Nonequilibrium Austenite Solidification in Fe-C-Al-Mn Welds: Results from Time-Resolved X-ray Diffraction Using Synchrotron Radiation.†

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Introduction

Interactions between dissolved oxygen, nitrogen, aluminum and carbon in Fe-C-Al-Mn self-shielded flux cored arc welds leads to complex AlN and Al_2O_3 inclusion formation and columnar δ-ferrite microstructure. Previous work using computational thermodynamic and kinetic models showed that these complex interactions can be described and the microstructure evolution in these welds can be predicted [1, 2]. In addition, the predicted phase stability of δ-ferrite and the absence of a pure austenite phase region in the heat-affected-zone (HAZ) were confirmed earlier with time-resolved X-ray diffraction (TRXRD) using synchrotron radiation [3]. In this work, the effects of rapid weld cooling conditions on the evolution of fusion zone (FZ) microstructure in Fe-C-Al-Mn steel were characterized using TRXRD.

Procedure

A flux-cored arc weld with Fe - 0.22 C - 0.56 Mn - 0.26 Si - 1.77 Al - 0.003 Ti - 0.006 O - 0.064 N (wt.%) composition was deposited as an overlay on a normal C-Mn steel bar. Stationary GTAW (Gas Tungsten Arc Welding) 'spot' welds were made on these weld overlay surfaces by striking an arc on a stationary bar and then terminating this arc after the weld pool had achieved its maximum diameter. During this process, the welding power was maintained constant at 1.9 kW (110 A, 17.5V). The formation of a weld with 9-mm diameter required about 15 s of arc duration. This weld was made to cool rapidly by switching off the arc. In addition, some welds were made to cool more slowly by ramping down the current from 110 A to 0 A in 25 s. In-situ TRXRD measurements were performed during spot welding using the 31-pole wiggler beam line, BL 10-2 at the Stanford Synchrotron Radiation Laboratory with the Stanford Positron-Electron Accumulation Ring operating at an electron energy of 3.0 GeV and an injection current of ~100 mA. The measurements were made at intervals of 0.05 s in both the fusion zone (FZ) and the heat-affected zone (HAZ) regions.

Results and Discussion

One of the TRXRD measurements from the fusion zone region is shown in Fig. 1. The TRXRD results from the HAZ region presented earlier [3] showed the extended phase stability of δ-ferrite and the possibility of δ-ferrite acting as a potential substrate for epitaxial solidification of the fusion zone region. Therefore, the TRXRD measurements of the fusion zone were expected to show only δ-ferrite. However, the measurements (see Fig.1) showed surprising results. After the arc was extinguished, the liquid continued to exist as the only phase for an additional 0.2 s prior to the appearance of the austenite phase as indicated by the fcc (111) peak. This result showed that the austenite is the primary phase to solidify from the melt, which is contrary to the

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thermodynamic and kinetic calculations presented earlier [1]. This observation was verified through additional TRXRD experiments, and is also supported by the observation of fcc (200) and fcc (220) peaks, that are not shown in Fig. 1. The TRXRD results show that continued cooling to low-temperature leads to transformation of this austenite to the low-temperature ferrite form. Optical microscopy confirmed the presence of transformed austenite, i.e. martensite.

