Effect of alloy composition on the transformation kinetics of delta ferrite in type 316 stainless steel weld metal

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SYNOPSIS

The presence of delta-ferrite (2 to 10%) is essential in austenitic stainless steel weld metals to avoid the problem of hot tearing during solidification. However, during elevated temperature service or post-weld heat treatment, the delta-ferrite transforms to various secondary phases. The kinetics of transformation of delta-ferrite depends mainly on the growth kinetics of secondary phases, which in turn is dictated by the alloy composition. In this paper the results of investigations for the transformation kinetics of delta-ferrite conducted on several type 316 stainless steel weld metals of different compositions are given. Based on these data, it is found that the ageing time required to transform a given fraction of ferrite varies directly with "normalized equivalent chromium content" (NECC) of the alloy and that high values of NECC lead to a rapid decay of delta-ferrite.

1. Introduction

Type 316 stainless steel is preferred over type 304 as a major structural material for the Liquid Metal Fast Breeder Reactors due to its superior mechanical properties at elevated temperatures. During the operation of the reactor, the alloy in both the wrought and welded conditions is exposed at elevated temperatures (around 823 K) for long periods. Data on the behaviour of wrought 316 stainless steel are most extensive [1–4] than those concerning the weld metal.

In order to reduce the cracking susceptibility, the chemistry of the weld metal is suitably altered to provide some delta-ferrite (normally between 2 and 10%). However, the presence of delta-ferrite is detrimental under certain conditions : (a) an enhanced attack of the weld metal is seen in certain corrosive media(5,6), and (b) embrittlement result from the precipitation of sigma at high temperatures [7–13]. Though general trends in the behaviour of the weld metal are recognized, very little quantitative information is available on the kinetics of the decomposition of delta-ferrite, the growth of secondary phases and their effect on the corrosion and mechanical properties of the weld metal.

The duplex microstructure of the austenitic stainless steel weld metals is inherently unstable due to the presence of delta-ferrite. A 1323K post-weld heat treatment results in the total reversion of the ferrite to the equilibrium austenite condition; but an intermediate stress relief post-weld heat treatment at 923-1123K leads to the transformation of the ferrite to carbides and intermetallic phases. The rate of delta-ferrite transformation and the nature of the transformation products are determined by the composition of the weld metal and the transformation temperature [14]. It is essential that the kinetics of these reactions are understood and the influence they have on the tensile and impact properties as the transformation proceeds.

The present paper describes the results of an investigation to understand the changes in the transformation kinetics of delta-ferrite with minor variations in the chemical composition of type 316 stainless steel weld metal. An attempt has been made to select a common parameter to rationalize the difference in the rate of delta-ferrite transformation with alloy content.

2. Experimental Procedure

2.1 *Material and Heat Treatment*

Using the tungsten inert gas (TIG) and manual metal arc (MMA) welding processes, five bead-on-plate type of weld pads were prepared by depositing type 316 stainless steel metal on a 25mm thick, 300×100 mm mild steel base plate. The deposits were built up to a size of 300×25×25mm. The stainless steel deposit was sectioned at a distance of approximately 10mm from the mild steel base to reject the deposit which might have been contaminated by dilution from the base plate. The chemical composition of the weld deposits and the welding processes employed are given in Table 1. The five weld pads, differing predominantly in their carbon contents were designated as A,B,C,D, and E. Specimens of size 10×10×3mm were machined from the weld pads in a plane parallel to the welding direction and were encapsulated in quartz tubes under an argon atmosphere. The capsules were then aged at 923, 973, 1023 and 1073K for different durations (ranging from 0.05 to 100h) to study the transformation kinetics of delta-ferrite.

