JMEPEG (2010) 19:558–561
DOI: 10.1007/s11665-009-9515-6 1059-9495/$19.00

Correlation Between Hardness Measurements and Remaining Life Prediction for 2.25Cr-1Mo Steel Used in Power Plants

H.C. Furtado, L.H. de Almeida, J. Dille, and I. Le May

(Submitted April 22, 2009)

The Cr-Mo steels are widely used in the power generation industry for equipment used at high temperatures and remaining in service for long periods of time. Under such conditions, creep is the main cause for premature failure. The evolution of the precipitate carbides and the reduction in Mo concentration in solid solution are the controlling mechanisms responsible for their properties. Estimating damage and the remaining life of power plants or high-temperature pressurized petrochemical equipment has become relatively common. As operating conditions vary considerably over time in such plants, inspection techniques are necessary to estimate the extent of damage, although these may not always provide clear evaluations of remaining life. An alternative assessment method is to use hardness measurements that can be correlated with creep damage and remaining life. In this study, using such a correlation, specimens of 2.25Cr-1Mo steel from accelerated creep tests performed under different conditions of temperature and stress have been examined. The results indicate that the Larson-Miller parameter can be used to correlate the recorded hardness values and so estimate the extent of damage and of remaining life.

Keywords Larson-Miller parameter, remaining life prediction, Vickers hardness, 2.25Cr-1Mo steel

1. Introduction

The most important degradation mechanism of steel in high temperature applications is creep. This phenomenon in Cr-Mo ferritic steels initially involves the coalescence and structural transformation of the precipitated carbide network and, at an advanced stage, results in the formation of voids and microcracks. Life expectancy of components that work at high temperatures is, in most cases, based on the capacity of the material to maintain its creep resistance at high temperature for a period of at least twice the design life. Thus, methods to evaluate the creep resistance of the material based on physical changes taking place, as well as robust methods for data extrapolation are necessary.

Nearly half a century has elapsed since the introduction of time and temperature parameters for the correlation and extrapolation of creep data. The first study was made by Larson and Miller (Ref 1), who introduced the concept of a parametric function to include both stress and temperature as variables. This has the form:

H.C. Furtado, CEPEL, Rio de Janeiro, Brazil; **L.H. de Almeida** and **I. Le May**, COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil; **J. Dille**, Université Libre de Bruxelles, C.P. 194/03, Av. F.D. Roosevelt 50, 1050 Brussels, Belgium; and **I. Le May**, Metallurgical Consulting Services, Saskatoon, Canada. Contact e-mail: lha@ metalmat.ufrj.br.

$$\phi = f(\sigma, t)T(C + \log t) \qquad \text{(Eq 1)}$$

where σ is the stress, t the rupture time, T the absolute temperature, and C is a constant. Larson and Miller developed a method to unify a family of lines showing rupture time as a function of temperature at different stress levels, obtaining a single curve when log (rupture time) is plotted as a function of the Larson-Miller parameter. When this "master curve" is obtained, it can be used to estimate time to rupture at different values of stress and temperature within the limits set by the experimental data. This approach has been used to obtain interpolated values of time to rupture, as well as extrapolated values for times significantly greater than those for which experimental data are available. In order to apply this life estimation method during routine inspection in industrial plants, it is necessary to test extracted samples under conditions of accelerated creep. This procedure requires a considerable period of time, and it can lead to uncertain results.

Hardness measurements can also indicate a material's resistance to deformation and can provide an estimate of the extent of damage in a material exposed to temperature and stress for long periods. Thus, hardness has been used as a simple mechanical, non-destructive test method to estimate loss of mechanical resistance and creep resistance. Although empirical, it can be a useful complement to metallographic methods of evaluation. Efforts have been made to correlate hardness measurements with creep resistance (Ref 2), mainly on low alloy steels such as those used in power plants, where loss of resistance to deformation occurs through morphological changes to carbides present in the steel matrix. Recently, a correlation between hardness and Larson-Miller parameter was obtained for 9Cr-1Mo ferritic steel demonstrating the possibility of estimating the extent of damage based in hardness measurement (Ref 3).

