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1994 J. Phys.: Condens. Matter 6 10795

(http://iopscience.iop.org/0953-8984/6/49/020)

J. Phys.: Condens. Matter 6 (1994) 10795–10804. Printed in the UK

The magnetic transition due to plastic deformation in $Ni_{75+x}Al_{25-x}$ and $Ni_{77-x}Al_{23}Pd_x$ compounds

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Received 1 August 1994

Abstract. The influence of plastic deformation on magnetic properties has been studied in $Ni_{75+x}Al_{25-x}$ ($0 \leqslant x \leqslant 2$) and $Ni_{77-x}Al_{23}Pd_x$ ($0 \leqslant x \leqslant 3$) intermetallic compounds. The temperature dependence of the spontaneous magnetization, $M_s(T)$, has been analysed according to the self-consistent renormalization (SCR) theory of spin fluctuation. The qualitative agreement between the experimental result and the theoretical one is satisfactory in the plastically deformed samples. The value of $M_s(0)$ decreases slightly on compression; the reduction of $M_s(0)$ attains to 10% in the samples of 20% strain. However, the Curie temperature is constant within experimental error. The SCR theory indicates that plastic deformation gives an influence especially to the derivative of the density of states at the Fermi level. The dislocation distribution is observed under the electron microscope and its density, ρ, is obtained for several samples. The relationship between $M_s(0)$ and ρ suggests that the non-magnetic region spreads around the APB and CSF ribbons at least as far as 100 atomic distances, which are introduced between superpartial dislocations by plastic deformation.

1. Introduction

A great deal of experimental and theoretical effort has been devoted to the study of weakly magnetic materials, since they exhibit unusual electric and magnetic properties. Spin fluctuation has been introduced, as quite an important concept to understand the magnetism of transition metals and their alloys, by Moriya and Kawabata (1973). The magnetism of Ni_3Al intermetallic compounds has been explained by the self-consistent renormalization (SCR) theory of spin fluctuation, which takes account of coupling between different modes of spin fluctuations in a self-consistent way (Umemura and Masuda 1983, Sasakura *et al* 1984). Another interest is the magnetic transition due to plastic deformation. The strong influence of cold working on magnetic properties was found in the Ni_3Al compound: disordering by intense cold working causes the ferromagnetic properties to disappear (De Boer *et al* 1969). The cold-working effect was explained by one of the present authors and his co-worker in terms of the dislocation theory with consideration of the ferromagnetic and paramagnetic interactions of Ni atoms (Takahashi and Ikeda 1983): the spontaneous mangetization at 0 K, $M_s(0)$, decreases in proportion to the dislocation density, ρ, in the early stage of plastic deformation and to its square root in the advanced stage. Our interest is to examine experimentally the validity of the relationship between $M_s(0)$ and ρ.

The Ni_3Al intermetallic compound is brittle and inconvenient for homogeneous deformation. The poor ductility of Ni_3Al has been improved by doping with other elements B, Pd, Zr, ... (Aoki 1990, Chiba *et al* 1991). In the present study, the $Ni_{77-x}Al_{23}Pd_x$ system as well as the $Ni_{75+x}Al_{25-x}$ system is used to investigate the magnetic transition due to plastic deformation.

The magnetism of the $Ni_{77-x}Al_{23}Pd_x$ and $Ni_{75+x}Al_{25-x}$ systems has been investigated by the present authors recently: the temperature dependence of $M_s(T)$ has been successfully analysed according to the SCR theory of spin fluctuations (Takahashi *et al* 1994). Pd atoms in this system occupy the Ni site and the Ni atoms expelled by Pd atoms reside substitutively on the Al site. The magnetic behaviour of these Ni atoms is the same as the excess Ni atoms in the off-stoichiometric samples.

In order to study the influence of plastic deformation on the magnetic properties, the previous investigators used powder specimens, which were disordered by crushing or grinding (De Boer *et al* 1969), but it would be impossible to obtain accurate information about atomic arrangement. In the present study, the samples were compressed to 20% strain at most, they are then suitable to observe the dislocation distribution under the electron microscope.

The application of the Stoner model to the Ni_3Al compound was questioned by Robbins and Claus (1971) because of the disappearance of ferromagnetism on plastic deformation. They suggested that the deformation effect should be accounted for in terms of the local atomic environment. The same may be said of the SCR theory of spin fluctuation. It is also our interest to investigate the validity of the SCR theory of spin fluctuations in the plastically deformed samples: the temperature dependence of $M_s(T)$ in the plastically deformed samples has been analysed according to the SCR theory.

