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Validity of in-situ observations in welding for designing the weld microstructure

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Summary

The validity of in-situ observations in welding is presented by outlining the observation results in real and reciprocal lattice space. Those techniques were useful for identifying the morphological change of microstructure and phases in thermal cycle of welding. Especially, it is valid for microstructure design to track the nucleation site in phase transformation and non-equilibrium phase.

Introduction

The weld consists of two parts: weld metal and Heat Affected Zone (HAZ). In arc and laser welding, the heat source melts the material. Then, the microstructure of weld metal is formed through solidification and subsequent phase transformation, under the rapid cooling cycle. It is well understood that the microstructures in the HAZ are formed through solid-state phase transformation when the welds are heated under melting temperature and cooled to room temperature.

For controlling the weld microstructures to improve the mechanical properties, it is essential to understand the microstructure formation along characteristic thermal cycle for the interested part. In order to analyze and understand the microstructure developments during welding, it is valid to observe the microstructure formation in-situ. For example, in the case of weld metal of low-carbon steel in fusion welding, delta-ferrite crystallized as a primary phase in high temperature and play the important role for the weldability. However, it may disappear in room temperature due to solidification process and/or subsequent solid-state transformation. Furthermore, in the non-thermal equilibrium conditions, gamma-austenite may crystallize as a primary phase instead of delta-ferrite depending on the interface temperature [1]. The martensite phase is also typical non-equilibrium phase, which play the important role in high-strength steel weld. For tracking the formation behavior of those high temperature and non-equilibrium phases, direct observation is vital.

In the present work, "in-situ observation techniques" for the welding developed in our research group are outlined. In the direct lattice space, High-temperature laser scanning system is applied to the direct observation of the microstructure formation of weld. In the reciprocal lattice space, in-situ observation system is also applied. The application of "in-situ observation techniques" for the weld of steels and titanium are outlined as examples of observation results and its validity for the design of weld microstructure is presented.

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In-situ observation techniques in welding

If the microstructure change in the thermal cycle of weld is observed by using optical microscopy, thermal radiation makes the observation impossible around 1500 degrees centigrade. Our HLSCM system consists of infrared image furnace and Laser Scanning Confocal Microscopy. The schematic illustration of optical system of HLSCM is shown in Fig. 1. For the observation, laser beam is scanned on the specimen at a high-rate. High heating-rate is achieved by using infrared image furnace and the temperature control is very precise. Helium-Neon laser is introduced to the objective lens and the surface of sample is scanned. The reflected beam is introduced to the detector through the objective lens and the two-dimensional images are formed due to the scanning. In confocal microscopy, only the reflected beam at the focused focal point is detected through a pinhole in front of the detector as shown in Fig. 1. Furthermore, the brightness of laser provides excellent S/N ratio (signal to noise ratio). Thus, it is useful for images of microstructure to be observed at a high temperature range. The specimen is heated in a furnace and is observed through a observation window made of quartz glass, by using a long-focus objective lens. In order to observe metal specimens, the surface should be kept clean during the observation. For example, oxidation of the metal surface prevents the observation, and a reducing atmosphere should be kept in the furnace.

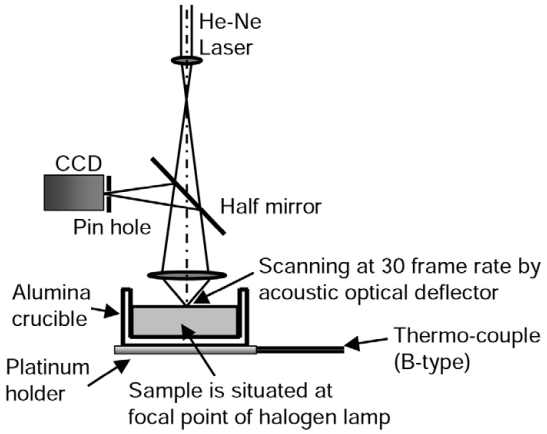

Figure 1: Schematic illustration of HLSCM system

With HLSCM system, direct identification of crystal structure is impossible. For the identification of crystal structure, X-ray diffraction experiments are suitable. However, the photon number of X-ray in house is not enough to observe the welding phenomena in real time. In other words, the time-resolution for identifying the crystal structure should be very short in order to observe the microstructure change during welding processes in real-time. Synchrotron radiation source

