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Larson–Miller correlation for the effect of thermal ageing on the yield strength of a cold worked 15Cr–15Ni–Ti modified austenitic stainless steel

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Abstract

For 20% cold worked 15Cr–15Ni–Ti modified austenitic stainless steel (Alloy D9), the Larson–Miller parameter can be used to describe the effects of prior thermal exposures to different time–temperature combinations on the 0.2% yield stress σ_{YS}, ultimate strength and total elongation in subsequent tensile tests at 300, 723 and 923 K. A single master plot for all the tensile test temperatures was obtained by plotting the Larson–Miller parameter against the ratio $S_{YS}=(\sigma_{YS}$ of thermally aged material)/(σ_{YS} of un-aged material) at identical tensile testing temperature.

Keywords: Ti modified austenitic stainless steel; Cold work; Thermal ageing; Larson–Miller parameter

1. Introduction

The Larson–Miller parameter, $P=T(\log_{10} t+C)$, where T is the absolute temperature, t the time and C a constant, had its origin in the tempering studies of Hollomon and Jaffe [1]. This parameter continues to be widely used for correlation of stress rupture data of various engineering materials [2,3]. The Larson–Miller parametric correlation has also been used for hardness and notch toughness of 2.25Cr–1Mo steel [4], the influence of ageing on the hardness of cold-worked austenitic stainless steel [5] and carbon concentration profiles in Alloy 800H/2.25Cr–1Mo steel joints welded with Inconel 82 consumables [6].

Titanium modified 15Cr–15Ni austenitic stainless steel (Alloy D9) is chosen for the hexagonal wrapper for fuel subassemblies of fast breeder reactors [7]. This material is generally used in a 20% prior cold worked condition, and there is an interest in assessing the influence of elevated temperature service exposure on the tensile deformation behaviour, specifically the 0.2% yield stress σ_{YS}, ultimate strength and total elongation. Vasudevan et al. [8] have extensively studied the recovery and recrystallization behaviour on static thermal ageing 20% cold worked 15Cr–15Ni–2.2Mo–Ti modified austenitic steel with various Ti/C ratios, using optical metallography, and room temperature hardness measurements and tension tests. They showed that recrystallization during prior static ageing leads to drastic decreases in hardness and strength values with corresponding increase in the elongation. The recrystallization temperature was found to be $\sim$973 K, considerably accelerated as ageing temperature increased, and depended on the Ti/C ratio. Metallographic observations [8] indicated the presence of grain boundary precipitates in the thermally aged alloys. In cold worked and thermally aged steel of this type, grain boundary precipitates of the type $M_{23}C_6$ and MC have been reported [9,10]. In this paper, it is shown that the Larson–Miller parameter can be used to describe the effects of static thermal exposure of 20% cold worked Alloy D9 on the subsequent tensile properties at 300, 723 and 923 K.

2. Experimental

The dimensions of the hexagonal wrapper tube are 131.3 mm wide across flat faces and 3.2 mm thickness. The chemical composition (wt%) of the material investigated was C: 0.045, Cr: 13.88, Ni: 15.24, Mo: 2.12, Ti: 0.23, B: 12 ppm, Mn: 2.12, Si: 0.64, Cu: 0.017, As: 0.0019, N: 0.0021, Al: 0.01, Co: 0.007, S: $<$0.005, P: $<$0.005, Nb: $<$0.005, V: $<$0.01, Ta: $<$0.01. The tubes were procured in the 20$\pm$4% cold worked condition. Tensile specimen blanks were cut from the flat faces of the wrapper tube in the axial direction and given an isothermal ageing treatment at a temperature in the range 823–1123 K for various durations up to 10,000 h, and then quenched in water to retain the microstructure developed

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Table 1
Yield strength σ_{YS}[a] of 20% prior cold worked Alloy D9 after thermal ageing

Ageing time (h)	Aged at 823 K			Aged at 923 K			Aged at 1023 K			Aged at 1123 K		
	300 K	723 K	923 K	300 K	723 K	923 K	300 K	723 K	923 K	300 K	723 K	923 K
10	651	623	520	646	553	517	614	473	445	508	402	384
50	707	563	525	720	574	510	588	494	425	399	323	307
100	666	588	491	727	560	545	565	443	416	390	235	197
500	685	543	474	663	517	473	471	368	357	257	200	167
1000	722	547	473	614	473	445	524	401	376	236	163	141
2000	718	562	485	588	494	425	429	323	302	237	161	142
5000	659	529	469	534	422	369	353	290	277	231	179	149
10,000	648	496	469	501	397	370	321	267	235	224	159	142

[a] σ_{YS} values in MPa.

during ageing. In all, 32 ageing conditions (Table 1) were used in this study. Flat tensile specimens having 25 mm gauge length and 4 mm gauge width were machined from the unaged as well as aged blanks.