2. Experimental procedure

Intermetallic compounds with the nominal composition $Ni_{77.0-x}Al_{23.0}Pd_x$ ($x = 0.4, 0.8, 1.8, 2.2$ and 3.0) and $Ni_{75.0+x}Al_{25.0-x}$ ($x = 0.0, 1.5$ and 2.0) were prepared by means of arc melting. The preparation procedure of the samples has already been described in detail in the previous work (Takahashi *et al* 1994).

The quasisingle-crystal samples with dimensions of approximately $2.5 \times 2.5 \times 5.0$ mm^3 were compressed at room temperature. They were formed for the magnetization measurement to be $2.5 \times 2.5 \times 2.5$ mm^3. Magnetization was measured by SQUID magnetic-flux meter (Quantum Design) at temperatures from 4.5 K to 100 K. Thin foils for electron microscopy investigation were prepared using a standard jet electropolishing technique; some of these samples were thinned through electropolishing in a solution of 95% ethanol alcohol and 5% sulphuric acid at 273 K and 12 V. All foils were observed under a 200 kV transmission electron microscope.

3. Experimental results

3.1. Magnetic measurements

The magnetization curves of $Ni_{75+x}Al_{25-x}$ and $Ni_{77-x}Al_{23}Pd_x$ compounds with plastic strains were measured in the temperature range of 4.5–110 K. Figure 1 shows the typical results for the magnetization in the form of an Arrot plot for the sample before plastic deformation (a), and after plastic deformation by 20% strain (b), in $Ni_{75.2}Al_{23}Pd_{1.8}$. The data for all the plastically deformed samples were represented well in the form of $M(H,T)^2 = M_s(T) + bH/M(H,T)$ at every temperature, except in the region of weak magnetic fields. The spontaneous magnetization at T K, $M_s(T)$, can be obtained by the extrapolation of the linear relation to $H = 0$. The Curie temperature T_C shows a slight decrease with plastic deformation. The spontaneous magnetization, $M_s(T)$, in the plastically

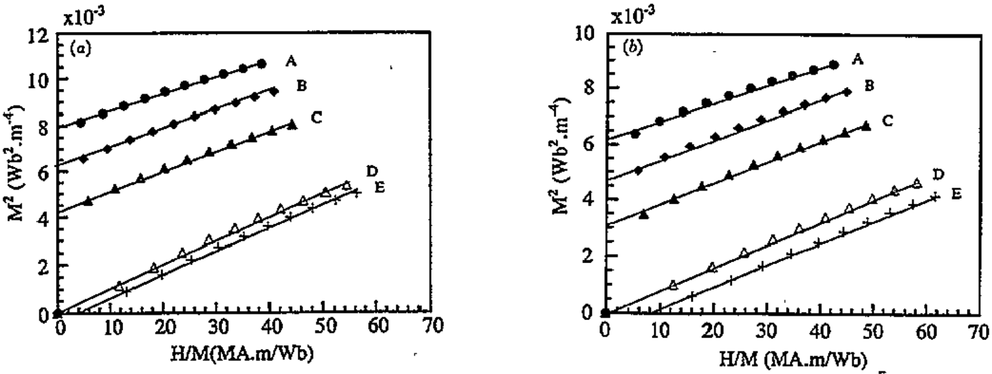

Figure 1. The Arrot plot of the magnetization of $Ni_{75.2}Al_{23}Pd_{1.8}$ (a) before plastic deformation, curve A, 40 K, curve B, 50 K, curve C, 60 K, curve D, 78 K, curve E, 80 K, and (b) after plastic deformation with $\epsilon = 20\%$ strain, curve A, 40 K, curve B, 50 K, curve C, 60 K, curve D, 76 K, curve E, 80 K.

deformed $Ni_{75+x}Al_{25-x}$ and $Ni_{77-x}Al_{23}Pd_x$ compounds is analysed from the viewpoint of the SCR theory of spin fluctuation. In the SCR theory the temperature dependence of $M_s(T)$ has the form of $M_s(T)^2 = M(0)^{2-}\eta T^2$ at low temperatures and $M_s(T)^2 = \zeta(T_C^{4/3} - T^{4/3})$ in a fairly wide temperature range below T_C. Figure 2 shows the temperature dependence of the square of the spontaneous magnetization $M_s(T)^2$ against T^2 in the $Ni_{75.0}Al_{25.0}$ sample without plastic deformation and with 10% and 17% strains (a), and in $Ni_{75.2}Al_{23}Pd_{1.8}$ with 0%, 10% and 20% strains (b). As can be seen from these figures, all the samples have the simple relationship that $M_s(T)^2$ is in proportion to T^2 at low temperatures. The spontaneous magnetization at $T = 0$ K, $M_s(0)$, is determined by the extrapolation of this linear relation of $M_s(T)^2$ against T^2 to $T = 0$. The values of $M_s(0)$ for $Ni_{75+x}Al_{25-x}$ and $Ni_{77-x}Al_{23}Pd_x$ compounds are given in tables 1 and 2, respectively. Figure 3(a) and (b) shows the temperature dependence of $M_s(T)^2$ on $T^{4/3}$ in the same samples as in figure 2(a) and (b), respectively. Figure 3 indicates that $M_s(T)^2$ has a $T^{4/3}$ dependence in a wide temperature range below T_C for each sample. The value of the Curie temperature is obtained by the extrapolation of the linear relation to $M_s(T) = 0$. The value of T_C is nearly the same as that obtained through the Arrot plot. The values of T_C in the $Ni_{75+x}Al_{25-x}$ and $Ni_{77-x}Al_{23}Pd_x$ systems are shown in tables 1 and 2, respectively.

