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Hydrogen influence on plastic deformation mechanism of β-titanium alloys of Ti–Nb system

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Abstract

The influence of hydrogen on the mechanism of cold plastic deformation at room temperature of β-Ti–Nb alloys with Nb content from 20 to 50 wt% is studied. It is shown that hydrogen increases the mechanical stability of the β-phase and hinders shape changes which occur due to a martensitic transformation or twinning. Hydrogen influences strongly the slip mechanism in the β-plane. The dislocation unpinning under hydrogen atmosphere during deformation causes the formation of 'upper' and 'lower' yield points. That causes the formation of a higher yield point during compression of the samples and leads to a strong location of deformation during tension tests. In general, hydrogen assists in lowering the deformation energy, and increases the ductility and mechanical instability of β-titanium alloys containing from 20 to 40% Nb.

Keywords: b.c.c. Ti–Nb alloys; Hydrogenising and mechanism of deformation; Internal friction

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1. Introduction

Shape changes of titanium alloys during cold plastic deformation take place sequentially or simultaneously according to one of the three following mechanisms: martensitic transformation, twinning or slipping. The deformation storage due to the martensitic transformation and twinning takes place in alloys containing the mechanically unstable β-phase and is limited (ϵ=5–8%) by crystallographic peculiarities of the $\beta \Rightarrow \alpha''$ transition and twinning [1]. The addition of hydrogen to titanium alloys influences significantly the β-phase stability as well as the development of the slipping process in β-phase [2]. So, the hydrogen influence on the mechanism of cold plastic deformation of β-titanium alloys is of considerable interest.

2. Materials and experimental procedure

All investigations were made using hot rolled Ti–Nb (from 20 to 50% Nb) rods alloys produced by multipass electric-arc remelting of iodide titanium with electrolytic Nb. Hydrogen was added to concentrations of 0.1–0.6% by the thermodiffusion method on a Sievert's type equipment. The samples were exposed to compression, tension and rolling at room temperature. Initial and deformed samples were studied by metallographic and X-ray analysis. Amplitude dependent internal friction (ADIF) measurements were carried out with the use of a free decay torsion inverted pendulum 'RKM-TPI' (f=1–2 Hz) in the amplitude range $\gamma = 10^{-6}$–10^{-3}. All ADIF measurements were performed without vacuum in order to avoid dehydrogenation.

3. Experimental results and discussion

The samples with 20–25% Nb (the hydrogen content in the initial state is about 0.005%) which are quenched from the temperature of the β-area contain in addition to the β- and α″-phase considerable amounts of ω-phase (Fig. 1). This causes a significant strengthening of the alloys and lowers ductility. When the Nb content is increased up to 35% the volume fraction of the ω-phase decreases an the structure of samples is characterized mainly by the β-phase and α″-martensite [3]. The σ–ϵ curve of such alloy samples during compression and tension are characterised by a low yield strength (YS=220–250 MPa) and the change of deformation stress is more than 5% (Fig. 2). This alloy does not have a high ductility and fails under a compression of 40–60% or a tension of 14–18%. X-ray structural analysis shows that during the deformation of the

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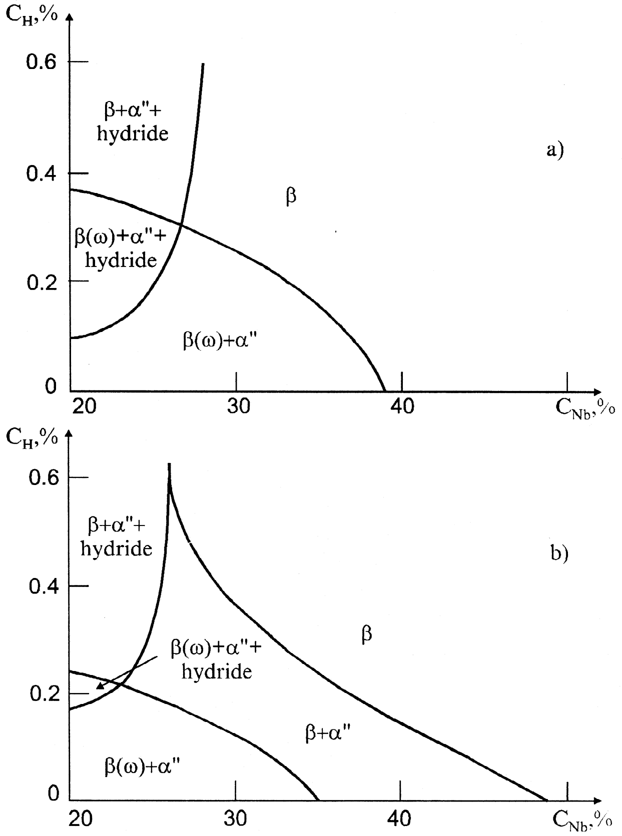