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Table 1 : Chemical compositions (wt.%) and welding processes for various weld metals

Sample designation	C	S	P	Cr	Ni	Mo	Mn	Si	Welding process
A	0.015	0.010	0.020	19.10	13.80	2.59	1.75	0.31	TIG
B	0.020	0.008	0.021	19.30	12.94	2.50	1.96	0.86	TIG
C	0.030	0.040	0.050	19.00	11.70	2.90	0.52	0.68	MMA
D	0.052	0.013	0.026	18.80	11.53	2.20	1.25	0.54	MMA
E	0.060	0.010	0.035	18.50	12.10	2.00	1.28	0.55	MMA

2.2 *Measurement of Delta Ferrite*

The delta-ferrite contents of the as-deposited and aged specimens were determined using a Magne-Gage which was calibrated by a no. 3 magnet in accordance with the procedures laid down in AWS standard A 42-74 [15]. During the course of the investigations, the Magne-Gage was calibrated from time to time, but no significant change in the calibration curve was noticed. A template of the specimens marked with grids of 2×2mm size was made to ensure that the delta-ferrite measurements were taken precisely at the same locations after ageing. Twenty five readings were taken on each specimen to arrive at the average value of the Ferrite Number (FN).

3. **Results and discussion**

The results of the present study can be discussed under three headings viz., (a) dissolution of delta-ferrite, (b) influence of precipitation on the dissolution of delta-ferrite, and (c) effect of alloy composition.

3.1 *Dissolution of Delta Ferrite*

The ferrite contents of the weld metals as estimated by Magne-Gage are shown in Table 2. The scatter in the values of the ferrite content was within acceptable limits. The ferrite content values were obtained before and after ageing at various temperatures for different durations. These were converted to "fraction of ferrite transformed" and plotted as a function of the ageing time (Fig.1). The kinetics of delta-ferrite transformation showed a signoidal behaviour for samples A,B and C as shown in Figs. 1 (a) to (c) respectively. The time taken to transform a particular fraction of delta-ferrite increased from samples A to C at any given temperature in the temperature range studied. However, the transformation behaviour of delta-ferrite followed a different trend for samples D and E (Figs. 1 (d) and (e). There was a rapid rate of transformation in the initial stages of ageing which slowed down on further ageing. The change in the transformation kinetics for these two sets of samples is evident from Fig. 1 (e). Though sample E transformed rapidly in the initial stages, longer cumulative time was required to transform delta-ferrite fully as compared to that for sample B.

Table 2 : Delta-Ferrite content of weld metals

Sample designation	Ferrite Number	Range (FN)
A	6.70	6.00—7.56
B	6.20	5.65—6.98
C	8.00	7.47—9.00
D	4.80	4.42—5.51
E	5.20	3.92—6.09