The experimental results for all samples, $Ni_{77-x}Al_{23}Pd_x$ and $Ni_{75+x}Al_{25-x}$, including the plastically deformed ones, are expressed well in the form of

$$M_s(T)^2 = M_s(0)^2 - \eta T^2 \tag{1}$$

at low temperatures and

$$M_s(T)^2 = \zeta(T_C^{4/3} - T^{4/3}) \tag{2}$$

in a wide temperature range below T_C. The values of η and ζ in the $Ni_{75+x}Al_{25-x}$ and $Ni_{77-x}Al_{23}Pd_x$ systems are given in tables 1 and 2, respectively. The strain dependence of $M_s(0)$ in $Ni_{75+x}Al_{25-x}$ and $Ni_{77-x}Al_{23}Pd_x$ compounds is shown in figure 4(a) and (b), respectively, where the value of $M_s(0)$ is normalized by the value without plastic deformation in each sample. $M_s(0)$ decreases as the strain increases in both systems. $Ni_{75+x}Al_{25-x}$ compounds are very brittle because of the poor ductility. Samples crack

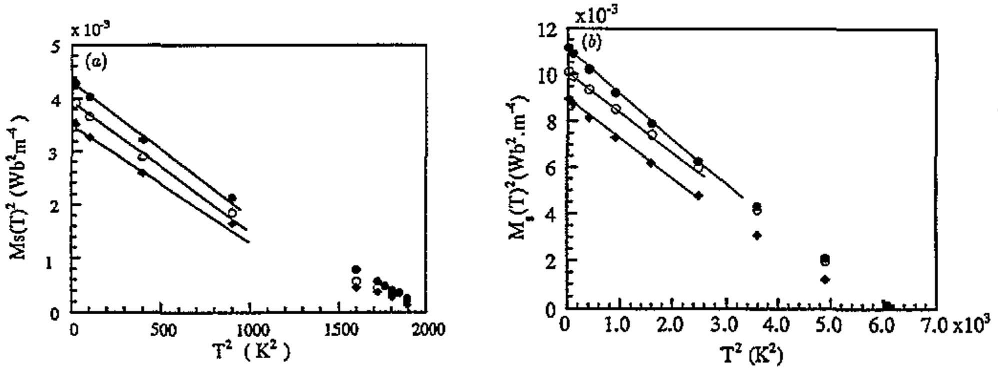

Figure 2. The temperature dependence of the spontaneous magnetization in $M_s(0)^2$ against T^2: (a) $Ni_{75}Al_{25}$, ϵ =0% (●), ϵ =10% (○) and ϵ = 17% (♦) and (b) $Ni_{75.2}Al_{23}Pd_{1.8}$, ϵ =0% (●), ϵ =10% (○) and ϵ =20% (♦).

