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# About Magnetic Measurements and Plastic Deformation of The $Ni_3Al$ Single Crystal

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**Abstract**
Magnetic measurements and structure of $Ni_3Al$ single crystal alloying with chromium and iron after high temperature superplastic and plastic deformations at 1123 K and 1423 K, respectively, have been provided. By the analysis of the structure evolution and magnetic properties of the deformed alloy, it is shown that plastic deformation introduces both, the local atomic dislocation disordering and changing of the electronic structure of the deformed material.

**Keywords:** $Ni_3Al$, magnetic properties, plastic deformation, defects.

## Introduction

Nickel superalloys are extensively used in high-temperature components of gas turbines due to their excellent creep, fatigue, and corrosion resistance at elevated temperatures. It is considered that these materials are paramagnetic at the range of working temperatures. $Ni_3Al$ intermetallic compound ($L1_2$, $\gamma'$-phase) is the main strengthening phase of nickel superalloys. Stoichiometric $Ni_3Al$ compound is a weak ferromagnet with a Curie temperature of 41 K. Magnetic properties of the intermetallic $Ni_3Al$ compound are highly sensitive to composition and plastic deformation. The strong influence of cold rolling upon the magnetic properties was found in the $Ni_3Al$ compound: the disordering by intense cold-working causes the ferromagnetic properties to disappear [2]. It was shown that the magnetization at 0 K decreases with the increasing of the dislocation density [3]. On the other hand, the strain-induced ferromagnetism arises because deformation disorders the compounds so that the atoms of the ferromagnetic element are no longer isolated from each other, and are therefore able to interact. In [7] was found the increasing of the magnetic susceptibility of the nickel superalloy after the long exploitation at high temperature. This effect was suggested to associate with the complex volume defects like V-faults formed inside the $\gamma'$-phase cuboids. Increasing of the magnetic susceptibility was also found in cyclically deformed $Ni_3(Al, Ti)$ single crystals. Anti-phase boundary tubes were observed in the structure of the single crystals after deformation [8].

Superplastic properties in $Ni_3Al$ were observed at the strain rate range of $10^{-3}$ m/s to $10^{-5}$ m/s and deformation temperatures $T \geq 1273$ K [4-6]. For a better understanding of the correlation between the magnetic properties and high temperature deformation behavior of the $L1_2$ type $Ni_3Al$ intermetallic compound, tensile tests at 1123 K and 1423 K were carried out on $Ni_3Al$ single crystals alloying with chromium and iron. Alloying of the iron increases the magnetic effect and chromium improves the ductility of the $Ni_3Al$-base alloys. In [1] was demonstrated that Fe is considerably more effective in inducing ferromagnetic order in this material. Iron atoms can be sited in both, Ni position and Al position in depending on the percent content of iron in the alloy. Value of the Curie temperature increases from ~140 K to ~223 K with the increasing of the Fe content from 1 to 3 atomic percent, respectively.

In the present paper, we investigate the processes of the plastic and superplastic deformations in the $Ni_3Al$ single crystal alloying with chromium and iron.

## Materials and Procedures

Single crystals of $Ni_3Al$ alloying with chromium and iron were grown using the Bridgman method. The composition of this material was Ni-74, Al-23, Cr-1 and Fe-2 in atomic percent. The orientations of the samples was [110]. The single crystals were homogenized at 1523 K for 24 h in a pure argon atmosphere. For tests, the cylindrical specimens were prepared and subsequently electropolished to remove the surface damage. Tensile tests were carried out at 1123 K and 1423 K in air. The magnetic properties of the alloys were investigated at $T \leq 400$ K and $H \leq 4$ MA/m using an MPMS-5XL SQUID magnetometer. The structure of the alloys was studied in the Test Center for Nanotechnologies and Advanced Materials at the Institute of Metal Physics, Ural Division, Russian Academy of Sciences, using a transmission electron microscope JEM-200CX. For study, we cut samples from the different parts of the deformed single crystals. We studied zone of fracture in the single crystal after deformation at 1123 K and area in 8 mm away from the zone of fracture in the single crystal after deformation at 1423 K.

**Results and Discussion**

Figure 1 shows the optical pictures of the deformed samples and tensile stress-strain curves of the deformed single crystals at 1123 K and 1423 K, respectively. One can see a superplastic behavior of deformed sample at 1423 K. The stress-strain curves are significantly dependent on strain rate and temperature. The yield stress and the fracture strength of the deformed specimen at 1123 K are higher than that of the deformed specimen at the 1423 K temperature. The deformed specimen at 1423 K exhibits a much higher elongation, as compared with the specimen deformed at 1123 K.