Fig. 1. The influence of hydrogen on (a) phase composition of β-Ti–Nb alloys after β-quenching and (b) the 20% deformation by compression.

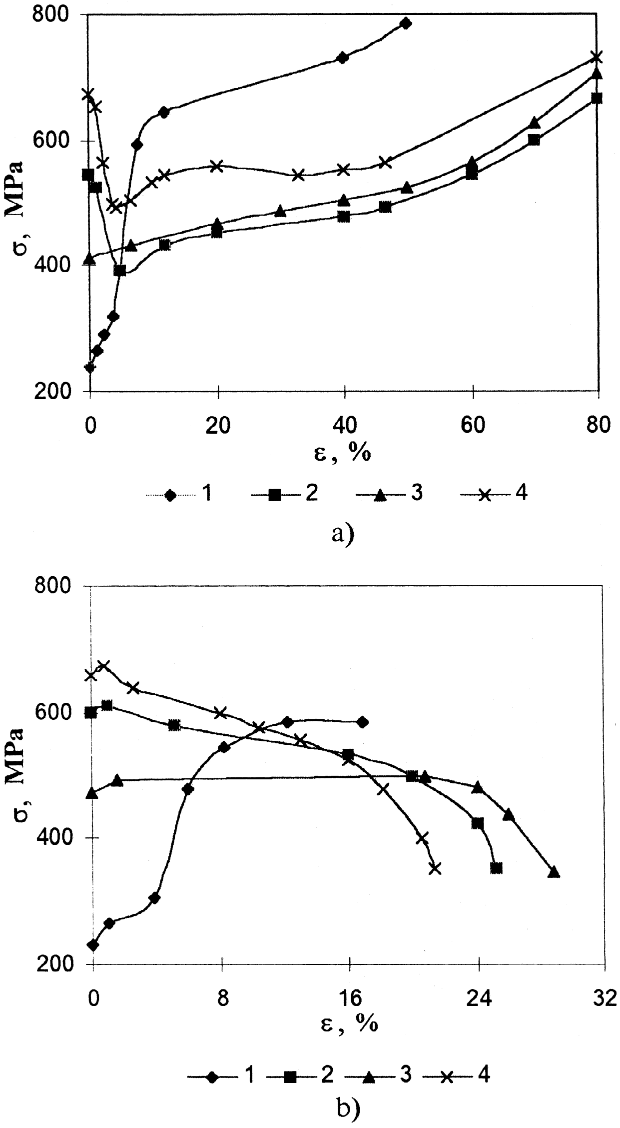

Fig. 2. Plastic deformation under (a) compression and (b) strain of Ti–35% Nb (1, 2) and Ti–50% Nb (3, 4) with initial hydrogen concentration (1, 3) and containing 0.4% H (2, 4).

samples in the range of $\epsilon = 5–8\%$ the mechanically unstable β-phase is transformed into the α″-martensite. In alloys with 30–35% Nb after 20% no deformation by compression of a higher ω-phase content was found. In alloys containing more than 48% of Nb the β-phase is mechanically stable and undergoes no transformations during the deformation. These alloys have a yield strength point of 400–450 MPa with the high ductility.