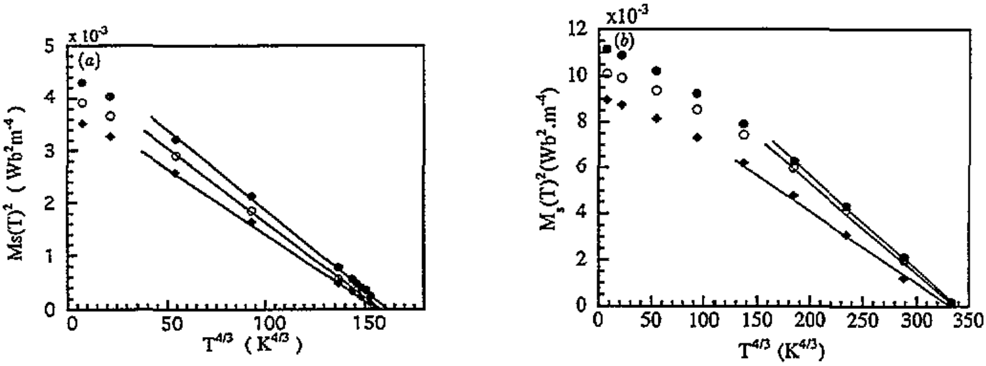

Figure 3. The temperature dependence of the spontaneous magnetization in $M_s(0)^2$ against $T^{4/3}$: (a) $Ni_{75}Al_{25}$, $\epsilon = 0$ (●), ϵ = 10% (○) and ϵ = 17% (♦) and (b) $Ni_{75.2}Al_{23}Pd_{1.8}$, ϵ = 0% (●), ϵ = 10% (○) and ϵ = 20% (♦).

so easily that it is difficult to give a homogeneous deformation. The scattering of $M_s(0)$ originates from the poor ductility of Ni_3Al compounds. On the other hand, $Ni_{77-x}Al_{23}Pd_x$ compounds have a good ductility and the scattering is very small in the strain dependence of $M_s(0)$. $M_s(0)$ decreases by (8 ± 2)% with 20% strain. On the other hand, T_C seems to decrease slightly with strain in both the $Ni_{75+x}Al_{25-x}$ and $Ni_{77-x}Al_{23}Pd_x$ systems. The small change of T_C would be due to experimental error. T_C is consequently independent of plastic deformation below 20% strain.

3.2. *The observation of superlattice dislocations*

The fully ordered $L1_2$-type structure was confirmed from electron diffraction patterns. The superlattice dislocation in Ni_3Al compound with the $L1_2$-type structure has been studied by several investigators (Baluc *et al* 1991). Figure 5(a) shows a weak-beam image of the dissociation of a [101] superlattice dislocation splitting into two $\frac{1}{2}$[101] superpartials coupled by a ribbon of APB in the $Ni_{77.0}Al_{23.0}$ compound with 10% strain. Almost all the superlattice dislocations are distributed in pairs as shown in the ternary compounds. The APB

Table 1. Experimental values of the spontaneous magnetization at $T = 0$ K, $M_s(0)$, the Curie temperature, T_C, the coefficient of the T^2 term in the M_s^2 against T^2 plot, η, and the coefficient of the $T^{4/3}$ term in M_s^2 against $T^{4/3}$, ζ, in the $Ni_{75+x}Al_{25-x}$ compounds with plastic deformation.

Ni_3Al samples	$M_s(0)$ ($\times 10^{-2}$) (Wb m^{-2})	T_C (K)	η ($\times 10^{-6}$) (Wb^2 m^{-4} K^{-2})	ζ ($\times 10^{-5}$) (Wb^2 m^{-4} K$^{-4/3}$)
$Ni_{75.0}Al_{25.0}$				
$\epsilon = 0\%$	6.58	43.5	2.09	2.73
$\epsilon = 10\%$	6.10	43.0	2.02	2.55
$\epsilon = 17\%$	5.95	42.6	1.75	2.31
$Ni_{76.5}Al_{23.5}$				
$\epsilon = 0\%$	9.89	82.0	2.17	2.69
$\epsilon = 10\%$	8.80	82.0	2.14	2.52
$\epsilon = 20\%$	8.01	81.5	2.05	2.29
$Ni_{77.0}Al_{23.0}$				
$\epsilon = 0\%$	12.0	86.0	1.42	4.28
$\epsilon = 10\%$	11.8	86.0	1.45	4.00
$\epsilon = 17\%$	11.1	86.0	1.40	3.57

Table 2. Experimental values of $M_s(0)$, the Curie temperature, T_C, the coefficient η and the coefficient ζ in the $Ni_{77-x}Al_{23}Pd_x$ compounds with plastic deformation.