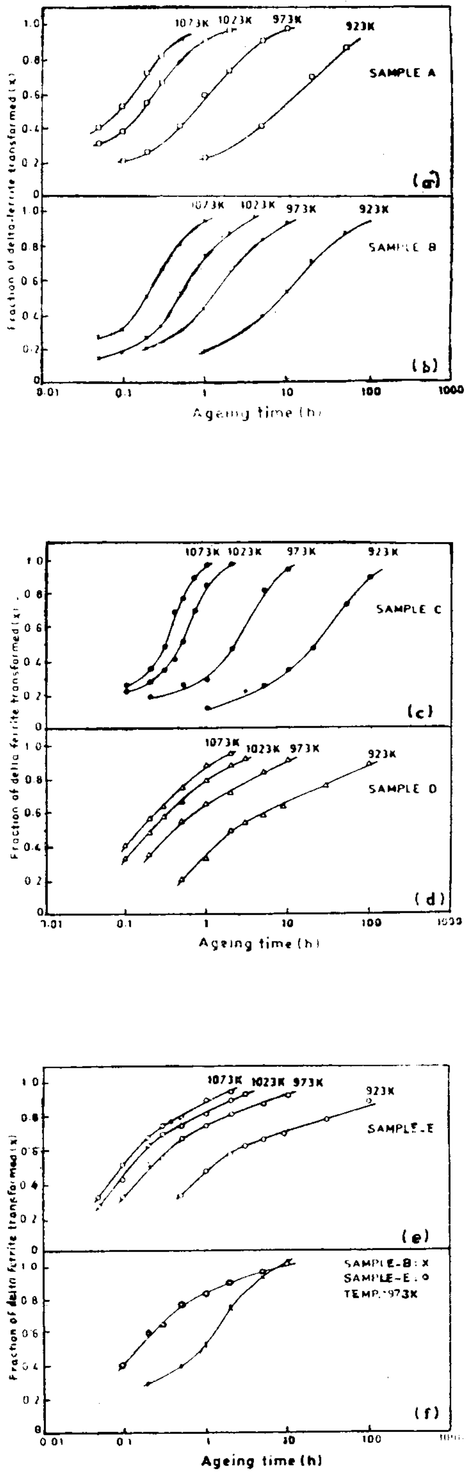

Fig. 1 The rate of delta-ferrite transformation on elevated temperature exposure for (a) Sample A, (b) Sample B (c) Sample C (d) Sample D and (e) Sample E (f) is the comparison between the kinetics of transformation of Sample B and E at 973K.

3.2 *Influence of Precipitation on the Dissolution of Delta-Ferrite*

The microstructural instability of the austenitic stainless steel weld metal can be rationalized on the basis of the relative stabilities of the austenite, ferrite and sigma phases [16], [17]. The behaviour of stainless steel weld deposits can be discussed under two categories namely those with low carbon content (less than 0.03% C) and those with high carbon content (greater than 0.03% C).

When the carbon content is high as in samples D and E, the delta-ferrite becomes depleted in chromium and molybdenum due to the rapid precipitation of carbide at the austenite/ferrite interface and therefore the ferrite composition approaches that of the austenite [10], [14]. The delta-ferrite particles should transform rapidly due to the carbide precipitation. It is reported that the delta-ferrite/austenite interface gradually shifts towards delta-ferrite and the carbides are left behind isolated in the austenite matrix [18]. Such ferrite particles either remain as ferrite or transform to austenite at a much slower rate on further ageing.

On the other hand, when the carbon content is low, as in samples A, B and C, the carbide precipitation at the austenite/ferrite interface is sluggish and the ferrite particles are not significantly depleted of solute elements like chromium and molybdenum. The chemical composition of such particles is very close to that of sigma and only a simple crystallographic change is required for the transformation of the delta-ferrite to sigma [14]. The nucleation and growth of the sigma phase seems to be the controlling mechanism that determines the rate of ferrite transformation in weld metals containing low carbon levels [19]. In the literature, the data pertaining to the kinetics of ferrite transformation have caused considerable controversy. This is not altogether surprising as the transformation kinetics of delta-ferrite depends not only on the alloy composition [14], [20] but also to some extent on the welding parameters [21] which affect the thermal history of the weld metal.

3.3 *Effect of Alloy Composition*

Since carbon level and growth kinetics of sigma influence the transformation kinetics of delta-ferrite significantly, it is essential to characterize the "sigma forming tendency" of the weld metal. Investigations to identify such a parameter have been very successful in the case of wrought stainless steels. Hull [22] investigated the effect of chemical composition on the embrittlement of a number of alloys and found a qualitative relationship between brittleness and the amounts of sigma and Chi phases present in the alloy. He defined an "equivalent chromium content" as

$$\text{Equivalent-chromium}(=)[Cr]+0.31\,[Mn]+1.76\,[Mo]+0.97\,[W]+2.02\,[V]+1.58\,[Si]+2.44\,[Ti]+1.70\,[Nb]+1.22\,[Ta]-0.266\,[Ni]-0.177\,[Co]$$

where [ ] indicates the weight percent of the element.

A high value of "equivalent chromium" indicates a strong tendency on the part of the alloy to form sigma.