Hydrogen alloying changes the phase composition and the shape of the $\sigma - \epsilon$ curves. First in alloys with 20–25% Nb the addition of hydrogen (>0.2%) suppresses the formation of the ω-phase and decreases the strengthening and the embrittlement connected with the ω-phase appearance. The hydride forming in this alloys was a badly centered tetragonal lattice and the chemical composition $(TiNb)_xH_{1-x}$, where x corresponds approximately to 0.5 [3]. It partly disappears and does not lead to an embrittlement. Second, hydrogen increases the β-phase stability against the martensitic transformation under quenching and deformation process. Therefore if hydrogen is added to titanium alloys with 30% Nb or more it is possible to obtain a thermally and mechanically stable single β-phase structure. The higher the Nb content in the alloy the lower the hydrogen concentration necessary for full stabilization of the β-phase (Fig. 1). Third, for all alloys investigated which contain more than 0.1% H a sharp upper yield point is observed in the compression and tension curves, and a significant loss of strength takes place immediately after the yield point has been reached (Fig. 2). As the hydrogen concentration in the single phase alloys increases the degree of deformation under compression increases (more than 80%) and is restricted only by the testing equipment. At the sample time the relative elongation of the deformed samples under tension decreases and the reduction area increases which shows the significant localisation of the sample deformation.

For the study of the hydrogen interaction which defects of the crystal structure in the β-phase measurements of the ADIF were made on Ti–50% Nb samples with various hydrogen concentrations. The measurements were made in annealed samples at 800 °C and after 2% deformation by natural ageing. The influence of hydrogenization on the

$\sigma-\epsilon$ curves is different in the range of elastic and plastic deformation. On the one hand the hydrogenizing leads to an increase of the upper yield point (from ~400 to ~700 MPa [4], on the other hand it leads to a decrease of the lower yield point for samples with a certain hydrogen concentration. The hydrogenation leads to a shift of the amplitude range of IF increase on ADIF curves to higher amplitudes and to the appearance of a new interval of ADIF curve with the relatively small slope Q^{-1} versus γ in the range of the lowest amplitude of deformations [4]. In the hydrogen-free sample this critical amplitude of deformation is $\gamma_{cr}\approx 2\cdot 10^{-4}$ and in hydrogenized samples the corresponding value is about $5\cdot 10^{-4}$.

Hydrogenation pins the dislocations existing in the alloy. A dislocation unpinning and corresponding increase of IF takes place only at an increase of applied stress. With an increase in amplitude of ADIF measurements up to $\sim 3\cdot 10^{-4}$ a sample hydrogenation causes a lowering of the ADIF level at a given amplitude of deformation (Fig. 3).

Immediately after deformation the dislocation mobility and corresponding IF do not strongly depend on the hydrogen concentration. During natural ageing (8–10 h) a significant increase of IF is observed on the amplitude dependence curves of IF in the range of low amplitudes of deformation (samples 0.2% H) (Fig. 4). For the sample with 0.45 wt.% H a similar effect is observed at higher amplitudes and thus it is not reflected in Fig. 3. After 100 h ageing the ADIF curve shifts nearer to the ADIF curve of the non-deformed annealed sample. The formation of an equilibrium hydrogen atmosphere at the dislocations as proven by the data given in Fig. 4 leads to the appearance of a sharp yield point, i.e. the 'fresh' dislocations cannot be pinned any more during an active plastic deformation [4].

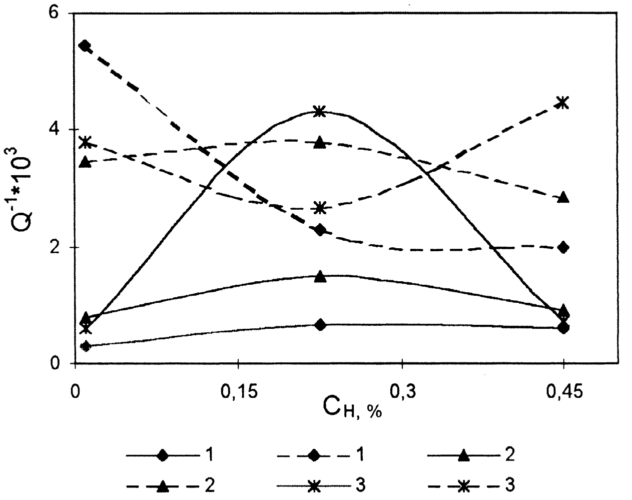

Fig. 3. The influence of hydrogen on the level of internal friction in Ti–50% Nb under a given amplitude of torsion deformation of $\gamma=3\cdot 10^{-5}$ (solid lines) and $\gamma=3\cdot 10^{-4}$ (dashed lines) after (1) quenching, (2) just after 2% deformation and (3) ageing for 8–10 h at room temperature.