Ni_3Al samples	$M_s(0)$ ($\times 10^{-2}$) (Wb m^{-2})	T_C (K)	η ($\times 10^{-6}$) (Wb^2 m^{-4} K^{-2})	ζ ($\times 10^{-5}$) (Wb^2 m^{-4} K$^{-4/3}$)
$Ni_{76.6}Al_{23.0}Pd_{0.4}$				
$\epsilon = 0\%$	11.3	82.0	1.74	4.06
$\epsilon = 10\%$	11.0	82.5	1.70	3.79
$\epsilon = 15\%$	10.5	82.8	1.67	3.55
$Ni_{76.2}Al_{23.0}Pd_{0.8}$				
$\epsilon = 0\%$	10.7	78.0	1.83	3.96
$\epsilon = 10\%$	10.1	78.0	1.70	3.51
$\epsilon = 20\%$	9.8	77.3	1.69	3.29
$Ni_{75.2}Al_{23.0}Pd_{1.8}$				
$\epsilon = 0\%$	10.9	78.0	2.15	4.04
$\epsilon = 10\%$	10.6	78.4	1.85	3.84
$\epsilon = 20\%$	9.8	77.3	1.83	3.41
$Ni_{74.8}Al_{23.0}Pd_{2.2}$				
$\epsilon = 0\%$	10.6	78.3	1.85	4.09
$\epsilon = 10\%$	10.3	78.9	1.80	3.60
$\epsilon = 20\%$	9.7	79.0	1.88	3.22
$Ni_{74.0}Al_{23.0}Pd_{3.0}$				
$\epsilon = 0\%$	9.8	71.0	2.33	3.39
$\epsilon = 20\%$	8.0	71.0	1.63	2.89

width is obtained as about 12 nm from the high-magnification photograph in figure 5(b). The individual $\frac{1}{2}[101]$ superpartial may be dissociated into two Schockley partials, but dissociation cannot be observed since the complex stacking fault energy is high.

Figure 6(a) and (b) is the electron micrographs of $Ni_{75.2}Al_{23.0}Pd_{1.8}$ specimens with strains of 10% and 20%, respectively. The Burgers vector and the glide plane of these dislocations are confirmed to be $(a/2)\langle 110\rangle$ and $\{111\}$, respectively. Almost all the dislocations make a pair in the other ternary compounds of $Ni_{77-x}Al_{23}Pd_x$.

The dislocation density, ρ, was measured by counting the intersection of dislocation lines with straight lines drawn randomly on photographic films. The dislocation density increases with increasing strain, from 10^9 to 10^{10} cm^{-2}. It contains about 30% experimental error

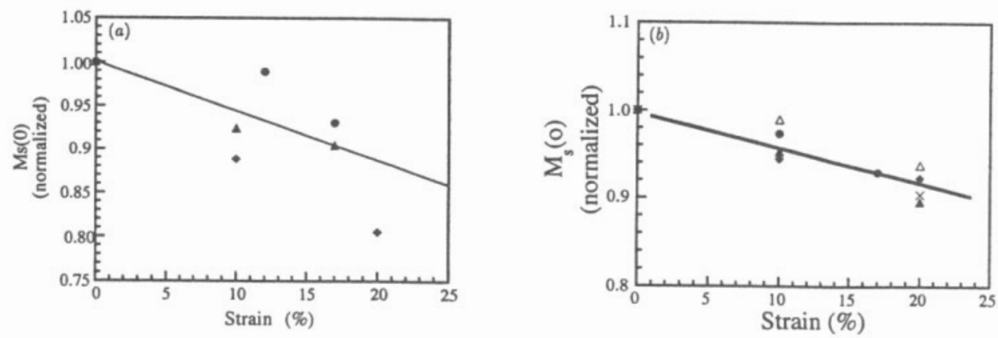

Figure 4. The strain dependence of the spontaneous magnetization at 0 K, $M_s(0)$: (a) $Ni_{75+x}Al_{25-x}$, $x = 0$ (●), $x = 1.5$ (♦), $x = 2.0$ (▲); (b) $Ni_{77-x}Al_{23}Pd_x$, $x = 0.4$ (●), $x = 0.8$ (♦), $x = 1.8$ (▲), $x = 2.2$ (△), $x = 3.0$ (×).

