

Computer Simulation of Hydrogen Storage Materials

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ABSTRACT

The microscopic mechanism of Hydrogen-Induced Amorphization (HIA) in AB₂ C15 Laves phase compound is studied. Experimentally, compounds in which the AA internuclear distance is reduced and BB internuclear distance expanded compared to pure crystals show Hydrogen-Induced Amorphization which suggests that *the relative atomic size is the controlling factor*. We investigate the role of the size effect by static and molecular Dynamics (MD) methods using Lennard-Jones pair-wise potentials. Our simulations show that in such a compound, the bulk modulus is remarkably reduced by hydrogenation compared to the isotropic tensile load, so that elastic instability is facilitated. This situation is caused by the negative increase of the pressure-fluctuation contribution in the elastic constant. An elastic analysis at sublattice level shows that one of the sublattices is less stable in the HIA material.

Keywords: molecular dynamics, elastic instability, amorphous, hydrogen, softening

1 INTRODUCTION

Hydrogen-Induced Amorphization (HIA) is a phase transformation from crystalline to amorphous induced by hydrogenation. HIA is a potential method for preparing amorphous alloys since hydrogenation and dehydrogenation can be done easily and rapidly. In addition, HIA has a close relation with the structural change of hydrogen-storage alloys which determines their performance [1]. For effective materials design using HIA, it is important to understand the atomistic mechanism of this process. For this purpose, computer simulation is a powerful tool.

Aoki et al. [2] studied HIA of C15 Laves phase AB₂ compounds experimentally. They reported that the relative atomic size is the controlling factor of the occurrence of HIA. HIA does not occur when the ratio of the Goldschmidt radii of A and B atoms, R_A / R_B, is less than 1.37 (A = rare earth, B = Al). In this ratio, the internuclear distances between both AA and BB atoms contract compared to those in the pure crystals [2]. On the other hand, HIA occurs when the ratio is larger than 1.37 (A = rare earth, B = Fe, Co, Ni). In this ratio, the AA internuclear distance contracts and BB internuclear distance expands. Thus it is known that the size effect is essential. Our goal is to reveal the role of

the size effect at the trigger of HIA [2-5].

2 METHOD

2.1 Model

YAl₂ and CeNi₂ were modeled. YAl₂ is a non-HIA material and CeNi₂ is a HIA material. We used pair-wise Lennard-Jones (L-J) 12-6 potential to reveal the size effect. For different species pairs, the geometric combination rule was used. As for hydrogen, only repulsion was taken into account [4]. By the analysis of the equation of state using our potential, it is known that *both the YY and AAl internuclear distances contract in YAl₂, while CeCe internuclear distance contracts and NiNi internuclear distance expands in CeNi₂*. This corresponds to experimental results reported by Aoki et al. [2]. The ratio R_Y/R_{Al} is 1.27 and R_{Ce}/R_{Ni} is 1.46 in our model. Details of the interatomic potentials are in a reference [2]. We compared non-hydrogenated systems under isotropic tensile load and hydrogenated systems at zero pressure.

2.2 Elastic Stability

We treat homogeneous systems which do not contain any surface or defect. The dynamical stability of homogeneous lattice can be discussed by elastic stability [6]. We calculated elastic constants C^{ijkl} by fluctuation formula [7] from microcanonical molecular dynamics data.

$$C^{ijkl} = -\frac{\Omega_0}{kT} \delta(P^{ij}P^{kl}) + \frac{2MkT}{\Omega_0} (\delta^{il}\delta^{jk} + \delta^{ik}\delta^{jl}) + \frac{1}{\Omega_0} \langle \sum_a \sum_{b(>a)} \left(\frac{u''-u'/r_{ab}}{r_{ab}^2} \right) r_{ab}^i r_{ab}^j r_{ab}^k r_{ab}^l \rangle \quad (1)$$

Each term shows the pressure-fluctuation, kinetic and potential contributions, respectively. Ω_0 is the total volume, T the temperature, k the Boltzmann factor and M the number of metal atoms. The superscripts i, j, k and l are the Cartesian indices. P^{ij} is the pressure tensor, $\langle \rangle$ the ensemble average and $\delta(P^{ij}P^{kl})$ the ensemble fluctuation. Note that the summations are taken over the metal atoms excluding hydrogen. By using the elastic constants obtained here, we calculated the elastic stability criteria for cubic symmetry at external pressure P [6].

$$B = \frac{1}{3}(C_{11} + 2C_{12} + P) \quad (2)$$

$$G' = \frac{1}{2}(C_{11} - 2C_{12} - 2P) \quad (3)$$

$$G = 4(C_{44} - P) \quad (4)$$

Here, $P < 0$ for tension. All are finite and positive so that the crystal lattice is elastically stable [6]. The vanishing of the bulk-modulus B is the instability of the lattice decohesion by pure dilation with no symmetry change. The vanishing of the tetragonal shear-modulus G' leads to symmetry breaking (bifurcation) with volume conservation. The vanishing of the rhombohedral shear-modulus G gives a simple shear instability along one of the symmetry directions with volume conservation [6].