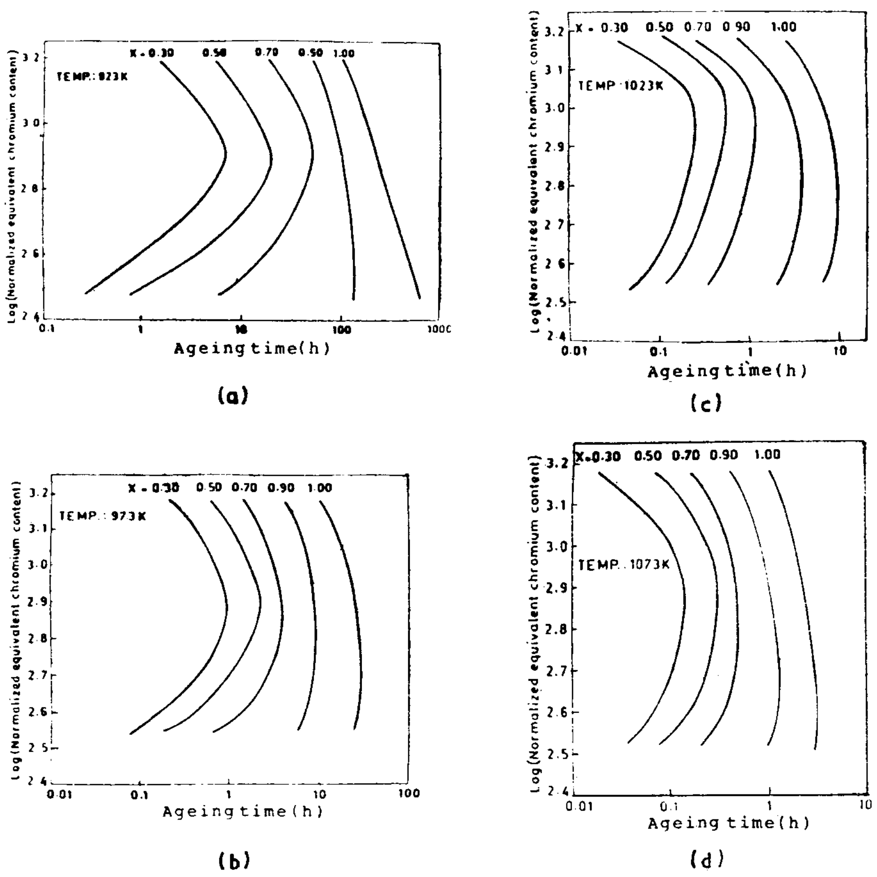

Fig. 2 : Variation of time to transform (X=0.30, 0.50, 0.70, 0.90 and 1.0) fractions of delta-ferrite with normalized chromium content at (a) 923K (b) 974 (c) 1023K and (d) 1073K.

Hull's "equivalent chromium" does not take into account the contribution of interstitial elements, as in his experiments the presence of carbon and nitrogen did not significantly contribute to the embrittlement of the alloys. However, Grott and Spruiell [4] modified Hull's proposal and introduced a concept called "effective equivalent chromium content". The effective equivalent chromium content is essentially Hull's "equivalent chromium content" remaining in the matrix after the precipitation of carbides. It is found that higher carbon contents in the wrought alloy result in more $M_{23}C_6$ precipitates and decrease the "equivalent chromium content" of the matrix (which in turn suppresses the formation of intermetallic compounds). Extending the above arguments to the case of weld metals, the choice of "equivalent chromium content" to characterize the "sigma forming tendency" is found to be reasonable. However, the strong influence of carbon content of the welds on the ferrite transformation kinetics has to be incorporated suitably.

To incorporate the effect of carbon content, the "equivalent chromium content" has been normalized with respect to the carbon content. The "normalized equivalent chromium content" (NECC) for the alloys used in the present investigations was calculated to be 1412, 1122, 741, 417 and 331 for samples A,B,C,D and E respectively. Fig 2 (a) to (d) shows the variation in the ageing time required to transform 0.3, 0.5, 0.7, 0.9 and 1.0 fractions of delta-ferrite at 923, 973, 1023 and 1073K respectively as a function of NECC. It is noticed that the curvature of the curves decreases with increase in the fraction of delta-ferrite transformed.

The time-transformation-alloy content diagrams for the transformation of delta-ferrite can be used to predict the ageing time required to transform various fractions of delta-ferrite in type 316 stainless steel weld metals. Correlation of mechanical property data with different fractions of delta-ferrite transformed may also throw some light on the usefulness of these curves.

4. Conclusions

(a) The transformation kinetics of delta-ferrite depends mainly on the carbon content of the weld metal.

(b) A "normalized equivalent chromium content" parameter can be used to rationalize the changes in the transformation of delta-ferrite with alloy content.

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