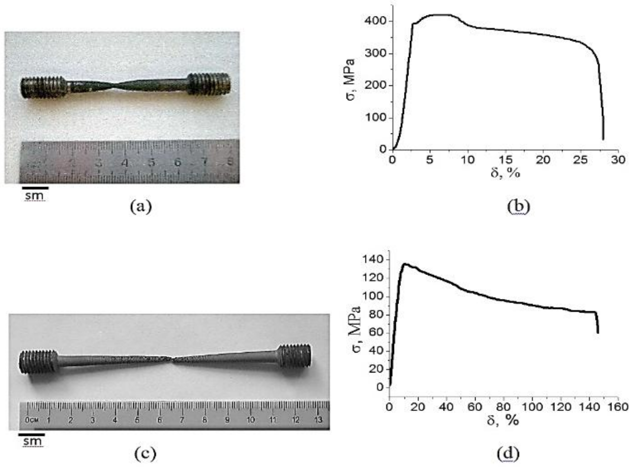


**Fig. 1. Optical pictures of the deformed samples and tensile stress-strain curves of alloy at various deformation conditions: a-b-sample 1 (T=1123 K), c-d-sample 2 (T=1423 K)**

Results of the mechanical test are presented in Table 1.

**TABLE. 1. Results of mechanical tests**

| N | Temperature, K | Strain rate | $\sigma_{0.2}$, MPa | $\sigma_b$, MPa | δ, % |
|---|---|---|---|---|---|
| 1 | 1123 | 0. 8 x $10^{-5}$ m/s | 415 | 440 | 29 |
| 2 | 1423 | 2 x $10^{-5}$ m/s | 125 | 140 | 140 |

Figure 2 shows the results of the magnetic measurements. The Curie temperatures of the studied alloys at the initial state are 135-136 K. In compare with the initial state, the value of ac-magnetic susceptibility decreases in the samples after deformation. Value of Curie temperature decreases too in the sample cut from the zone of fracture of the alloy after deformation at 1123 K. However, a Curie temperature is very close to the initial one in the sample cut in 8 mm away from the zone of fracture of the alloy after deformation at 1423 K.

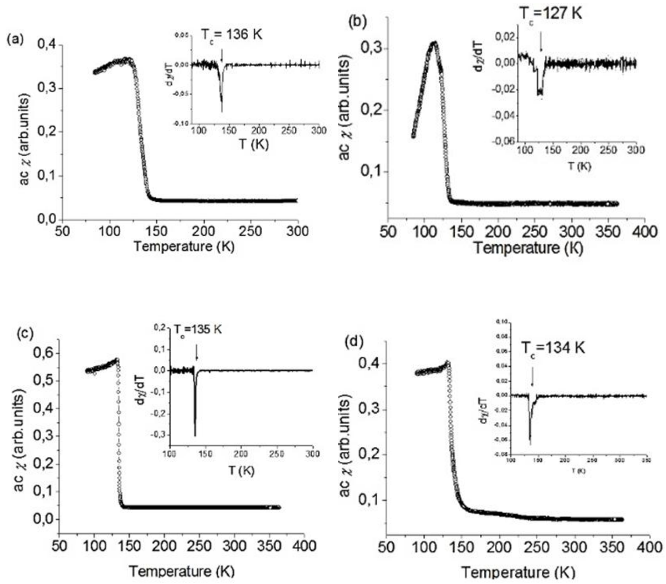


**Fig. 2. Temperature dependence of the ac-magnetic susceptibility and Curie temperature for the deformed samples: a-b –sample 1, (a)-initial; (b)-after the deformation at T=1123 K, zone of fracture; c-d – sample 2, (c) –initial, (d)-after the deformation at T=1423 K, 8 mm away from the zone of fracture**

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The defect structure of the deformed samples is shown in Figures 3-4. After deformation, alloys retain a single crystal state. We did not found complex volume defects (APB tubes or V-faults) in the structure of both deformed alloys. Microstructural observations of the zone of fracture of the alloy after plastic deformation at 1123 K reveal the twins, high density of dislocations, and fragmentation process (Fig. 3). In 8 mm away from the zone of fracture of the alloy after deformation at 1423K, one can see the dislocation walls (Fig. 4a), dislocations with the stacking faults (Fig. 4b), and subgrains (Fig. 4c). We did not found the recrystallized grains and disordered area in the studied alloys after deformation. The diffraction patterns taking from the different places of the foils have the super structural reflexes of the ordered γ′-phase ($Ni_3Al$) (Fig. 3c and Fig. 4d).

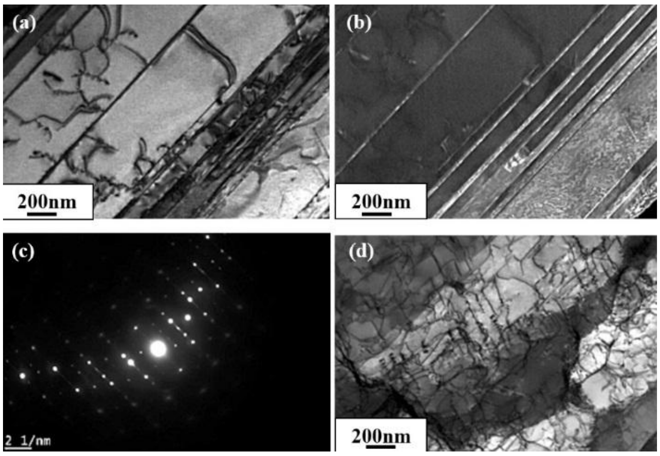


**Fig. 3. Microstructure of the sample 1 deformed at 1123 K, TEM, zone of fracture: a-the bright field image of the twins, b-the dark-field image in the twin reflex; c-diffraction pattern to a-b, zone axis [110]$Ni_3Al$; d-fragmentation of the structure, bright-field image**

