in which e_A of the base alloy, $Cr_{99.7}Ru_{0.3}$, is changed on alloying with Mn or V by changing e_A of the main component (Cr) only, instead of using series in which it is changed for both components of the base alloy. Two alloy series, $(Cr_{1-x}Mn_x)_{99.7}Ru_{0.3}$ and $(Cr_{1-y}V_y)_{99.7}Ru_{0.3}$ with nominal ranges of x and y each up to about 0.008, were therefore prepared by arc melting in a purified argon atmosphere as previously described [6]. The starting materials were 99.99% pure Cr, 99.99% Mn, 99.9% V and 99.9% Ru. The alloys were homogenized for three days at 1000 °C and then quenched into water. Electron microprobe analyses were used to determine the actual concentrations of the alloys. They were found to be homogeneous to within 5% of the determined concentration. The actual Ru concentrations of both series were found to be close to 0.3 at.%, to within about 8% or better of this concentration. Samples with flat parallel surfaces of about 6 mm in length were spark cut from the ingots for ultrasonic wave velocity measurements. T_N as well as the ISDW–CSDW transition temperature, T_{IC}, were determined from measurements of the temperature dependence of the longitudinal ultrasonic wave velocity, v_L, in the alloys. It is known [4, 7] that well defined anomalies appear at both these temperatures on v_L–T curves of Cr–Ru alloys. Ultrasonic (10 MHz) wave velocities were determined using a standard phase comparison method [8] in the temperature range 77 K to 500 K. The sensitivity of the equipment is about one part in 10^3. No hysteresis effects were observed during heating and cooling experiments through T_N of the alloys. Hysteresis effects were however observed at T_{IC} of the Cr–Mn–Ru series as is known [4] to be present on v_L–T and v_L–p curves of $Cr_{99.7}Ru_{0.3}$. The results reported here were taken during heating runs only and are then compared with the corresponding (p–T) phase diagram [4] obtained during increasing pressure runs. Figure 1 shows typical examples of the measured v_L–T curves, one for each of the Cr–V–Ru and

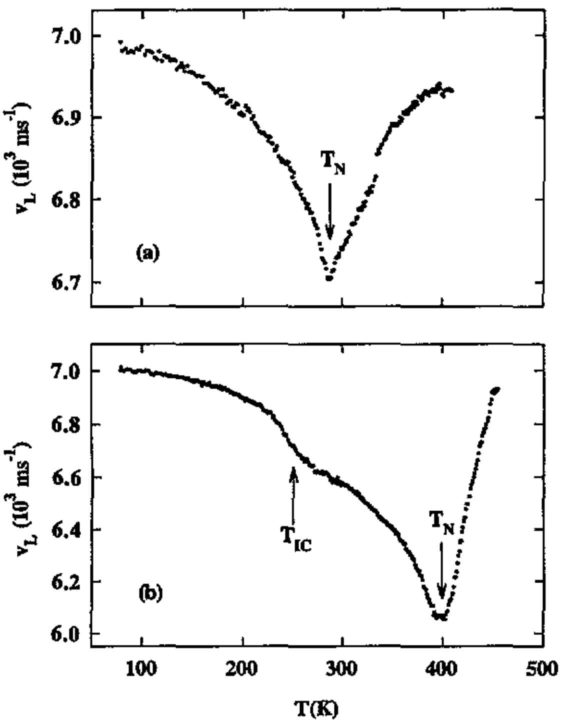

Figure 1. Longitudinal ultrasonic wave velocity, v_L, as a function of temperature for (a) $(Cr_{0.9959}V_{0.0041})_{99.7}Ru_{0.3}$ and (b) $(Cr_{0.9976}Mn_{0.0024})_{99.7}Ru_{0.3}$. The Néel temperature, T_N, and the ISDW–CSDW magnetic phase transition temperature, T_{IC}, are shown.

Cr–Mn–Ru series. Two anomalies were observed on the v_L–T curve of all the Cr–Mn–Ru alloys studied. One anomaly, at T_N, is in the form of a deep minimum and the other, at T_{IC} ($< T_N$), in the form of a steplike decrease in v_L on heating. T_N was defined at the temperature of the minimum and T_{IC} at the temperature of the inflection point of the step. In the case of the Cr–V–Ru series only one anomaly, that at T_N, was observed for all the alloys studied in this series. The measurements at the lowest V concentration suggest that the ISDW–CSDW phase transition is absent in this series and that they are all in the ISDW phase below T_N. T_N for this series was also defined at the temperature of the deep minimum on the v_L–T curve. The magnetic phase diagram in the (e_A–T) plane is shown in figure 2. e_A is decreased from the value $e_A = 6.006$ for $Cr_{99.7}Ru_{0.3}$ by the addition of V ($e_A = 5$) in the Cr–V–Ru series and it is increased from this value by adding Mn ($e_A = 7$) in the Cr–Mn–Ru series. The corresponding Mn and V concentration scales are also shown in figure 2. The triple point concentration in figure 2 is taken at $T = 317$ K and $e_A = 6.00471$.

