DISCUSSION

G. S. Hartman[1] *(discussion question)*—What were the nitrogen levels in the two production tubesheet forgings?

R. L. Bodnar (author's response)—The nitrogen levels were as shown in Table 1.

In the annealed and PWHT/FC conditions, the nitrogen is tied up as AlN or M_2X (<5 ppm mobile nitrogen were detected). As we discussed in the paper, some of the M_2X carbonitrides dissolve at the PWHT temperature of 727°C, and some of the carbon and nitrogen are trapped interstitially upon air cooling (PWHT/AC). As a result, there is probably more interstitial nitrogen for solid-solution strengthening in the ESR steel in the PWHT/AC condition due to its higher total nitrogen content. This may be the reason for the slightly higher yield strength of the ESR steel compared to the VAR steel in the PWHT/AC condition.

TABLE 1—*Nitrogen levels in production tubesheet forgings.*

Steel	Total N
ESR	120 ppm
VAR	60 ppm

G. S. Hartman (discussion question)—Why did the VAR steel have a slightly coarser ferrite grain size and more bainite compared to the ESR steel?

R. L. Bodnar (author's response)—This is presumably due to the slightly coarser austenite grain size of the VAR. The austenite grain size is controlled by the precipitation of AlN. Since the VAR steel has less total aluminum than the ESR steel (0.004 vs. 0.009%), the VAR steel is expected to have less AlN precipitates, which are less effective for the pinning of austenite grain boundaries. The slightly coarser austenite grain size of the VAR steel enhances hardenability (more bainite) and is responsible for the slightly coarser ferrite grain size of the VAR steel (36 μm versus 24 μm).

G. S. Hartman (discussion question)—Did you attempt to coarsen the austenite grain size of the ESR steel to enhance hardenability, which would hopefully result in a higher yield strength in the PWHT/FC condition?

R. L. Bodnar (author's response)—Yes, although this work is not included in our paper since it is not consistent with our general theme of residual copper in steel. We have found that the yield strength requirement can be met with the ESR steel if it is step-annealed at 1120°C, cooled to 940°C and annealed according to specification. At 1120°C, the AlN precipitates dissolve and the austenite grains can coarsen. Upon cooling from the 940°C annealing temperature at a maximum cooling rate of 56°C/h, up to 48% bainite can form. This additional bainite in the microstructure raises the yield strength to approximately 242 MPa in the PWHT/FC condition. Unfortunately, such a heat treatment was not allowed by the specification.

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