3 ELASTIC INSTABILITY BY ISOTROPIC TENSILE LOAD

Figures 1 and 2 show the MD snapshots of the fracture for *non-hydrogenated* YAl_2 and $CeNi_2$ caused by an isotropic tensile load at temperature, $T_s = 0.05$ and 0.06 , respectively. Here the temperature is scaled by the melting one calculated by MD simulation [4]. YAl_2 shows a kind of cleavage-like structural change by decohesion with maintaining the local lattice structure. On the other hand, $CeNi_2$ shows the amorphous-like structural change. By examining snapshots during the amorphization process it can be seen that the trigger of the amorphization is the movement of the expanded Ni atoms rather than the contracted Ce atoms, as also seen in the HIA modeled by the embedded-atom potential [3]. A discontinuous potential-energy decrease is observed [4]. It suggests that the structural change is a kind of mechanical melting and should be distinguishing from solid-liquid melting.

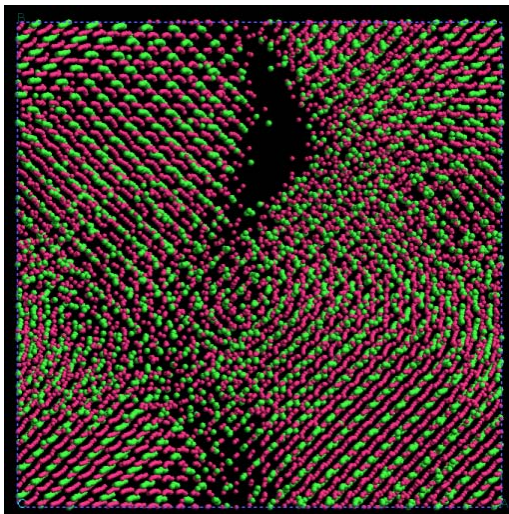


Figure 1: MD result of the cleavage-like structural change by isotropic tensile load for YAl_2 .

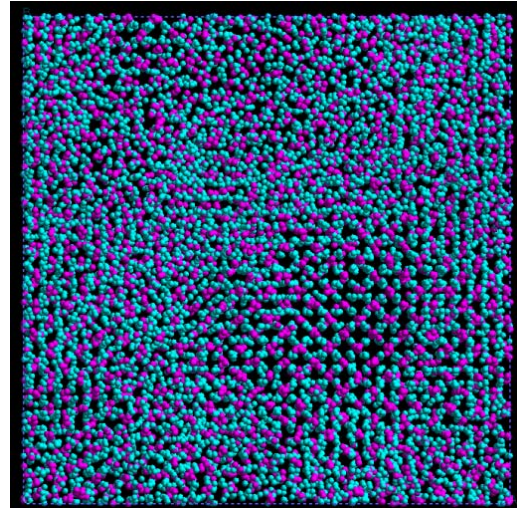


Figure 2: snapshot of the amorphous-like structural change by isotropic tensile load for $CeNi_2$.

4 ELASTIC INSTABILITY BY HYDROGENATION

We consider the elastic response of the lattice to hydrogenation. Figures 3 and 4 show the elastic stability of YAl_2 and $CeNi_2$ by hydrogenation at zero pressure. In the figures, \times denotes the bulk-modulus B -stability in Eqn.2 and $+$ denotes the shear-modulus G' -stability in Eqn.3. For comparison, B and G' -stabilities of non-hydrogenated systems under isotropic tensile load are also shown by \circ and \square , respectively. In $CeNi_2$, the bulk-modulus B is reduced by hydrogenation (denoted by \times), leading to a lattice instability: Unlike B , G' does not soften. The elastic constants C_{11} and C_{12} decrease with hydrogenation, but for G' which is the difference between C_{11} and C_{12} (Eqn.3), the softenings are canceled. In YAl_2 , we did not observe any evidence of such a softening effect. We found that hydrogenation and isotropic tensile loading gave similar elastic stability changes. This suggests that hydrogenation simply causes a volume expansion, and the softening due to the volume expansion is observed. On the other hand, the softening by hydrogenation in $CeNi_2$ is caused by the negative increase of the pressure-fluctuation term in the elastic constant. The softening in a simple volume expansion of $CeNi_2$ is caused by the decrease of the potential term in the elastic constant as in Eqn.1. Such a softening by volume expansion needs a large expansion to reach the elastic instability for amorphization. However, amorphization by hydrogenation occurs at a lower volume. The reason for the reduction in the pressure-fluctuation term in the fluctuation formula is that metal atoms in the neighborhood of hydrogen deviate locally from their equilibrium positions. Even if such a relaxation is energetically small, the change in the pressure fluctuations is large.