Table 1 Chemical composition of 2.25Cr-1Mo steel (wt.%)

Element:	C	Mn	P	S	Si	Cr	Mo
ASTM A 387-92 (Ref 5)	0.05-0.15	0.30-0.60	0.025 max	0.025 max	0.50 max	1.90-2.60	0.87-1.13
Analysis	0.11	0.51	0.020	0.011	0.34	2.24	0.97

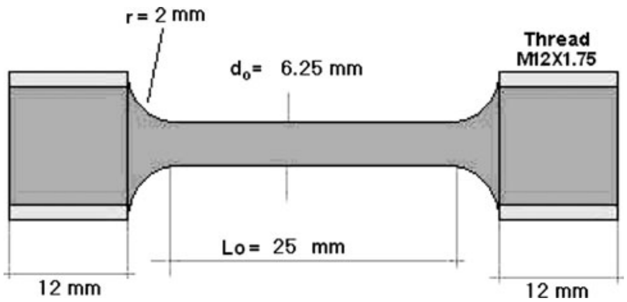

Fig. 1 Reduced conventional test specimen for creep test, 2.25Cr-1Mo

The recovery process for strain-hardened or quench-hardened steel was described in 1943 using the Hollomon-Jaffee parameter (Ref 4), a time-temperature parameter, where hardness was related to the time needed to attain a specific hardness value. Larson and Miller (Ref 1) later used this approach for creep life prediction.

A relationship between the Larson-Miller parameter and the changes in hardness can be developed: if the initial hardness (H_0) at time $t = 0$ is known, the material can be aged at temperature T, then from the values of H obtained at different times, the relation $H = f(P)$ can be determined for the particular material. For field measurements of hardness of components that have been in service for long periods, the effective or main value of temperature to which they were exposed can be estimated if the quantities P and H_0 are known. As in most cases H_0 is unknown, it can be estimated from known data for similar materials. Another application for hardness measurements is to relate them to microstructural observations. Locally degraded regions will have a reduced hardness, and such measurements can supply additional useful indications of the material damage caused by creep.

The aim of this study was to examine the correlation between hardness measured in creep specimens deformed under different conditions and the Larson-Miller parameter. The study was made on 2.25Cr-1Mo steel. Accelerated creep tests were made, and subsequently, the test specimens were analyzed by means of Vickers hardness tests.

2. Materials and Methods

The material studied was 2.25Cr-1Mo ferritic tubular steel, whose chemical analysis is given in Table 1.

Vickers hardness tests were performed at room temperature on the as-received tube and on the post-rupture creep test specimens. Vickers hardness was measured with a WPM Vickers/Brinell machine with a 30-kg load. Hardness tests rather than Vickers microhardness tests were preferred as they have the advantage of acting over a greater area and, consequently, the influence of local effects from heterogeneous carbide distribution in the microstructure is less significant. The hardness impression measurements were taken only in the central part of the creep test specimens.

Table 2 Conditions of creep tests realized on 2.25Cr-1Mo steel tube

	Test temperature, °C						
Stress, MPa	510	524	538	552	566	579	593
100					X	X	X
120		X	X	X	X	X	X
140	X	X	X	X	X		
165	X	X	X				
190	X				X		

Accelerated creep tests were performed on specimens machined from a tube with a 10-mm wall thickness, according to ASTM E8M and NRIM 1986 (Ref 6, 7) as shown in Fig. 1. Table 2 shows the chosen conditions for creep tests on the 2.25Cr-1Mo steel tube. All tests were of creep rupture type.

3. Results

The hardness of the as-received tube was 170 ± 3 HV. This value was within the expected range of the nominal material specification 130-196 HV (Ref 8).

Table 3 presents creep rupture times for different combinations of stress, temperature, and Vickers post-rupture hardness obtained on the reduced-size test specimens.

4. Discussion

When Larson and Miller developed their parameter, they used the value of $C = 20$ because that was the best fitted value for the steel that was studied. Subsequently, this became the commonly used value for Cr-Mo steels, as it is an adequate approximation for most steels that are used at high temperature. However, the use of an optimized C-value for each material results in more accurate predictions.

Extrapolation carried out from creep rupture data using several established parametric methods have shown different degrees of correlation between predicted and experimental rupture times depending on the parametric method used. The analysis of these data demonstrated that the best correlation was obtained using the Larson-Miller parameter with $C = 18.78$ (Ref 9). This value was obtained by optimizing the Manson and Medelson (Ref 10) method of least squares for the experimental data. Figure 2 shows the master curve for Larson-Miller parameter with $C = 18.78$ using the Spera equation (Ref 11),

Table 3 Creep and hardness test results for 2.25Cr-1Mo steel

Stress, MPa	Temperature, °C:	510	524	538	552	566	579	593
100	Time to rupture, h					1547.96	756.24	298.38
	Hardness, HV					135 ± 3	139 ± 4	141 ± 3
120	Time to rupture, h		3276.45	968.56	412.85	226.94	98.25	46.71
	Hardness, HV		136 ± 1	139 ± 4	142 ± 3	142 ± 1	146 ± 3	146 ± 5
140	Time to rupture, h	795.22	389.75	211.84	83.41	26.78		
	Hardness, HV	142 ± 2	142 ± 6	144 ± 2	150 ± 1	158 ± 3		
165	Time to rupture, h	127.55	87.59	35.81				
	Hardness, HV	150 ± 5	151 ± 7	156 ± 4				
190	Time to rupture, h	35.82				1.16		
	Hardness, HV	155 ± 2				165 ± 1		