(Spring-8) was applied to defeat the problem. The ultra-bright beam (undulator beam) was used as a probe to observe the welding phenomena in real time. The photon energy of 18 KeV was chosen by using mirror and Si crystals. The GTA welding system was assembled with the multi-axis gonometer in the beam line (46XU). The experimental set up is shown in Fig. 2. The incident beam irradiated fixed area on the welding line. The welding arc crossed the irradiated area in constant welding speed and the corresponding diffraction patterns were recorded on the two-dimensional pixel detector [2] in time resolution of 0.02 seconds. Then, phase changes in the thermal cycle of GTA welding were in-situ recorded. The scattering geometry for the experiments is shown in Fig. 2. The slit size was 0.1 mm*0.5 mm and the irradiated area resulted in 0.288 mm^2. The penetration depth of X-ray can be calculated by using the linear absorption coefficient [3], angle with the surface of steel plate made by incident beam and angle with the surface of steel plate made by diffracted beam []. The penetration depth of X-ray resulted in 16.91 μm. Thus, observation volume of current experimental setup resulted in 5.29*10^{-12} m^3.

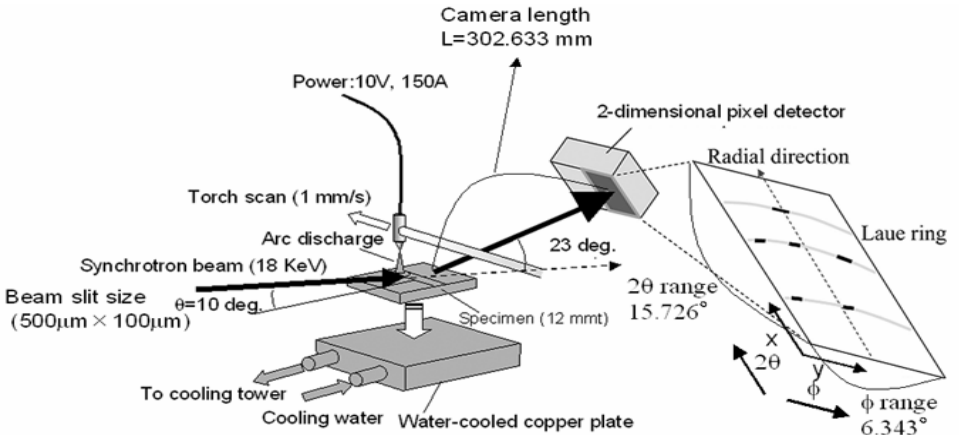

Figure 2: Schematic illustration of in-situ observation system in welding

Results and discussion

The HSLCM is suitable for the observation of (1) the nucleation site of phase transformation (2) the non-equilibrium phase. Observing them is valid for understanding the microstructure formation and designing it. Three examples are presented as follows. Figure 3 shows perlite precipitation in eutectoid carbon steel (0.81 mass%), during the continuous-cooling process which simulates GTA welding at a heat input of 1500 J/ mm. Triple point for the grain-boundary of austenite is observed in Fig. 3 (a) and it became the origin of the phase precipitation as shown in Fig. 3 (b)-(c). It is well-known that the triple points of grain boundary has lower nucleation barrier than that of simple grain boundary. On the other hand, for steels

in low carbon -Ti-B system, the nucleation site of acicular ferrite is oxide within austenite grain. Figure 4 shows the nucleation and growth of acicular observed by HLSCM. The grain boundary of austenite is well suppressed by the segregation of boron element and the grain size of austenite is large due to high heat input of welding. Thus the oxide within austenite grain become nucleation site of acicular ferrite in cooling thermal cycle. As shown these example, the nucleation site in phase transformation could be directly confirmed by using HLSCM. Figure 5 shows martensite transformation in eutectoid carbon steel (0.81 mass%). The cooling rate of welding is so rapid that the atoms (Fe, C) could not jump in low temperature. It means that the diffusional transformation mechanism does not work in low temperature. Thus, the austenite phase is retained until martensite start (Ms) temperature (Fig. 5 (a)). At Ms temperature, the phase stores enough energy to transform in displacive manner as shown in Fig. 5 (b)-(d). The non-equilibrium phase due to rapid cooling welding could be also observed in-situ by using HLSCM.

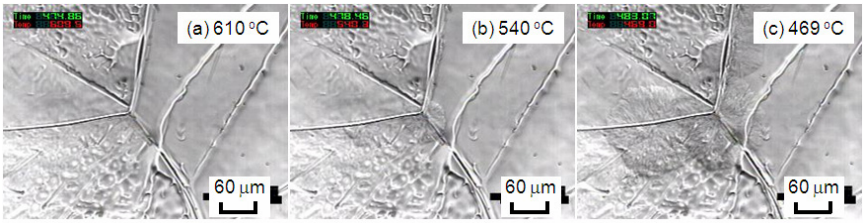

Figure 3: Perlite precipitation at the triple point and grain boundary of austenite

