Technical Note: Comment on the Transformation $\delta \rightarrow \gamma$ by a Massive Mechanism in Austenitic Stainless Steel

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A recent paper by Lyman\(^1\) presented experimental results on the delta ferrite and austenite composition of a weld metal of Type 304L stainless steel and proposed a massive transformation in the formation of the duplex microstructure. This type of transformation generally has certain special features.\(^2\) There is no change in the overall composition and no characteristic orientation relationship between the parent and product phases. Most atomic mobility is limited to the interface region, and massive reactions are therefore an example of predominantly interface-controlled reactions involving only localized diffusion.

Lyman's argument was based on the rapid cooling typical of weld metal and the Cr and Ni composition profiles between the delta ferrite regions as determined by STEM high spatial resolution microanalysis. We have studied the transformation $\delta \rightarrow \gamma$ in the welds in which the cooling rate was at least equally as high as in Lyman's experiments\(^3,4\) and have obtained results that show this transformation can be interpreted as being controlled by diffusion.

Mechanism of the Transformation

The mechanism of the transformation can be explained to a certain extent on the basis of the morphology of the retained ferrite, which depends on the composition, and thus on the solidification mode. Welds having a high ratio of the Schaeffler equivalents $(\text{Cr}_{\text{eq}}/\text{Ni}_{\text{eq}} \geq 1.95)$ solidify as single-phase ferrite.\(^5,6\) The austenite nucleates only in the solid state, preferentially at ferrite grain boundaries, and grows into the ferrite by an acicular mechanism during cooling, resulting in a lathy morphology. This transformation must be interpreted as a diffusion-controlled Widmanstätten mechanism,\(^7\) for the microstructure at room temperature (RT) is characterized by straight phase boundaries, distinct orientation relationships between the austenite and ferrite, and partitioning of the substitutative elements.

Lathy ferrite can also be observed in welds with a ratio in the range $1.48 \leq \text{Cr}_{\text{eq}}/\text{Ni}_{\text{eq}} \leq 1.95$, which solidify in a ferritic-austenitic manner.\(^8,9\) The delta ferrite is the leading phase during solidification, and the austenite is formed between ferrite cells or dendrites through a three-phase reaction between liquid, ferrite, and austenite. The main type of retained ferrite, however, and almost the only type at low values of the ratio $\text{Cr}_{\text{eq}}/\text{Ni}_{\text{eq}}$ is the vermicular one, as a consequence of an equiaxial transformation.\(^10\) This transformation begins at a point closer to the liquidus temperature than does the decomposition of the ferrite by the Widmanstätten mechanism in welds solidifying as single-phase ferrite. Consequently, there is all the more reason to claim that it is controlled by diffusion, and that it is not massive in character.

The weld studied by Lyman was a typical example of those in which the delta ferrite has mainly been transformed to austenite by the equiaxial mechanism. The weld thus exhibited a vermicular morphology, as can also be inferred from photomicrographs and from its composition $(\text{Cr}_{\text{eq}}/\text{Ni}_{\text{eq}} = 1.8)$.

Distribution of Alloying Elements

According to Lyman,\(^1\) the fact that the measured Cr and Ni concentration profiles are consistent with the calculated one confirms the role of the massive reaction. We do not have access to the exact calculations on which the verification of this hypothesis was based, but, to our understanding, it seems that Lyman's treatment took no account of possible homogenization before the formation of austenite.

In spite of the high cooling rate, the diffusion distance in the ferrite is $2\sqrt{\frac{Dt}{1}} \approx 1 \mu m$ for $D = 10^{-5} - 10^{-7} \text{ cm}^2/\text{s}$ and for $t = 1/4 \text{s}$, i.e., of the same order as the thickness of particles of the retained ferrite. It is thus unlikely that such sharp Cr maxima and Ni minima measured from the retained ferrite would exist within ferrite dendrites just below the liquiudus and remain essentially unchanged during cooling, as Lyman presented.\(^1\) Furthermore, the good fit reported in Lyman's paper was achieved using non-relevant distribution coefficients between solid and liquid phases. These values $(1.444$ for Cr and $0.409$ for Ni) deviate markedly from unity, in which case a corresponding treatment of austenitic solidification, which produces more pronounced segregation (and/or less homogenization), would result in much greater differences in composition than observed in either castings\(^7\) or welds.\(^8\)

The exact interpretation of the distribution of alloying elements at RT is a complex one, since this distribution is affected by segregation, homogenization, and partitioning during the phase transformation $\delta \rightarrow \gamma$. We would assert, however, that the concentration profiles presented in Lyman's paper can be explained qualitatively on the basis of the model used by Fredriksson\(^9\) in his theoretical approach to directional solidification in austenitic stainless steels. The composition of the delta ferrite in the weld metal at RT (25 wt-% Cr and 5 wt-% Ni) is, in fact, quite similar to that determined in ingots solidifying in the ferritic-austenitic manner.\(^7,8\) Also, the ratios of Cr...
and Ni in the dendritic ferrite to those in the adjacent austenite (i.e., the partition ratios) calculated on the basis of Lyman’s results are also of the same order as in ingots. These facts reveal an attractive similarity between concentration profiles in welds and ingots.

**Effect of Cooling Rate**

The above discussion does not exclude the possibility of a massive reaction. We have carried out experiments in which small steel specimens of Type 304 (Cr$_{eq}$/Ni$_{eq}$ = 1.8) were annealed at subsolidus temperatures in a purified argon atmosphere and cooled (or quenched) at variable rates. The annealing produced a temperature and time-dependent delta ferrite fraction which then decomposed during cooling or quenching. The mechanism of this transformation was studied by light microscopy and to a lesser extent by TEM and EPMA.

The slowest cooling, i.e., with the furnace (dT/dt < 0.5 °C/s) produced a microstructure that contained more or less distinct rod-like ferrite particles. At moderate cooling rates (air cooling, quenching in oil and in salt water) the mechanism of the transformation was acicular (independently of the cooling rate), resulting in a lathy morphology of the retained ferrite (Fig. 1a and 1b). This microstructure was characterized by partitioning of the substitutional elements (Fig. 1), and also by distinct orientation relationships between the austenite and ferrite, thus resembling the structure found in welds solidifying as single-phase ferrite.

The most rapid rates of cooling, i.e., quenching to liquid tin bath (dT/dt > > 100 °C/s) resulted in a entirely different microstructure, however, with no magnetic ferrite present, but with austenite of two different compositions (Fig. 1c). It is this transformation, in our opinion, that fulfills the requirements for a massive reaction. Thus, a massive mechanism indeed seems to be possible but is not likely at cooling rates typical of arc welding.

**References**

AN INVITATION TO AUTHORS

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The American Welding Society will hold its 63rd Annual Meeting and 1982 AWS Welding Show in Kansas City, Missouri, during April 26-30. One of the most important events of our 63rd Annual Meeting will be its technical papers program.

It is indeed a pleasure to invite you as Authors to be participants in the technical program of our 63rd Annual Meeting. On this occasion, the Society is offering an opportunity to Authors to bring the results of outstanding work on their part to the attention of our entire membership, the welding industry, and the nation's metalworking industries.

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Sincerely yours,

\[signature\]

Perry J. Rieppel
Acting Executive Director

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