Impact of massive-like ferrite to austenite transformation during and after solidification on microstructure evolution in steels

The peritectic reaction in the Fe–C system is taught as a fundamental transformation mode in undergraduate courses on solidification and casting of metallic alloys. During solidification in peritectic FeC systems with carbon contents of less than 0.5 mass% C, the primary solid phase (ferrite, body-centered cubic) grows as a high-temperature phase and the secondary solid phase (austenite, face-centered cubic) is produced through reaction between ferrite and the remaining liquid phase. As a result of the peritectic reaction, ferrite is covered with austenite. This multiphase solidification model has been accepted for many years.

In solidification and casting processes of steels, the peritectic solidification reaction is key to understanding formation of casting defects, such as unevenness of solidifying shells and hot tears (cracks). Volume change owing to the transformation from ferrite to austenite can contribute to formation of these defects. Thus, the previous studies focused on the mechanism of casting defect formation based on the peritectic transformation. Apart from solidification, the undesirable coarsening of austenite grains has been recognized during subsequent cooling. Until recently, rapid coarsening and peritectic solidification were considered as separate phenomena.

Time-resolved and *in situ* observations of solidification in steels, which were performed at SPring-8 **BL20B2** and **BL20XU**, proved that ferrite could transform massively to austenite in Fe–C peritectic systems (referred to as a massive-like transformation) [1]. The preliminary findings introduced some challenges for further understanding by X-ray imaging techniques: one question was whether the massive-like transformation influences the subsequent microstructure evolution; another is whether the massive-like transformation applies to industrial solidification and casting processes. Progress in understanding of this massive-like transformation was recently reviewed [2].

Figure 1(a) shows a typical setup for transmission imaging with X-ray diffraction (XRD). Transmission images were observed by a beam monitor (pixel size: 1 μm × 1 μm to 5 μm × 5 μm; frame rate: up to 100 fps). XRD images were observed by a panel-type detector to identify the crystal structure. XRD images help to detect a phase transformation, even though the Bragg condition is rarely satisfied because of the highly coherent and monochromatized X-rays of these beamlines. Figure 1(b) shows a time-resolved tomography (4D-CT) and XRD setup. Projected images for three-dimensional (3D) reconstruction were observed by a beam monitor (pixel size: 6.5 μm × 6.5 μm; typical frame rate for steels: 100 fps). XRD spots were observed by a panel-type detector (pixel size: 100 μm × 100 μm; frame rate: 30 fps). The crystallographic orientation was analyzed from the XRD spot positions and sample rotation angle. The typical temporal resolution was 4 s for steel solidification. This technique was also used to observe the distribution of crystallographic orientations before and after the massive-like transformation.

This transmission imaging showed the impact of the massive-like transformation from ferrite to austenite on subsequent microstructure evolution. Figure 2 shows dendrite arm fragmentation that was induced by the massive-like transformation in Fe–0.45% C–0.6% Mn–0.3% Si alloys [3]. The ferrite dendrites were maintained at approximately 20 K below the peritectic temperature (after 152 s), allowing austenite to thermodynamically nucleate and grow. The massive-like transformation from ferrite to austenite occurred at 346 s. Austenite with a perturbed interface grew rapidly into the liquid phase. Dark spots in the dendrite arms indicate that multiple austenite grains formed within the ferrite dendrite arms. Liquid film formation at austenite grain boundaries was also detected, as indicated by the blue arrows. In addition, the austenite boundaries (liquid film) migrated with a velocity as fast as 1 μm/s. As a result of the liquid film formation and austenite coarsening, the austenite

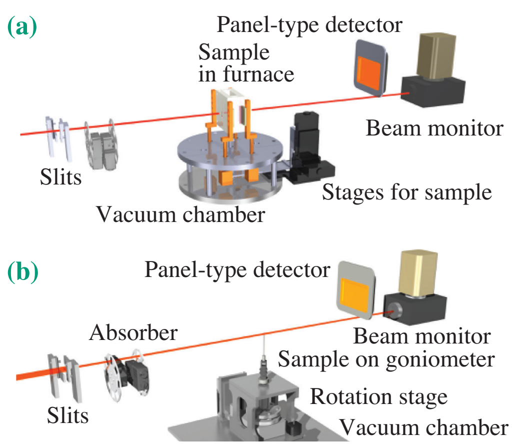

Fig. 1. Typical setups to observe steel solidification and transformation from ferrite to austenite. **(a)** Transmission imaging (2D observation) with X-ray diffraction and **(b)** time-resolved tomography (3D+time observation, 4D-CT) with X-ray diffraction.

