

Stabilization of Laves phase by silicon in a heat-resistant steel casting and its effect on creep-rupture life

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Failure of engineering materials to perform their prescribed functions is expected to occur at the weakest link in the inter-related processes of design, fabrication, and service. Therefore, one of the most important requirements of a material selected for a given application is its compatibility with fabrication techniques. Heat-resistant steels based upon the Fe–Cr–Ni systems are used in many structural applications in the petrochemical industry on the basis of their 100 000 creep-rupture strength, e.g., steam reformer pipes [1, 2]. Such steels derive their high-temperature strength from carbide precipitates and solid-solution strengtheners particularly refractory transition metals such as Mo, W, and Nb. To improve their resistance to high-temperature carburization attack, Si is usually added to these alloys in amounts ≥ 1 wt%. Typically, these alloys are processed into casting products due to the lack of sufficient ductility associated with the relatively high carbon content precluding the processing of wrought products. Therefore, to produce the desired length of a pipe, individual sections are joined by welding. It is the objective of this paper to demonstrate that the incompatibility between the composition of a heat-resistant steel (Table I) and fabrication by welding could lead to premature failure because of microstructural instability involving the precipitation of Laves phase in the weld heat-affected zone.

Fig. 1 shows comparative stress-rupture lives at 873 °C of specimens removed from the base metal and weld heat-affected zone. The data were extrapolated from 1000 to 100 000 hrs. As can be seen, the rupture life characteristic of the weld heat-affected zone was about one-third that of the base metal. Microstructural characterization revealed that the heat-affected zone was distinguished by the presence of a massive network of lamellar grain boundary precipitates as demonstrated in the backscattered electron images of Fig. 2a and b. Microchemical analysis showed that the main elemental constituents of the precipitates were Ni, Nb, and Si. In comparison with matrix composition, the precipitates were highly enriched in Si as demonstrated in the energy dispersive X-ray spectra of Fig. 2c and d. An example illustrating the identification of the precipitates by analytical electron microscopy is shown in Fig. 3. The precipitates were characterized by a high density of stacking faults as shown in the bright-field TEM image of Fig. 3a. Electron diffraction patterns derived from the precipitates were consistent with a hexagonal-type phase ($a = 0.481$ nm, $c = 0.783$ nm)

TABLE I Nominal chemical composition of the alloy investigated wt%

Fe	Ni	Cr	Nb	Mo	Co	Si	Mn	C
Balance	31–35	19–22	0.8–1.2	1.3–1.5	1 ^a	0.9–1.2	0.2 ^a	0.09–0.12

^aMaximum.

as demonstrated in the [0001] microdiffraction pattern in the inset of Fig. 3a. Streaking of diffraction maxima along $\langle 1100 \rangle$ directions could be related to stacking faults on the $\{1100\}$ planes. A corresponding energy dispersive spectrum and the results of quantifying the spectral data using the thin-film approximation are shown in Fig. 3b. Combining the results of electron diffraction and microchemical analysis could lead to the conclusion that the precipitates were of a hexagonal Laves phase of the type $\text{Ni}_3\text{Nb}_2\text{Si}$. Although a binary Ni–Nb Laves phase is thermodynamically unstable, it can be stabilized by Si [4]. This could be related to the effect of Si on the average electron concentration. It is known that Laves phases are unstable in binary systems with an average electron concentration equal to or greater than 8 [4]. However, Si could have the effect of shifting the average electron concentration to a lower level stabilizing Laves phases in transition metal systems with Fe, Ni, and Co, which do not ordinarily form binary Laves phases as demonstrated in the present system.

Precipitation of lamellar or cellular precipitates at grain boundaries is known to occur by a discontinuous mechanism involving grain boundary migration. The kinetics of the reaction are rather rapid and therefore, it can occur during relatively slow cooling from a high temperature, e.g., during welding operations. It is well

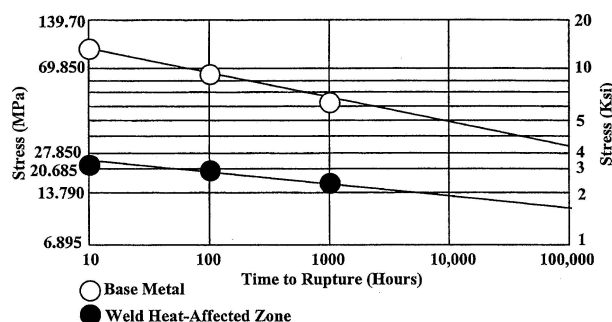


Figure 1 Comparative stress rupture lives at 873 °C.

