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Mechanical properties of nanocrystalline Ni-20%Fe alloy at temperatures from 300 to 4.2 K

E.D. Tabachnikova[a,*], A.V. Podolskiy[a], V.Z. Bengus[a], S.N. Smirnov[a], M.I. Bidylo[a], H. Li[b], P.K. Liaw[b], H. Choo[b], K. Csach[c], J. Miskuf[c]

[a] B. Verkin Institute for Low Temperature Physics and Engineering, 47, Lenin Avenue, Kharkov 61103, Ukraine
[b] Department of Materials Science and Engineering, University of Tennessee, Knoxville 37996, USA
[c] Institute of Experimental Physics, SAS, Watsonova 47, 04353 Kosice, Slovakia

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ABSTRACT

Mechanical properties of the nanocrystalline Ni-20%Fe alloy (the average grain size is 22 nm) have been studied under uniaxial compression at different strain rates (from $10^{-5}\,s^{-1}$ to $10^{-1}\,s^{-1}$) and temperatures from 300 to 4.2 K. Comparison of the strength characteristics, strain and failure peculiarities of the nanocrystalline and coarse-grained structural states of Ni-20%Fe alloys is carried out. Micromechanisms of plastic deformation in this nanocrystalline alloy (including increase of the slip localization at low temperatures) are discussed.

1. Introduction

Nanocrystalline (NC) materials (grain size less than 100 nm) show considerable promise from the applied viewpoint due to their super strength (flow stress values are approximately 2 GPa at a temperature of 300 K) while retaining enough ductility [1,2]. These materials are also extremely interesting from the fundamental point of view because of the unique possibility to study grain-boundary properties when their volume fraction is high (it can constitute ∼15% of the material's volume [3], while the average grain size is ∼22 nm). It is especially important to understand peculiarities of plastic deformation mechanism changes at cryogenic temperatures: transition from dislocation processes in grains to the emission of mobile dislocations by grain boundaries and intergranular sliding [4].

At present the information on these problems is very limited [4], though prospects of NC materials for structural applications at cryogenic temperatures are highly promising. Investigation of NC alloys is particularly interesting in this connection, as addition elements enable further strength increase of such ultra-fine-grained materials [5]. A more thermodynamically stable state can be produced as well [6,7].

In the present work a detailed investigation of mechanical properties of an electrodeposited Ni-20% Fe nanocrystalline alloy is carried out in the 300–4.2 K temperature range and in the 10^{-5} to $10^{-1}\,s^{-1}$ strain rates interval.

2. Experimental materials and procedures

An electrodeposited Ni-20% Fe nanocrystalline alloy has been studied. Compositional distribution of the alloy is quite homogeneous throughout the whole deposit [5,8]. The alloy has a single FCC phase, indicative of a complete solid solution of Fe into Ni. The grain size ranges are 5–50 nm and average grain size is 22 nm. Most grain boundaries are atomically sharp and the crystallinity is maintained up to the boundary [5,8].

Mechanical characteristics have been studied under uniaxial compression with four different strain rates: $3\times10^{-5}\,s^{-1}$, $3\times10^{-4}\,s^{-1}$, $5\times10^{-3}\,s^{-1}$, $1\times10^{-1}\,s^{-1}$ for the NC alloy, and also for the coarse-grained (CG) alloy of the same composition (with an average grain size of 35 μm) at a strain rate of $3\times10^{-4}\,s^{-1}$. Stiffness of the straining machine is about 7×10^{6} N/m. Tests have been carried out at 4.2 K (in liquid helium), 77 K (in liquid nitrogen), 170 K (in cryogenic nitrogen steam), and 300 K. Specimens for

* Corresponding author. Tel.: +380 573410831; fax: +380 573403370.
E-mail address: tabachnikova@ilt.kharkov.ua (E.D. Tabachnikova).

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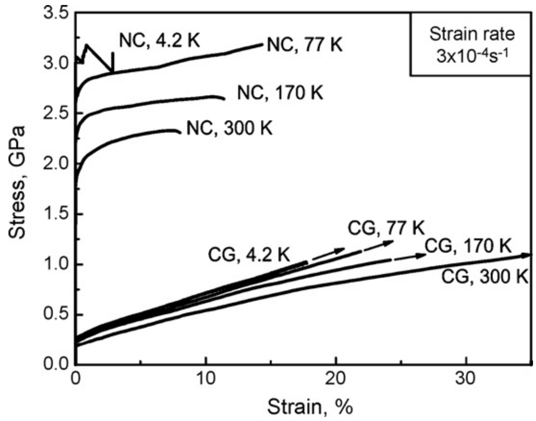

Fig. 1. Typical stress–strain compressive curves of nanocrystalline Ni-20%Fe alloy in nanocrystalline (nc) and coarse-grained (CG) states at temperatures 300, 170, 77, and 4.2 K for $3 \times 10^{-4}\,s^{-1}$ strain rate (arrows indicate that for the CG state an additional deformation is possible).

compression were rectangular prisms: $1.5 \times 1.5 \times 3$ mm for NC state and $2.8 \times 2.8 \times 5$ mm for CG state.

Yield stress $\sigma_{0.2}$, maximum stress σ_{max}, and maximum plastic strain ε_f values have been measured from deformation curves $\sigma - \varepsilon$ (engineering stress – plastic engineering strain).