The solid lines for the ISDW–paramagnetic, CSDW–paramagnetic and ISDW–CSDW phase lines in figure 2 were obtained from the (p–T) magnetic phase diagram of a $Cr_{99.7}Ru_{0.3}$ alloy of [4], by using a scaling factor of 4.4 GPa per 1% change in e_A. This choice of scaling factor gives the most reasonable fit to the experimental points for the CSDW–paramagnetic transition line when the zero of pressure is chosen at the triple point.

The following observations are made from figure 2.

(1) Increasing pressure is equivalent to decreasing electron concentration.

(2) The slopes of the phase transition lines in the (e_A–T) plane are all of opposite signs to that of the equivalent lines in the (p–T) plane.

(3) A choice of a scaling factor of 4.4 GPa per 1% change in e_A gives fairly good

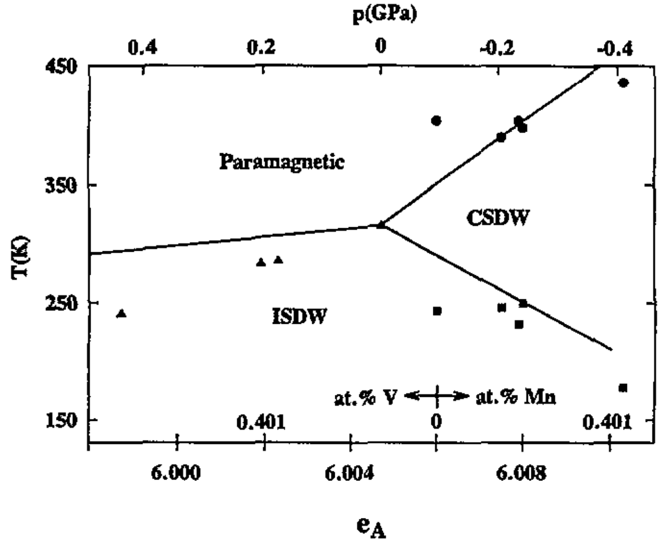

Figure 2. Dependence of the magnetic phase transition temperatures on electron concentration, e_A, and pressure, p. Points ▲ are for ISDW–paramagnetic transitions, ● for CSDW–paramagnetic transitions and ■ for ISDW–CSDW transitions. The estimated experimental errors in the Néel points and ISDW–CSDW transition temperatures are respectively 4 K and 6 K. The V or Mn concentrations, given conveniently here in at.% of the specific ternary Cr–V–Ru or Cr–Mn–Ru alloy, all with constant Ru content (0.3 at.% Ru), that correspond with each e_A value along the abscissa, are also shown. The solid lines were obtained from the $(p–T)$ phase diagram of [4] by using a scaling factor of 4.4 GPa per 1% change in e_A.

correspondence between the CSDW–paramagnetic and ISDW–CSDW phase transition lines in the $(p–T)$ plane and the corresponding lines in the $(e_A–T)$ plane. The absolute values of the slopes of these two lines are furthermore nearly the same in both phase planes. The absolute value of the slope of the ISDW–paramagnetic phase line is however about 3.5 times smaller in the scaled $(p–T)$ plane than that in the $(e_A–T)$ plane. The slopes of this phase line in these two planes are nevertheless of opposite sign, as should be the case for good correspondence between the $(e_A–T)$ and $(p–T)$ phase diagrams.

In conclusion, reasonably good correspondence between the $(e_A–T)$ and $(p–T)$ magnetic phase diagrams of $Cr_{99.7}Ru_{0.3}$ is found. The magnetic transition temperatures are not only influenced by changes in e_A but also by effects of impurity scattering [1] and changes in the intra-atomic Coulomb potential at the impurity site [1] on alloying with V or Mn. Both of these effects tend to lower T_N. Figure 2 suggests that these effects play a lesser role in the observed similarity between the $(e_A–T)$ and $(p–T)$ phase diagrams. The major role seems to be played by changes in e_A and therefore in changes in the nesting of the electron and hole Fermi surface sheets. This also seems to play the major role in the $(x–T)$ magnetic phase diagrams of Cr–V and Cr–Mn alloys [9].

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