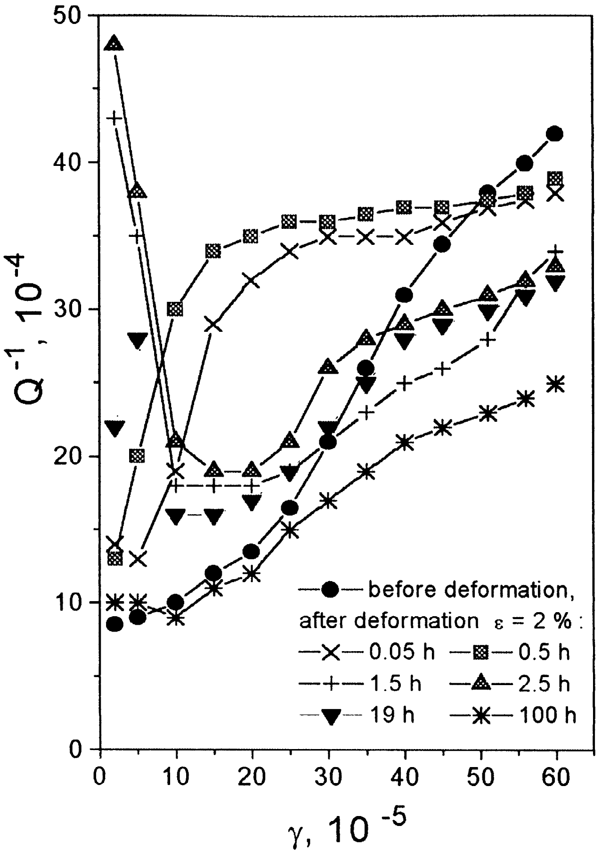

Fig. 4. The influence of strain-ageing time at room temperature of ADIF curves for a Nb–Ti alloy with 0.22 wt.% H.

In the compression test curves with the loading rate $\epsilon=0.024\ s^{-1}$ the upper yield point ($\approx$700 MPa) appears for all the Nb–50 wt.% Ti samples with hydrogen contents of 0.2 wt.% and higher (Fig. 2a). The height of the upper yield point is practically independent from hydrogen content within 0.1–0.8 wt.%.

This shows that hydrogen influences significantly the mechanism of elastic, microplastic and plastic deformation of β-Ti–Nb alloys at room temperatures. Being a strong β-phase stabiliser, hydrogen increases the mechanical stability of the β-phase and promotes an increase of the slipping mechanism contribution during the shape changes of titanium alloys [5]. Having a high mobility at room temperature hydrogen influences the slipping character. Hydrogen forms Cottrell-type atmospheres and pins existing dislocations. This leads to an increase of the stresses at which they start to move and the appearance of the 'upper' yield strength of the material. At the same time, the hydrogen dissolved in β-phase decreases the elasticity stresses from dislocations and other defects of the crystal lattice, which lowers the stresses needed to move the dislocations, i.e. to unpin them from the hydrogen atmospheres. This causes a decrease of the 'lower' yield strength and of the deformation strengthening. As a result, during compression tests of hydrogenated titanium samples, having the structure of mechanically unstable β-phase, the formation of a sharp yield point is observed, and its value can reach 30% of the value of 'lower' yield strength. The deformation loss of strength during the tension tests of the same alloys is observed immediately after reaching a specific yield strength. This is connected with the localisation of the deformation, when only a small volume of the active part of the sample reaches the values of the 'upper' yield strength stresses during deformation, and the total deformation is concentrated in this part of the sample.

Thus, the limited ductility of hydrogenated alloys is mainly determined by the deformation scheme. In the case of rolling or damaging the samples with hydrogen, where the whole volume is deformed, their ductility is very high. At the same time during drawing the possibility of deformation localisation and further failure due to low ductility is possible.

4. Conclusions

Hydrogen significantly influences the mechanism of plastic deformation of β-alloys based on Ti–Nb. It increases the mechanical stability of the β-phase, hinders shape changes due to martensitic transformation and twinning, and promotes the plastic deformation development by slip mechanism. Formation of impurity atmospheres at dislocations hydrogen increases the starting stress for dislocations movement, simultaneously lowering the elastic misfits from crystal structure defects the leads to a decrease of 'friction forces' in the crystal lattice.

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