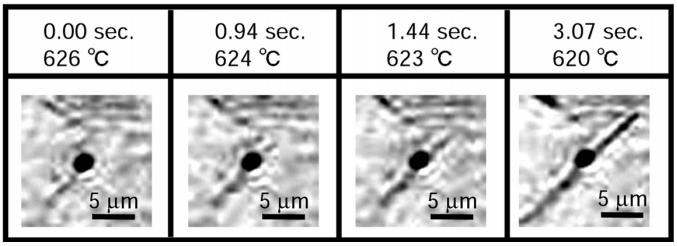

Figure 4: Acicular ferrite nucleated from oxide within austenite grain

As an example of observation of the phase evolution during welding by using synchrotron radiation, the diffractions pattern corresponding to solidification process of 13CrNiMo steel weld was presented in Fig. 6. The origin of torch position was set to where the welding torch is just on the irradiated area of X-ray (0 mm). At +1.39 mm (just after the 0.14 seconds from the primary delta-phase), γ-200 reflection was detected and there were three phase: δ-ferrite, γ-austenite and liquid phase (halo pattern), as shown in Fig. 6 (a). From +1.43 mm to +1.66 mm, the δ200 reflection and halo pattern disappeared and the solidification is finished

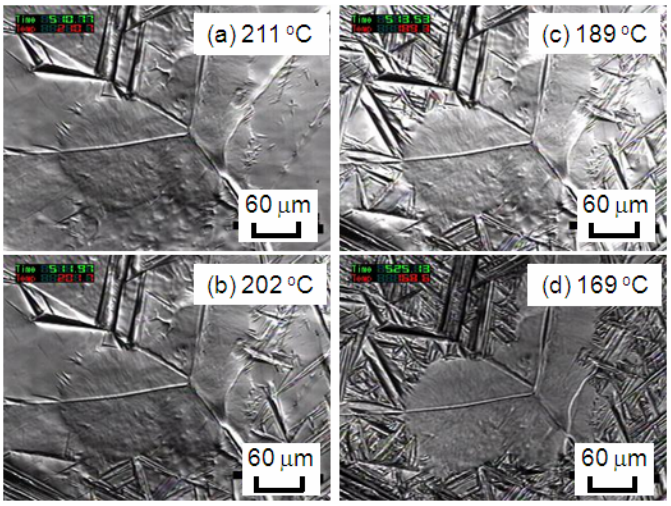

Figure 5: in-situ obseravation of martensite transformation

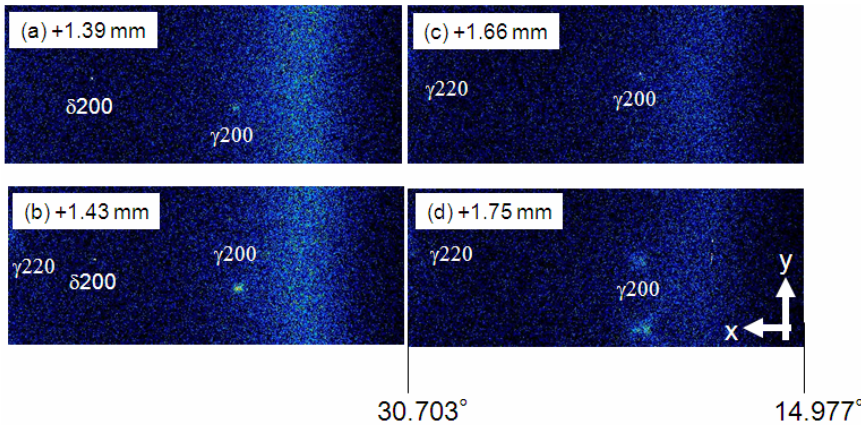

Figure 6: Diffraction pattern for peritectic reaction in solidification process of GTA welding

with γ-mono-phase. From these changes of diffraction patterns, it was clear that the austenite phase surround the δ-ferrite phase in peritectic reaction and the solidification finished when all δ-phase transformed to γ-austenite phase. As this example, the phase transformation in high temperature and rapid cooling process could be tracked and analyzed by using in-situ observation system in welding. The solidification process of welding is the entrance of microstructure formation in fusion welding and it governs the weldability and mechanical properties of weld. Thus, this techniques is also valid for the microstructure design of weld and it is effective to use the technique with the HLSCM observation.

Conclusion

An in-situ time resolved X-ray diffraction technique using intense synchrotron radiation compared to the morphological observation in real space was outlined for microstructure changes during welding and subsequence cooling processes. Those techniques have validity for the understanding and analyzing the nucleation site of phase transformation and identifying phase in time-series in high temperature and rapid- cooling conditions and it is useful tools for designing the microstructure of weld by controlloning the chemical composition.

References

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