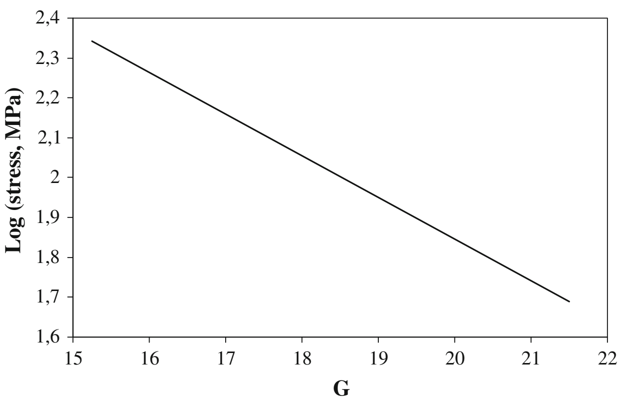

Fig. 2 Master curve for Larson-Miller parameter with $C = 18.78$ using the equation of Spera (Ref 8)

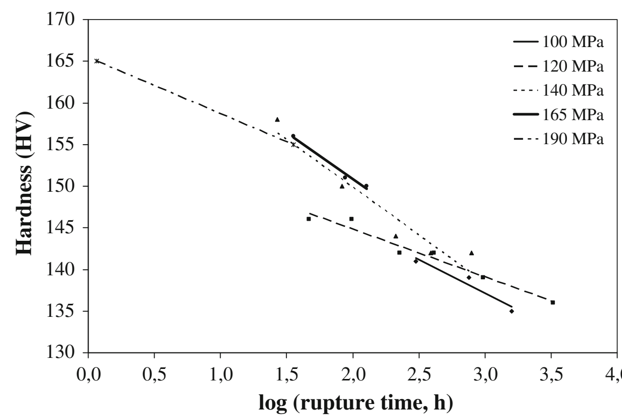

Fig. 4 Isostress lines for the post-rupture hardness of 2.25Cr-1Mo steel tested to rupture at different stress levels

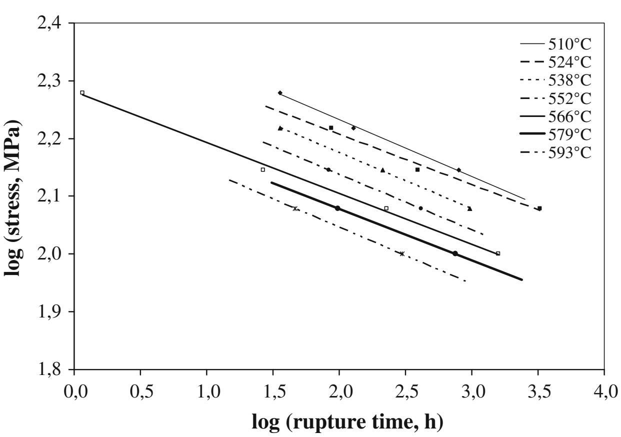

Fig. 3 Logarithmic curves of stress versus rupture time for experimental data based on the Larson-Miller parameter with $C = 18.78$

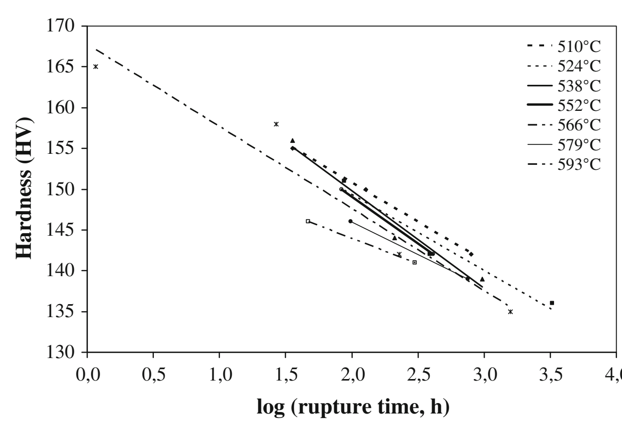

Fig. 5 Isothermal lines of post-rupture hardness for 2.25Cr-1Mo steel tested at different temperatures

as described elsewhere (Ref 9). The horizontal axis is the G parameter, a function of stress, and defined according to Spera (Ref 11) and Manson and Ensign (Ref 12).

Figure 3 presents isothermal plots of time to rupture obtained from the experimental data in Table 3 using the parameter of Larson-Miller with $C = 18.78$.

