Combined Strain- and Stress-Induced Phase Transformations and Microstructure Evolution under High Pressure

Valery LEVITAS (Iowa State University, USA)

Abstract

Phase transformations (PTs) under plastic compression and compression and torsion, using metallic or ceramic anvils (which are traditional for high-pressure torsion) or a diamond anvil cell (DAC) and a rotational DAC (RDAC), are referred to as plastic strain-induced PTs under high pressure [1]. They require completely different thermodynamic and kinetic descriptions and experimental characterization than pressure-induced PTs (under hydrostatic loading) and stress-induced PTs (with external stresses below the yield strength). Since strain-induced PTs stop when plastic straining stops, it is generally accepted that their kinetics is determined by plastic strain rather than time; time is not an important parameter [1].

However, recently, the *time dependence of strain-induced PT* in DAC at constant plastic strain was revealed with in situ x-ray diffraction studies on α-ω PT in Zr at room temperature [2]. After nucleation, the high-pressure phase grows over the next hour until reaching a steady state. This was formalized via two similar strain-controlled kinetic equations for the instantaneous and steady-state volume fractions of the high-pressure phase *c*, connected by Arrhenius-type thermally activated growth kinetics.

Also, during torsion in dynamic RDAC of Fe-7%Mn alloy at 1,000 and 1,500 RPM (strain rate up to $2 \cdot 10^3$/s), which causes BCC→HCP PT, the volume fraction of the HCP phase *c* does not change. After torsion stops, *c* increases by 30% within a few minutes after 1,000 RPM and $c \to 0$ after 1,500 RPM [3]. Thus, nuclei of the HCP phase are generated during straining at high strain rate, but growth or disappearance occurs on a few-minute time scale under stress, depending on the local pressure. Crystallite size, microstrain, and dislocation density also continue to evolve after torsion stops.

These results imply that a combined theory of plastic strain- and stress-induced PTs and microstructure evolution under high pressure, accounting for the effect of plastic strain rate, must be developed. Phase-field simulations also show that, after nucleation of a high-pressure phase at the tip of a strain-induced dislocation pileup, high-pressure regions grow and coalesce at a fixed plastic shear [4]. Also, steady state *c* and phase microstructure for almost every interface and for the entire polycrystalline sample are determined by the phase equilibrium criterion for stress-induced PTs, i.e., by stresses or (in the simplest case) applied pressure instead of plastic strains. This suggests an important hint and imposes a strong constraint on the future general theory for combined plastic strain- and stress-induced PTs. In fact, phase-field theory and simulations in [4] are an example of such a theory at the microscale, but macroscale thermodynamic and kinetic approaches, generalizing those in [1], are to be developed.

Independently, plastic straining has a strong effect on both direct and reverse BCC↔HCP PT in Fe-7%Mn alloy, which leads to the simultaneous occurrence of the direct and reverse PTs in the pressure range 3.20 GPa < p < 6.17 GPa. The kinetic equation for strain-induced PTs, which takes into account both direct and reverse PTs, admits a steady solution depending on pressure. It describes well the experimental results for the BCC↔HCP PT in the Fe-7%Mn alloy, which allows the determination of the material parameters in this equation.

References

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