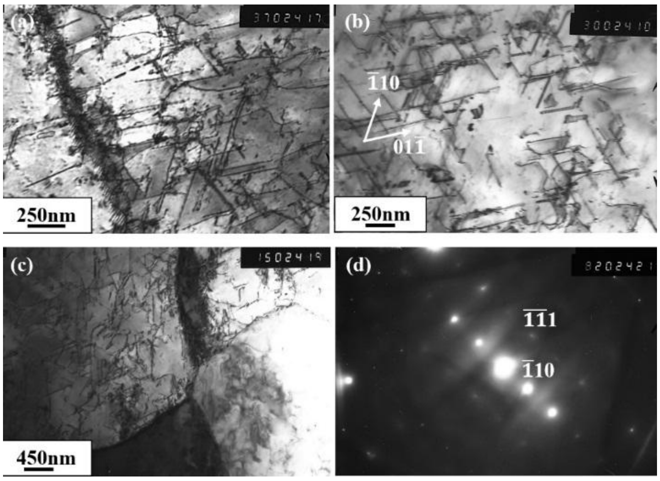


**Fig. 4. Microstructure of the sample 2 deformed at 1423 K, TEM, 8 mm away from the zone of fracture: a-b dislocations, bright-field image; c-subgraines, bright-field image; d-diffraction pattern to (c), zone axis [112]$Ni_3Al$**

In the $Ni_3Al$ ($L1_2$), there are two dissociation schemes for a $a$[101](111) glide dislocation [6]:

$$a[101] \rightarrow a/2[101] + \text{APB} + a/2[101] \quad (1)$$

$$a[101] \rightarrow a/3[211] + \text{SISF} + a/3[112] \quad (2)$$

First equation presents the scheme when dislocations are essentially dissociated into two like superpartials with a/2<110> Burgers vector separated by an antiphase boundary (APB). With increasing temperature of deformation above 1073 K, <110>{111} slip systems are favored and dislocations consisting of pairs of $a$/3[112] superpartials bounding superlattice intrinsic stacking faults (SISFs) are observed. Twinning also can be seen at high temperature deformation [7].

In our case, we found twins and high dislocation density in the zone of fracture of the alloy after deformation at 1123 K. This is usual high temperature deformation behavior of the $Ni_3Al$ single crystals. According to [3] decreasing of ac-magnetic susceptibility and a Curie temperature in the deformed alloy may be explained the by the local atomic dislocation disordering of the $Ni_3Al$ crystal lattice. The alloy deformed at 1423 K showed superplastisic behavior with the dynamic recovery as a basic mechanism of relaxation. We also observed the decreasing of the value of ac-magnetic susceptibility after deformation of the alloy (Fig. 4 c-d). However, we did not find any change in the value of Curie temperature.

In [9] was suggested two variants of disorder in the $Ni_3Al$, such as composition disorder and site disorder. With increasing of the compositional disorder, Curie temperature $T_C$ decreases; site disorder leaves $T_C$ essentially unaltered [9].

$Ni_3Al$ has the anti-site atomic behavior. However, site disorder does not mean absolute disordering of the $Ni_3Al$ crystal lattice; instead, the uniform statistical distribution of the anti-site defects in the alloy are observed. Composition disorder deals with a non-uniform distribution of the alloy components across the ingot. Usual plastic deformation creates a local composition disorder by the dislocation movement and change of the number of neighboring AI/Fe atoms around the host Ni atom; the dislocation density increases with increasing of the percent of deformation. Under superplastic behavior occurring due to dynamic recovery, the dislocation reorganization and annihilation occur; the dislocation density does not increase or increases very slowly with the increasing of the percent of deformation. As the result, we can suggest that the superplastic deformation does not introduce a composition disorder in our alloy. We have also a site disorder by the uniform distribution of Fe and Cr in the initial $Ni_3Al$ alloys; the Curie temperature of the $Ni_3Al$ alloying of Fe and Cr is increased at the initial state in comparison with that of stoichiometric $Ni_3Al$.

Thus, dislocation movement only cannot explain the decreasing of magnetic susceptibility of the alloys after plastic and superplastic deformations. On the other hand, the value of the magnetic susceptibility is associated with electronic structure of the material. It means that the plastic deformation process includes both, the local atomic dislocation disordering and changing of the electronic structure of the deformed material.

## Conclusion

This work shows that the magnetic measurements can be useful for understanding of the deformation process of the low magnetic materials and alloys. The high temperature superplastisity regime can be also used for mechanical treatments of the nickel superalloys.

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