In-situ Observations of Weld Solidification in Fe-C-Al-Mn steels

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Introduction

There is an impetus to apply computational thermodynamic and kinetic models to describe microstructure evolution in welds. However, there is a critical need to evaluate these models under slow and rapid weld cooling conditions. The present research describes ongoing research of in-situ monitoring of phase transformations in Fe-C-Al-Mn welds using Time-resolved X-ray diffraction (TRXRD) technique with Synchrotron radiation. Under normal weld cooling conditions, the Fe-C-Al-Mn steel welds containing 1.7 wt.% aluminum solidify as δ-ferrite [1]. The TRXRD observations confirmed this δ-ferrite solidification mode and this observation is in agreement with equilibrium thermodynamic predictions. However, under rapid weld cooling conditions, nonequilibrium austenite solidification was observed [2]. The calculations using interface response function models showed that the above transition is related to complex interaction between dissolved aluminum and carbon on the relative stability of liquid, δ-ferrite and austenite [3]. In this work, the above effects were investigated further by monitoring the phase selection in Fe-C-Al-Mn welds containing 3.7 wt.% aluminum concentrations.

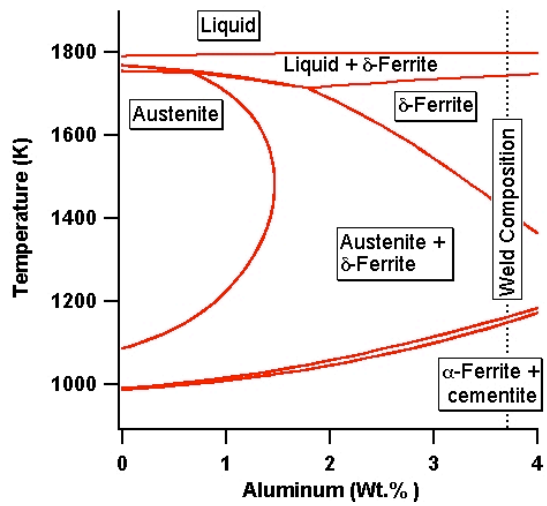

Fig. 1 Calculated Fe-C-Al-Mn quasi-binary diagram showing the present weld composition

Procedure

A flux-cored arc weld with Fe - 0.28 C - 0.45 Mn - 0.39 Si – 3.7 Al - 0.004 Ti - 0.003 O - 0.035 N (wt.%) composition was deposited as an overlay on a normal C-Mn steel bar. The aluminum concentrations in these deposits are higher than that (1.7 wt.%) used in the previous research [1]. 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 or after certain hold time. Similar to previous work rapid and slow cooling rates were achieved by extinction of the arc and slow slope down of welding current, respectively. In addition, experiments were performed to simulate arc-strike phenomenon, by melting and solidifying within one second on the surface of the sample under the tungsten electrode. 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 a time resolution of 0.05 and 0.1 second.

Results and Discussion

A quasi-binary diagram of Fe-C-Al-Mn steel is shown in Fig.1. As per the above diagram, the steel with 3.7 wt.% aluminum should always solidify as δ-ferrite. Both the spot welds with rapid and slow cooling conditions showed conclusively that initial solidification occurs by δ-ferrite formation. However, during the last stages of slope-down experiment, due to the instability of the arc plasma at low current, the arc deviates from the original position below certain welding current. This phenomenon leads to an increase in cooling rate for the remainder of liquid steel. As a result, the liquid/solid interface velocity increases rapidly. Under these conditions, nonequilibrium austenite solidification was again observed. This was confirmed by both TRXRD results as well as optical microscopy. The optical microscopy showed gradual change in δ-ferrite solidification to austenite mode of solidification (see Fig. 2).

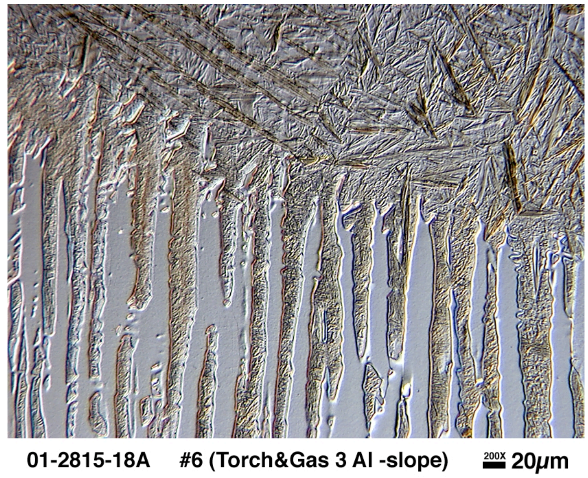

Fig. 2 Optical micrograph showing the transition from δ-ferrite solidification to austenite (transformed to martensite on cooling) solidification with an increase in liquid-solid interface velocity (from bottom to top of the image).

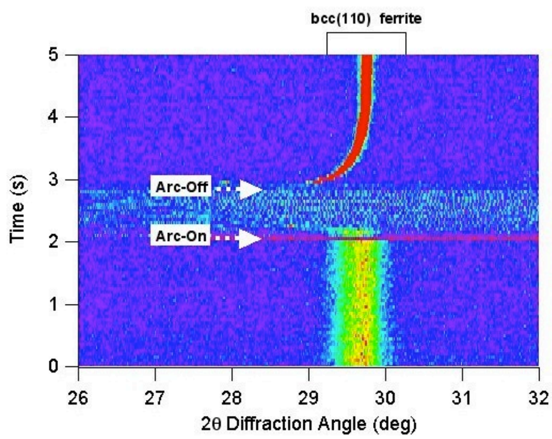

Fig. 3 TRXRD results from arc-strike experiment that shows the rapid melting and emanation of ferrite (BCC) phase.

To evaluate this solidification mode change further, the TRXRD measurements were made during arc-strike experiment. The result is shown in Fig. 3. The plot shows the bcc (110) diffraction from 0 to 2 s. As soon as the arc was struck at 2-s, rapid melting was observed. During the arc-on time for ~1 s, there were no diffraction information indicating the presence of liquid. With the arc extinction, the diffraction measurements show the emanation of bcc (110) peak confirming that the primary mode of solidification in this weld is indeed δ-ferrite. The optical microscopy also confirmed the presence of columnar δ-ferrite. The above results show that the primary mode of solidification is very complex and requires detailed theoretical analysis by coupling interface response function models with numerical heat-transfer models.

Conclusions

Under rapid cooling conditions experienced during GTA spot welding, the Fe - 0.28 C - 0.45 Mn - 0.39 Si – 3.7 Al - 0.004 Ti - 0.003 O - 0.035 N (wt.%) steel solidified as δ-ferrite. This result is in agreement with thermodynamic ad interface response function calculations. However, nonequilibrium solidification to austenite was observed when the interface velocity increased continuously during welding current slope down experiment. Theoretical rationale for these transitions based on nucleation and growth of solid phase from liquid steel will be presented.

Acknowledgements

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