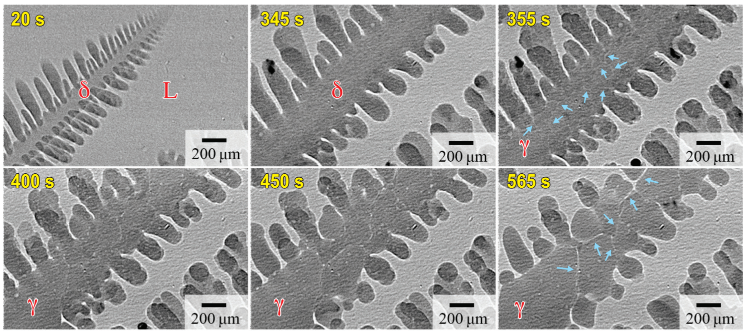

Fig. 2. Fragmentation of γ grains induced by massive-like δ–γ transformation in 0.45 C steel (0.45 C, 0.6 Mn, 0.3 Si in mass%) [3]. Transformation occurred at 20 K below the peritectic temperature after 152 s. Liquid film produced at γ grain boundaries indicated by blue arrows. The X-ray energy and exposure time were 21 keV and 50 ms, respectively.

grains were isolated by the liquid phase, as shown in the image at 565 s. These observations demonstrated that solidified dendrites could be remelted and fragmented by the massive-like transformation. The multiple austenite grains produced by the massive-like transformation consequently influence formation of the subsequent microstructure.

From industrial considerations, it was critical to confirm whether ferrite massively transformed into austenite or austenite grew in the diffusion-controlled mode. Time-resolved and *in situ* observation using transmission imaging was performed to observe the microstructure evolution during unidirectional solidification [4]. The massive-like transformation was selected at a growth rate of as low as 50 μm/s. The peritectic reaction, which was controlled by atomic diffusion, only occurred at growth velocities of less than 10 μm/s. Growth velocities in industrial processes exceed 10 μm/s, so the massive-like transformation is expected to be selected for conventional processes.

Time-resolved XRD measurements using the 4D-CT setup were performed to observe austenite coarsening [5]. Fine austenite grains, in which strains were induced, were produced in a ferrite grain through the massive-like transformation. After the transformation, the austenite grains coarsened and/or vanished. Simultaneously, the induced strains were released and new γ grains were even created. Grain formation during coarsening cannot be simply explained by typical coarsening controlled by the curvature effect: the massive-like transformation should be included to understand the coarsening kinetics in subsequent cooling after solidification.

Figure 3 shows a schematic illustration of possible transformation modes from ferrite to austenite in Fe–C alloys. As proved by recent studies [1–5], the massive-like transformation—rather than the peritectic reaction—occurs in conventional solidification processes. However, this transformation mode has not, to date, been explicitly included in modeling of solidification and casting defect formation. This will be critical for improving our understanding of the transformation and casting defect formation from an industrial perspective.

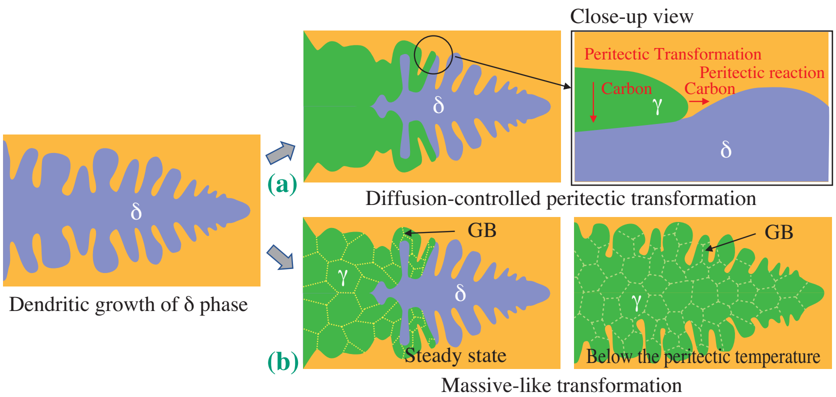

Fig. 3. Possible of transformation modes in peritectic Fe–C alloy systems [2]. **(a)** Diffusion-controlled peritectic transformation and **(b)** massive-like transformation. X-ray imaging studies in SPring-8 proved that the latter mode is selected in conventional processes.

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References

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