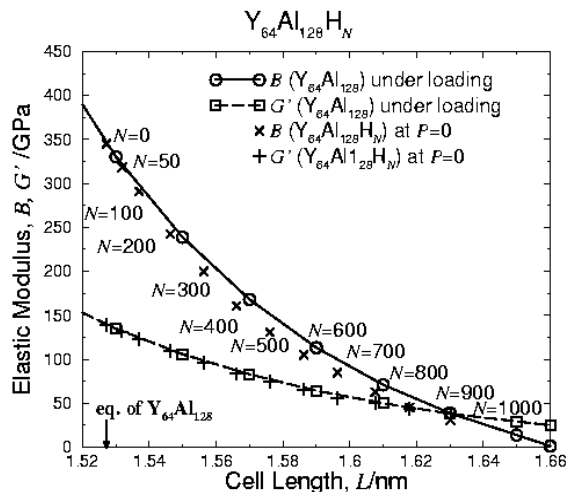


Figure 3: Elastic stability under isotropic tensile loading or by hydrogenation for YAl_2 .

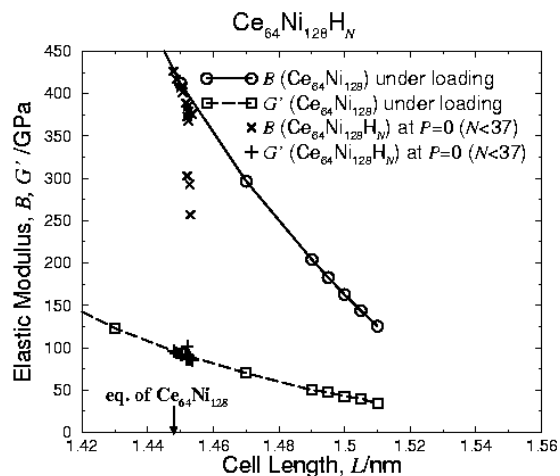


Figure 4: Elastic stability under isotropic tensile loading or by hydrogenation for $CeNi_2$.

5 CONCLUSIONS

Hydrogen-Induced Amorphization (HIA) was simulated by static and molecular dynamics (MD) methods. We compared non-HIA and HIA materials, YAl_2 and $CeNi_2$, respectively. The changes of the elastic stability by the isotropic tensile load and the hydrogenation were calculated.

The fracture process of non-hydrogenated systems by isotropic tensile load was simulated by MD. The lattice fractured at the cell length where the bulk modulus falls to zero. In YAl_2 , the bulk moduli of total lattice and sublattices fall to zero at a similar volume, and a cleavage surface is created. On the other hand, in $CeNi_2$, the bulk modulus of Ni sublattice is relatively small and falls to zero first. The amorphous-like structure is obtained. Such a difference in the mode of fracture is caused by the size effect. Compared to the pure states, Y and Al internuclear

distances contract, while Ce internuclear distances contract and Ni internuclear distances expand in Laves phase. In $CeNi_2$, the bulk-modulus stability of Ni sublattice is low due to the expansion of the internuclear distances and falls to zero first.

We incorporated hydrogen into the systems. YAl_2 did not show HIA. On the other hand, once the amount of hydrogen atoms exceeds a critical value, $CeNi_2$ showed HIA [4]. In YAl_2 , hydrogenation simply increases the volume and the bulk modulus is reduced because of the non-linearity of the interatomic potentials. A similar reduction is observed under an isotropic tensile load. The main cause of the reduction is the potential term in the elastic constant. On the other hand, in $CeNi_2$, hydrogenation greatly reduces the bulk modulus. This reduction is mainly caused by the negative increase of the pressure-fluctuation term in the elastic constant. As a result, hydrogenation leads to the amorphization at a much smaller volume than under a load. The increase of the pressure-fluctuation is the result of the atomic relaxation induced by hydrogenation. In $CeNi_2$, the contraction and expansion are realized simultaneously, and relaxation can occur by hydrogenation. Even if the potential-energy change resulting from the relaxation is small, the change in pressure fluctuation is high.

These features can also be understood by the consideration of the equation of state for these compounds. When the size ratio exceeds 1.37, the bulk-modulus stability of the sublattice of B-atoms becomes low compared to that of A-atoms. However, there is no evidence that the ratio of 1.37 gives the critical ratio for HIA. The stability changes continuously as the ratio increases. This suggests that the mechanism of HIA cannot be understood by simple volume expansion and the atomic relaxations play an important role in it. When the internuclear distances of one sublattice expand and the other contract relative to pure crystals, relaxation occurs.

It is concluded that the role of the size effect in HIA is to allow the atomic relaxation on hydrogenation and to facilitate the elastic instability by the increase of pressure fluctuations. It is necessary to consider the dynamical feature to understand the role of the atomic size ratio in the amorphization. Classical molecular dynamics gives a good example to reveal the role of the size effect from viewpoint of the parameter physics.

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