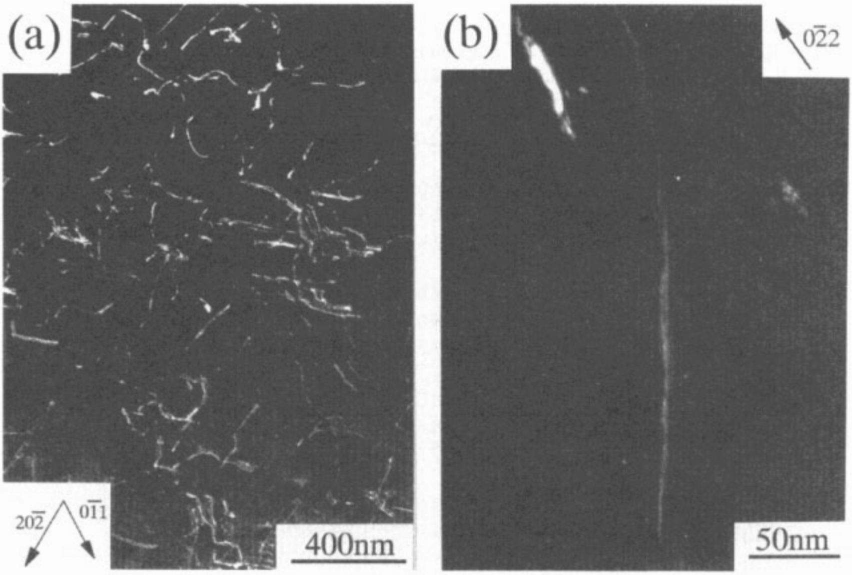

Figure 5. A weak-beam image of the dissociation of a superlattice dislocation (a) and a high-magnification photograph (b) for $Ni_{77}Al_{23}$ compounds compressed by $\epsilon = 10\%$. The beam direction in both observations is parallel to [111].

from the ambiguity of the thickness of specimen.

3.3. *Atomic configuration in the vicinity of APBs and CSFs*

Superlattice dislocations are an essential factor in the reduction of $M_s(0)$ in the $Ni_{75+x}Al_{25-x}$ and $Ni_{77-x}Al_{23}Pd_x$ systems. The important parameter of plastic deformation is the dislocation density. The dependence of $M_s(0)$ on ρ in $Ni_{75.2}Al_{23.0}Pd_{1.8}$, $Ni_{74.8}Al_{23.0}Pd_{2.2}$ and $Ni_{77.0}Al_{23.0}$ samples is shown in figure 7. The $Ni_{77.0}Al_{23.0}$ sample could be plastically deformed homogeneously compared to the other binary compounds. $M_s(0)$ is normalized by the undeformed value. The plastic strain, ϵ, has a simple relationship with ρ in general, and it is proper to consider that the other samples have the same relationship between $M_s(0)$

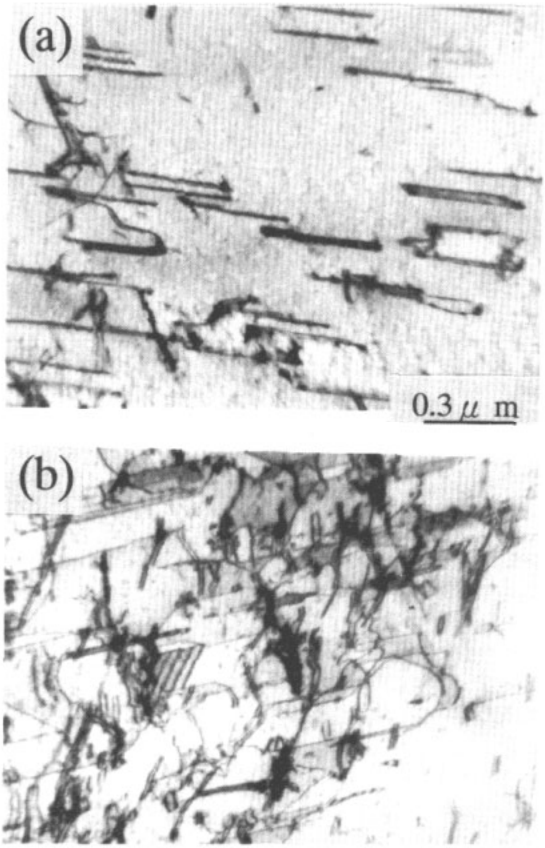

Figure 6. The electron micrographs of $Ni_{75.2}Al_{23}Pd_{1.8}$ compounds deformed plastically: (a) $\epsilon = 10\%$; (b) $\epsilon = 20\%$.

and ρ as in figure 7, since the same relationship is obtained between $M_s(0)$ and ϵ in all the samples as shown in figure 4(a) and (b).

Superlattice dislocations have antiphase boundaries (APBs) and complex stacking faults (CSFs) between superpartials and between Shockley partial dislocations, respectively, in the $\{111\}$ glide plane as shown in figure 5. Two or three atomic configurations coexist in the present samples deformed plastically. One is the $L1_2$-type structure, which produces the weak itinerant ferromagnetism. The other atomic configurations are induced by plastic deformation near APBs and CSFs, whose magnetic structure is paramagnetic because of the disappearance of ferromagnetism in the heavily plastic deformation (De Boer *et al* 1969). The magnetic structure changes gradually with the increase of APBs and CSFs from ferromagnetism to paramagnetism. Consequently the values of $M_s(0)$ are a function of the number of atomic configurations in the vicinity of APBs and CSFs, which increases proportionally to the dislocation density. The relationship was obtained by one of the present authors and his co-worker (Takahashi and Ikeda 1983). The net magnetization of the plastically deformed compounds at 0 K can be written as

$$M_s(0) = (N_0 - N)\mu_L \tag{3}$$

where N_0 and μ_L are the total number of Ni atoms and their magnetic moment before plastic deformation, respectively. N is the number of Ni atom near the APBs and CSFs,