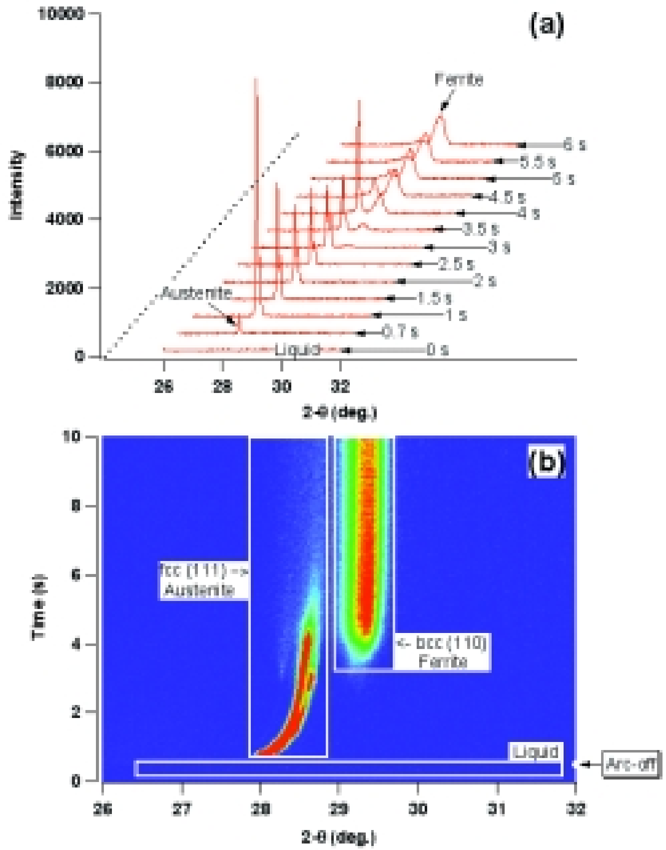

Figure 1. TRXRD results from the FZ as a function of time for various 2-θ positions (*a*) three-dimensional and (*b*) image representation of the data are given. The three-dimensional plots show the relative intensity; the image representation gives the details of the measurements and time resolution. The colors in the image indicate the diffracted beam intensities (red: strong and blue: background).

To evaluate the mechanism for nonequilibrium austenite formation in this stationary spot weld, cooling rates were measured by plunging thermocouples into the weld metal region under identical conditions. The measured cooling rates were of the order of ~1500 Ks^{-1} near the liquidus temperature of this alloy [4], which is 10 to 50 times larger than the cooling rates measured in normal self-shielded flux cored arc welding processes. This higher cooling rate is responsible for the dramatic change in microstructure from primary columnar δ-ferrite at low cooling rates to primary columnar austenite at high cooling rates..

In the second experiment, the weld cooling rate in the spot weld was reduced by ramping down the current from peak value of 110 A to 0 A in 25 s. The TRXRD measurements from the fusion zone region showed the formation of ferrite as shown in Figure. 2. Optical microscopy confirmed the presence of columnar δ-ferrite networks in this weld.

Preliminary calculations using dendrite growth theories using multicomponent thermodynamic models suggest that such transition from equilibrium ferrite to nonequilibrium austenite formation may be due to interaction between carbon and aluminum in these welds.

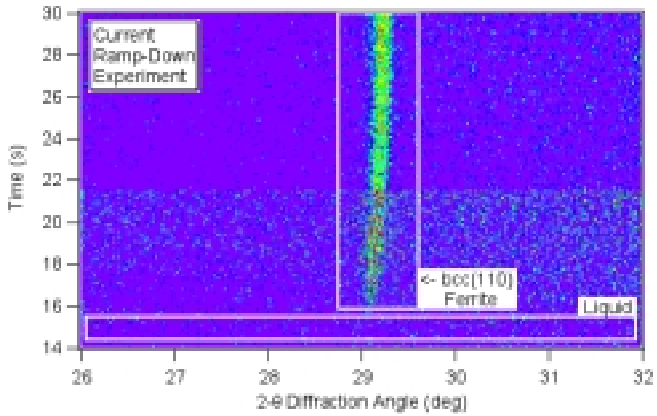

Figure 2. TRXRD results from the FZ as a function of time for various 2-θ positions during current-ramp down experiment. The results show the primary solidification to be ferrite.

Conclusions

Nonequilibrium austenite formation in a Fe-C-Al-Mn weld in an arc-spot weld was monitored using in-situ TRXRD technique with synchrotron radiation. The nonequilibrium austenite formation is contrary to the ferrite solidification that is expected under normal welding conditions. The transition from equilibrium ferrite solidification to austenite solidification was attributed to the high cooling rates in the arc-spot welds. Further experiments with arc-spot welds with current-ramp down showed that on reducing the cooling rate, the primary solidification of the weld to δ-ferrite could be restored.

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