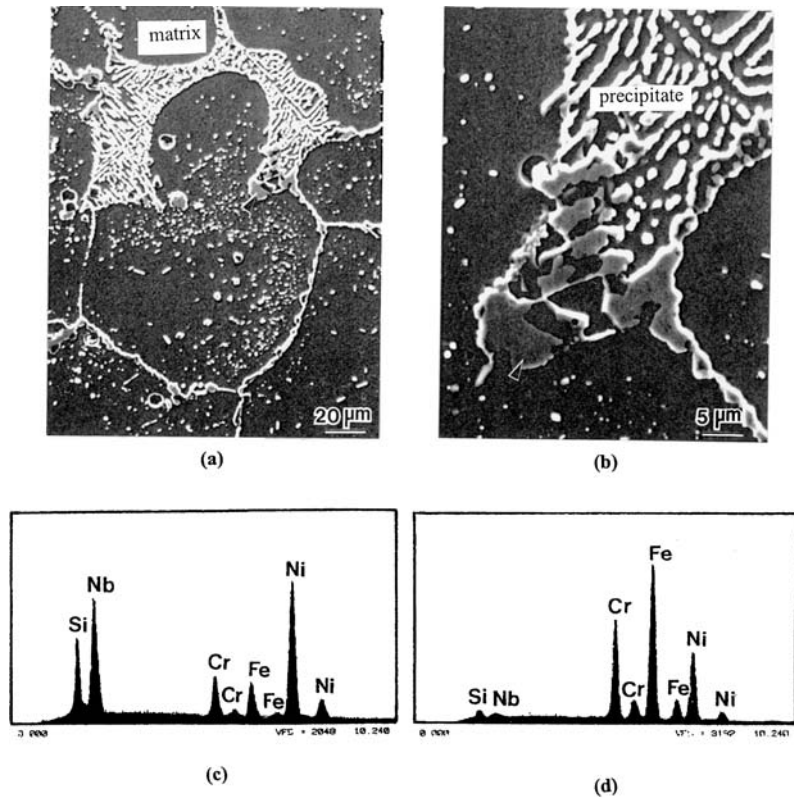


Figure 2 Characteristic microstructural features within the weld heat-affected zone: (a) and (b) are backscattered electron images of the same region viewed at different magnifications and illustrating a high density of lamellar precipitates at grain boundaries. (c) Energy dispersive X-ray spectrum illustrating the elemental composition of the precipitates. (d) Energy dispersive X-ray spectrum illustrating the elemental composition of the matrix phase.

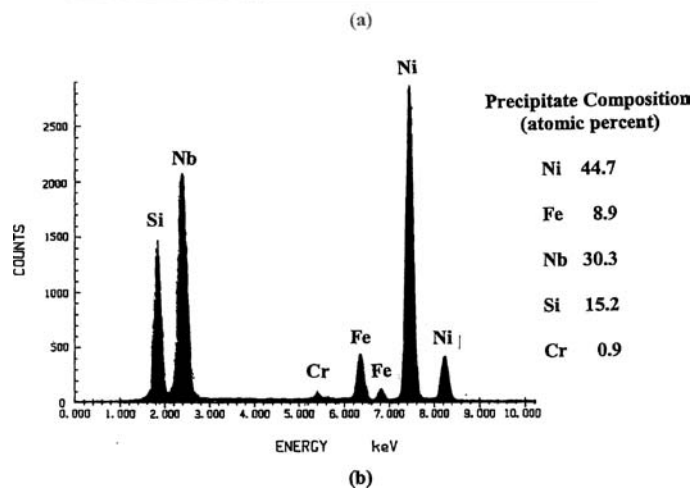
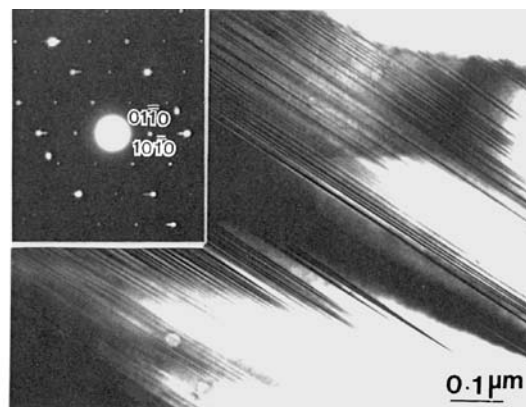


Figure 3 An example illustrating the identification of the grain boundary precipitate by analytical electron microscopy in the TEM mode. (a) Bright-field TEM image of a heavily faulted precipitate particle; the inset is a microdiffraction pattern of the hexagonal Leaves phase in [0001] orientation showing streaks along $\langle 1\bar{1}00 \rangle$ directions due to stacking faults on the $\{1100\}$ planes. (b) Corresponding energy dispersive X-ray spectrum and the results of quantifying the spectral data.

known that precipitation of Laves phase particularly in lamellar morphology at grain boundaries could lead to a considerable embrittlement and loss of rupture ductility [4], which could explain the stress-rupture data of Fig. 1.

References

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