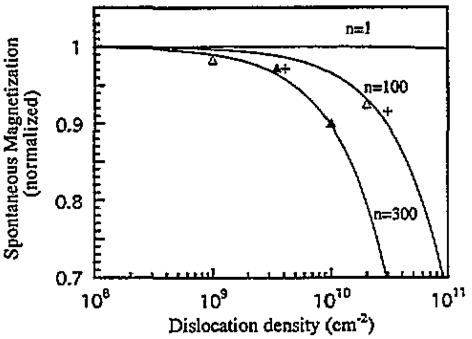

Figure 7. The spontaneous magnetization, $M_s(0)$, versus the dislocation density, ρ: experimental results for $Ni_{75.2}Al_{23}Pd_{1.8}$ (▲), $Ni_{74.8}Al_{23}Pd_{2.2}$ (+) and $Ni_{77}Al_{23}$ (△); experimental results and calculated ones—according to equation (3), when superlattice dislocations are distributed as pairs. n indicates the degree of magnetic influence of the ferromagnetic Ni atoms near APBs and CSFs.

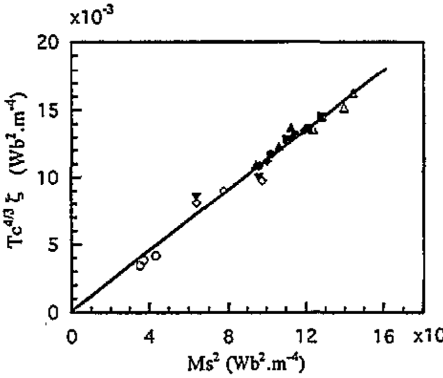

Figure 8. $T_C^{4/3}\zeta$ versus $M_s(0)^2$ in Pd-doped Ni_3Al and Ni_3Al compounds with and without plastic deformation. ζ is the coefficient of the $T_C^{4/3}$ term in the $M_s^2(0)$ versus $T^{4/3}$ plot. $Ni_{77+x}Al_{25-x}$: $x = 0$ (○); $x = 1.5$ (◇); $x = 2.0$ (△). $Ni_{77-x}Al_{23}Pd_x$: $x = 0.4$ (■); $x = 0.8$ (●); $x = 1.8$ (◆); $x = 2.2$ (▲); $x = 3.0$ (▼).

whose magnetic moment is zero. The number of Ni atoms in the vicinity of the APBs and CSFs is given as follows, when the superpartial dislocations distribute in pairs:

$$N_1 = 2\sqrt{3}a^{-2}(\bar{r}_1 + \bar{r}_2)\rho \tag{4}$$

where a is the lattice constant and $\bar{r}_1$ and $\bar{r}_2$ are the average separations of superpartials and of Shockley partial dislocations, respectively. They were obtained through electron microscopy observation; $r_1 = 12$ nm and $r_2 = 4$ nm. The relations between $M_s(0)$ and ρ are shown in figure 7 in comparison with the experimental results. The comparison of the experimental and calculated results suggests that disagreement exists between them; the experimental result is 100–300 times as large as the calculated one, i.e. $N = 100N_1$–$300N_1$. This disagreement will be discussed later.

4. Discussion

In the $Ni_{77-x}Al_{23}Pd_x$ system, Pd atoms have a strong tendency to occupy the Ni sites. Ni atoms expelled by the Pd atoms occupy the Al site. The substitutive Ni atoms take the same magnetic behaviour as the excess Ni atoms in the off-stoichiometric Ni_3Al binary compounds (Takahashi *et al* 1994). This substitutive Ni atom at the Al site, which has only Ni nearest neighbours, does not carry a magnetic moment different from that at the Ni site (Felcher *et al* 1977). This result is consistent with the weak itinerant ferromagnetism due to the SCR theory of spin fluctuation.

The temperature dependence of spontaneous magnetization agrees with the SCR theory of spin fluctuation even in the plastically deformed samples, which indicates that the magnetism in the plastically deformed samples can be represented by the spin fluctuation as well as the band structure. According to the SCR theory of spin fluctuation, the temperature dependence of the spontaneous magnetization is given by

$$M_s(T)^2 \propto \Gamma_1/R(T_C^{4/3} - T^{4/3}) \tag{5}$$

where R and Γ_1 are parameters depending on the band structure, and the Curie temperature is represented as

$$T_C \propto [(\alpha - 1)/\Gamma_1)]^{3/4}. \tag{6}$$

Here $(1-\alpha)$ is the inverse susceptibility enhancement factor; $\alpha = IN(E_F)$, i.e. the product of the intra-atomic exchange constant, I, and the density of states, $N(E_F)$, at the Fermi level, E_F.