Hardness clearly decreases as the duration of the creep test increases as seen in Table 3. Figure 4 shows the hardness data of Table 3 plotted as a function of stress and rupture time. The graph shows that for any given rupture time, the higher the stress, the greater the hardness. On the other hand, Fig. 5 shows the hardness data from Table 3 plotted as a function of rupture time and temperature. As can be seen from Fig. 4 and 5, hardness at rupture time is related to three variables: stress, time, and temperature.

As previously discussed, in one of the first studies on time-temperature parameters, performed in 1943 by Hollomon and Jaffee (Ref 4), there was a relation between these two variables and the changes in hardness of quenched steels. Because of the similar dependency between post-rupture hardness and rupture

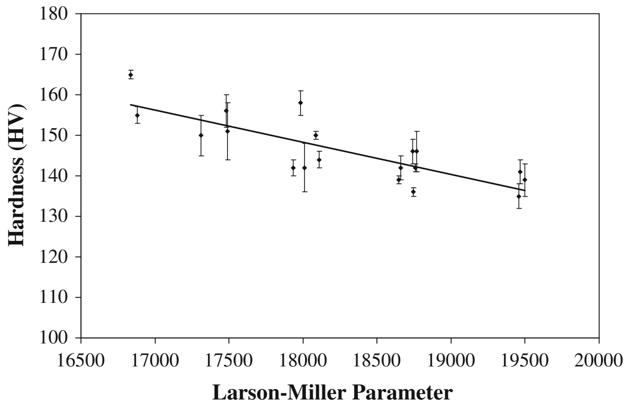

Fig. 6 Graph of post-rupture hardness against the Larson-Miller parameter for 2.25Cr-1Mo steel tested at different stresses and temperatures

time with respect to time and temperature, it should be possible to correlate hardness with creep resistance or to relate the post-rupture hardness with the Larson-Miller parameter for any specific steel. Figure 6 shows the post-rupture hardness plotted against the Larson-Miller parameter for 2.25Cr-1Mo steel. Hardness is reduced when the Larson-Miller parameter increases. This is an expected behavior as the hardness measurement was sensitive enough to be associated with carbide coalescence and with the contribution of solid solution to material strength reduction.

5. Conclusions

From the results and analysis, it can be concluded that:

- There is a similar relationship between hardness of a ruptured creep specimen of 2.25Cr-1Mo steel, time, and temperature as is found in correlating rupture time, stress, and temperature with the Larson-Miller parameter. Thus if the appropriate Larson-Miller parameter for a specific Cr-Mo steel and the operating temperature are known, it should be possible to estimate the extent of damage and remaining life based on hardness measurements.
- The changes of hardness for high temperature units operating with varying load, and temperature cycles can be used to estimate the damage, and remaining life under such conditions.

References

1. F.R. Larson and J. Miller, A Time-Temperature Relationship for Rupture, and Creep Stress, *Trans. ASME*, 1952, **74**, p 765–771
2. W. Kohlhöfer and R.K. Penny, Hardness Testing as a Means for Creep Assessment, *Int. J. Press. Vessel Pip.*, 1996, **66**, p 1–3
3. H.C. Furtado, L.H. de Almeida, and I. Le May, Damage, and Remaining Life Estimation in High Temperature Plant with Variable Operating Conditions, *OMMI Power Plant: Oper. Maint. Mater. Issues*, 2008, **5**, p 1–10
4. J.H. Hollomon and L.D. Jaffee, Time-Temperature Relations in Tempering Steel, *Trans. AIME*, 1943, **162**, p 223–249
5. ASTM A 387-92, "Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum," 1994
6. ASTM E 8M, "Standard Test Methods for Tension Testing of Metallic Materials," 1994
7. NRIM, Data Sheets on Elevated Temperatures Properties of 2,25 Cr-1Mo Steel for Boilers, and Heat Exchanger Seamless Tubes(STBA 24), National Research Institute of Metals, Japan, 1986
8. Key to Steel, http://steel.keytometals.com/Search.aspx?id=RegSearchLM&LN=PT&SessionID=16179252232009163313 2675ETICGZJB90M0O6QS, 2008
9. H.C. Furtado, L.H. de Almeida, I. Le May, and R. Peace, Correlation, and Extrapolation of Creep Rupture Data: A Case Study Using 9Cr-1Mo Steel Data, *Trans. Can. Soc. Mech. Eng.*, 2005, **29**(1), p 1–21
10. S.S. Manson and A. Mendelson, "Optimization of Parametric Constants for Creep-Rupture Data by Means of Least Squares," NASA Memorandum 3-10-59E, 1959, p 1–34
11. D.A. Spera, "A Linear Creep Damage Theory for Thermal Fatigue of Materials", Ph.D. Thesis, University of Wisconsin, 1968
12. S.S. Manson and C.R. Ensign, "A Specialized Model for Analysis of Creep-Rupture Data by the Minimum-Commitment, Station-Function Approach," NASA TM.X-52999, 1971, p 1–14