Isothermal tensile tests were carried out in a universal testing machine at a constant cross head speed of 2 mm/min (nominal strain rate $= 1.33\times10^{-3}\ s^{-1}$). The load and elongation were recorded using the chart drive attached to the machine. The elevated temperature was controlled within ± 2 K over the gauge length using a three zone resistance-heating furnace. Prior cold worked (PCW) and prior cold worked and aged (PCWA) specimens were tested at 300, 723 and 923 K.

3. Results and discussion

The typical true stress strain curves for the aged materials are compared with that of the as received material in Fig. 1. It is observed that particularly higher ageing temperatures and longer durations lead to substantial changes in strength and ductility, reflecting changes in microstructure during static thermal ageing. The average values (from a minimum of two tests) of σ_{YS} of the cold worked material as a function of ageing conditions and test temperature are shown in Table 1. The combined effects of thermal ageing is sought to be expressed using the Larson–Miller parameter

$$P = T_A(\log_{10} t_a + C) \quad (1)$$

where T_A (in K) and t_a (in h), are, respectively, ageing temperature and duration and C, a constant to be determined. Using this parameter, the dependence of σ_{YS} (in MPa) on prior thermal ageing could be expressed using a polynomial of degree 3:

$$\sigma_{YS} = a_0 + a_1P + a_2P^2 + a_3P^3 \quad (2)$$

The degree of the polynomial was fixed as optimal by trial and error. For a fixed value of C, the polynomial coefficients in Eq. (2) were determined from a least squares fit. The value of the constant C was varied to identify the polynomial fit that gave the highest correlation coefficient R. The variations of the correlation coefficient R with the Larson–Miller parameter constant C are shown in Fig. 2. The C value corresponding to the highest correlation coefficient was found to be 13, independent of the tensile test temperature. The optimal values for the constants in Eq. (2) thus determined are shown in Table 2.

The variation of σ_{YS} with P for the three tensile test temperatures is shown in Fig. 3; the firm lines in this figure represent the optimal fits to Eq. (2). As this figure shows, a separate correlation is obtained for each of the tensile test temperatures, although with very similar trends in variation of σ_{YS} with P: initially a slight increase, followed by a rapid decrease, followed by a trend to saturation at large P values.

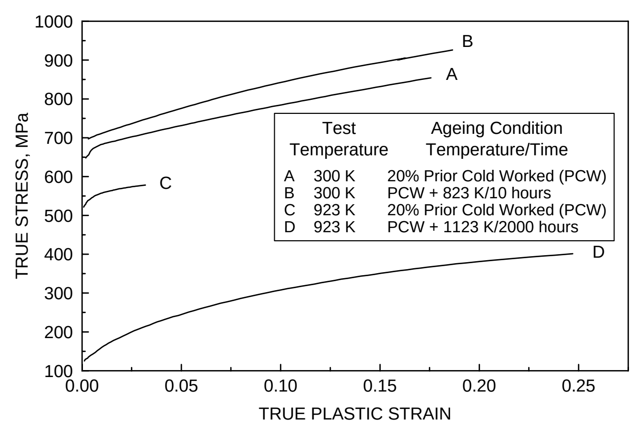

Fig. 1. Typical stress–strain curves of Ti modified austenitic stainless steel in cold worked and subsequent thermal ageing conditions at 300 and 923 K.

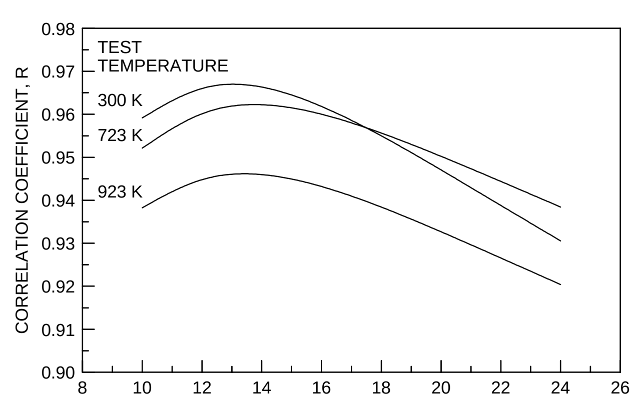

Fig. 2. Variation of correlation coefficient for fit with Eq. (1) as a function of Larson–Miller parameter constant C at various test temperatures.