Sasakura *et al* (1984) gave experimentally a simple relationship between T_C and $M_s(0)$ in $Ni_{75+x}Al_{25-x}$ compounds, i.e.

$$T_C^{4/3}\zeta = KM_s(0)^2 \tag{7}$$

where K is a constant. Equation (7) can be obtained by supposing that $(\alpha - 1)/R = (\alpha_0 - 1)/R_0$, where α_0 and R_0 are the values at $T = 0$ K. The relationship of equation (7) has been examined in the present study. Figure 8 shows the relation between $T_C^{4/3}\zeta$ and $M_s(0)$, which indicates that the magnetism in the present binary and ternary compounds, including the plastically deformed ones, can be explained by the SCR theory of spin fluctuation.

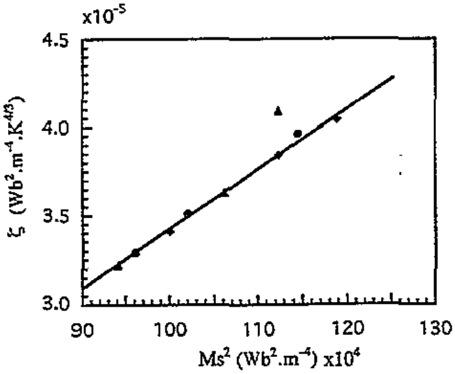

Figure 9. ζ versus $M_s(0)^2$ in $Ni_{76.2}Al_{23}Pd_{0.8}$ (●), $Ni_{75.2}Al_{23}Pd_{1.8}$ (♦) and $Ni_{74.8}Al_{23}Pd_{2.2}$ (▲) compounds with and without plastic deformation.

Plastic deformation does not exert any influence on the value of T_C as shown in tables 1 and 2, though $M_s(0)$ decreases with plastic deformation in all the samples. The values of T_C in the samples of $Ni_{76.2}Al_{23}Pd_{0.8}$, $Ni_{75.2}Al_{23}Pd_{1.8}$ and $Ni_{74.8}Al_{23}Pd_{2.2}$ are nearly the same before and after plastic deformation. The equation (7) indicates that in these samples, $M_s(0)^2$ decreases directly in proportion to ζ. Figure 9 shows the experimental relationship between $M_s(0)$ and ζ. $M_s(0)$ decreases with increasing plastic strain (see figure 4). The parameter ζ has a direct influence on plastic deformation and is a function of the dislocation density, ρ. $\zeta(\rho)$ corresponds to Γ_1/R. According to equation (6), Γ_1 would be independent of ρ, since T_C is independent of ρ. R increases as ρ increases. R can be represented by the first and second derivatives of $N(E_F)$ (Moriya and Kawabata, 1973) i.e.

$$R = N'(E_F)^2/N(E_F)^4 - N''(E_F)/3N(E_F)^3. \tag{8}$$

Plastic deformation would exert some influence on the derivative of $N(E_F)$ rather than $N(E_F)$.

Plastic deformation changes atomic configurations in the vicinity of APBs and CSFs between superpartial dislocations and Shockley partials, respectively. The atomic configurations play an important role in the reduction of $M_s(0)$ in the plastically deformed samples. If only Ni atoms near the APBs and CSFs carry no magnetic moment, the paramagnetic region should spread at least as far as 100 atomic distances from the APB and CSF ribbon as shown in figure 7. If the Ni atoms carry a small size of magnetic moment near the APB and CSF ribbon, the influence of APB and CSF ribbons would spread farther than 100 atomic distances. The change of atomic configuration occurs only in the APBs and CSFs. Almost all the atomic structures of paramagnetic state are the $L1_2$ type. It is impossible to explain the long-range distance interaction on the basis of the localized model. The long-distance interaction is consistent with itinerant electron ferromagnetism.

The electron microscopy observation indicates that a bundle of four Shockley partial dislocations distribute: the separations of Shockley partials composing APBs and CSFs are 12 nm and 4 nm, respectively, in the edge component. The dislocation density in the 10% strained sample is $(2 \pm 0.5) \times 10^9$ cm^{-2}. APB and CSF ribbons with 20 nm width distribute with separation, 10^3 nm distance. These APB and CSF ribbons break the periodicity of the atomic arrangement. The derivative of the density of states at the Fermi level or the curvature of the Fermi surface would be sensitive to plastic deformation and is easy to change by the introduction of APB and CSF ribbons.

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