Note that in uniaxial compression ε_f values can be registered only for the NC alloy, since in this case at all testing temperatures specimens experienced shear failure in two pieces along planes inclined at 45° relative to the compression axis. As distinct from this, CG alloy specimens gained a tubby shape in the course of compression, and it is hard to register ε_f values correctly.

Stress relaxation curves have been registered for several NC and CG Ni-20%Fe specimens. From these curves the activation volume for the thermally activated plastic flow has been calculated using the common method [9]. Investigation of the failure surfaces was carried out in the high-resolution scanning electron microscope JSM 7000F (operated with a field emission gun).

3. Experimental results and discussion

Fig. 1 shows typical stress-strain curves of the NC and CG alloys at different temperatures for the $3 \times 10^{-4}\,s^{-1}$ strain rate. One can see that the values of the applied stress for the NC state considerably exceed analogous characteristic of the CG alloy and achieve ~3 GPa at 4.2 K for the NC state. Initial stages of the stress–strain curves have a parabolic shape that afterwards changes into an extensive nearly linear part. Note that strain–hardening coefficient at all temperatures is smaller for the NC state than for the CG state.

At a temperature of 4.2 K stress–strain curves have a jump-like character, which is considerably different for the NC and CG states. In the case of the NC state several large stress jumps have been observed, their depth $\Delta\sigma$ increases together with strain ε. Near the yield stress values of the jumps are $\Delta\sigma \sim 0.1$ GPa, and achieve $\Delta\sigma \sim 0.3$ GPa at $\varepsilon \sim 4$–5%, followed by a failure of the specimen. In the case of CG state at 4.2 K small stress jumps ($\Delta\sigma \sim 0.004$ GPa) appear on the deformation curve only at the plastic strain $\varepsilon \sim 7.5\%$. The depth of the jumps increases at large strains up to $\Delta\sigma \sim 0.015$ GPa, this value is still considerably smaller than $\Delta\sigma$ for the NC state.

It is generally known that a jump-like character of stress–strain curves at 4.2 K is caused by localization of plastic deformation [10]. Localized plastic deformation is realized by shear bands and by twinning process. Presence of larger stress jumps in the NC state in comparison with the CG state means that the localization of plastic deformation in the NC state is more pronounced. Not only slip dislocations, but also twinning dislocations can realize the deformation at a temperature of 4.2 K. The process of twinning should be facilitated (especially at low temperatures) by generation of

Table 1
Yield stress $\sigma_{0.2}$, maximum stress σ_{max}, and maximum plastic strain ε_f values of nanocrystalline and coarse-grained Ni-20%Fe alloy at all investigated temperatures and strain rates

Temperature (K)	Strain rate												
	$3 \times 10^{-5}\,s^{-1}$			$3 \times 10^{-4}\,s^{-1}$				$5 \times 10^{-3}\,s^{-1}$			$1 \times 10^{-1}\,s^{-1}$		
	Nanocrystalline			Nanocrystalline			Coarse-grained	Nanocrystalline			Nanocrystalline		
	$\sigma_{0.2}$ (GPa)	σ_{max} (GPa)	ε_f (%)	$\sigma_{0.2}$ (GPa)	σ_{max} (GPa)	ε_f (%)	$\sigma_{0.2}$ (GPa)	$\sigma_{0.2}$ (GPa)	σ_{max} (GPa)	ε_f (%)	$\sigma_{0.2}$ (GPa)	σ_{max} (GPa)	ε_f (%)
300	1.82	2.17	5.0	1.92	2.27	5.3	0.19	1.90	2.38	11.6	2.08	2.46	15.9
170	2.23	2.48	3.7	2.37	2.80	11.6	0.23	2.34	2.87	17.0	2.37	3.07	27.6
77	2.79	2.92	2.0	2.67	2.99	9.8	0.24	2.85	3.27	19.0	2.83	3.17	26.7
4.2	3.22	3.47	1.6	3.08	3.26	3.6	0.28	2.98	3.08	0.5	2.97	3.09	2.6

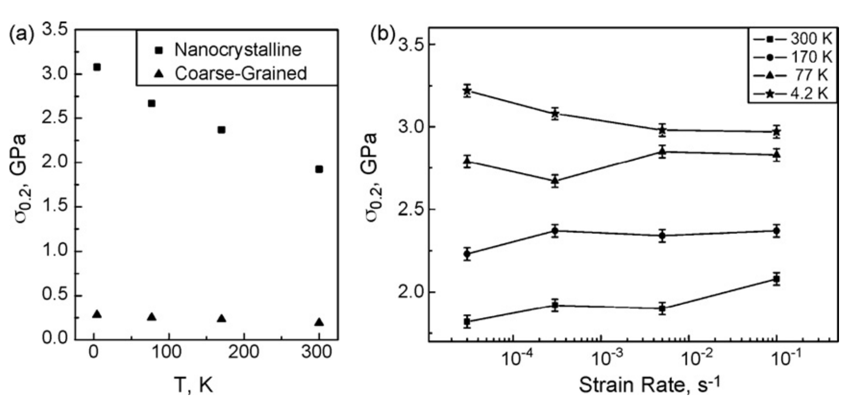

Fig. 2. (a) Temperature dependences of yield stress $\sigma_{0.2}$ of NC and CG Ni-20%Fe alloy under compression at $3 \times 10^{-4}\,s^{-1}$ strain rate and (b) strain rate dependences of $\sigma_{0.2}$ for the nanocrystalline Ni-20%Fe alloy at different temperatures.