Fatigue Behavior of X40CrMoV 51 at High Temperatures

Ruhi Yesildal, Sadri Sen, and Irfan Kaymaz

(Submitted 22 April 2002; in revised form 25 November 2002)

The fatigue characteristics of the hot work tool steel X40CrMoV 51 (UNS number T20811) at high temperatures is presented. The temperatures for the experiments were chosen between 50-600 °C. The experiments used B-type cylindrical specimens machined from X40CrMoV in an R.R. Moore rotating bending type fatigue test machine obeying the high cycle principle. The temperature intervals for the experiments were chosen as 50, 100, 200, 300, 400, 500, and 600 °C, for which the fatigue limit for each interval at 2 × 10^6 cycles was determined. The fatigue limit of the material at room temperature (RT) is observed as 432 MPa, whereas it drops to 383 MPa at 400 °C. On the other hand, it stays almost constant between 400-600 °C, indicating that the material includes the elements forming strong carbides such as V, Mo, and Cr, which prevent the decrease of the fatigue limit due to higher temperatures.

Keywords fatigue, high temperature, rotating bending

1. Introduction

Fatigue of mechanical parts can be described as the fracture of mechanical parts under varying loadings. In the past, when a mechanical component was designed, basic knowledge of strength and elasticity was used for considering the condition of use and other effects. However, the fracture of mechanical parts under varying loadings at which they should normally endure showed that those considerations were inadequate.[1] Since most of the loadings of the mechanical parts are dynamic, the effect of fatigue must be included in those calculations.[2] In this condition, time dependent fracture can be classified as creep and fatigue fracture, and only fatigue fracture is considered in this study. As numerous reasons cause fatigue, research on most of them has not yet been completed.[3] One of these is temperature and thus the effect of high temperature is considered in this study.[4,5] Studies on the effect of high temperature are reviewed and brief information is given regarding those studies.[6-8] Since the number of studies on the relationship between high temperature and fatigue are many, we restricted our review to the studies carried out from 1975 onwards, especially for alloyed steels.[9,10]

2. Experimental Studies

The hot work tool steel X40CrMoV 51 was studied in terms of the relationship between high temperature and fatigue, based on both the literature review and recent studies.[5,9] One of the main reasons for the selection of this tool steel is that it is produced to work at high temperatures.[9,10] As can be deduced from its name, high work tool steels are appropriate materials to use in conditions that involve high temperature processes such as forging and extrusion. Fatigue, one of the main reasons for material fracture, has a significant impact in conditions in which mechanical parts operate under constant stress.

Ruhi Yesildal, Sadri Sen, and **Irfan Kaymaz**, Department of Mechanical Engineering, Ataturk University, Erzurum, 25240, Turkey. Contact e-mail: sadrisen@yahoo.com.

2.1 Experiment Specimens

To investigate whether the material supplied has the properties given by the manufacturer, a spectral analysis was carried out for different samples selected from the materials, and the test results are given in Table 1. As seen in the table, the results obtained indicate that the alloy elements and components of the materials supplied are in the range of the elements of the hot work tool steel X40CrMoV 51. The B-type specimen given in the ASTM standard[11] was selected as the experiment specimen and its properties are given in Figure 1. The specimens were machined on a computerized numerical control lathe (CNC) to have the same dimension. They were also ground with silicon carbide paper ranging from 120-1200 mm, and then alumina polishing (0.05 μm of grain size) was applied to the specimens. They were normalized inside a furnace and then cooled in air to remove all stresses left in the materials due to the manufacturing of the specimens that occurred before the experiments.

To study the characteristics and the effects of heat treatments on the mechanical properties of the material supplied, hardness and tensile tests were carried out. It was observed from the results before and after the heat treatment that the heat treatment did not significantly change the mechanical properties of the material as indicated in Table 2.

2.2 Experimental Set-Up

Among the fatigue test machines, rotating bending fatigue test machines have an important place in fatigue tests.[11] In this study, the rotating bending test machine was selected not only because it is widely used in fatigue studies performed in the literature,[12] but also because of the existence of rotation in the working environment of the mechanical parts transmitting loads and moments. By considering those effects and the temperature, the experiments were carried out with an RR Moore (SATEC, Grove City, PA) type rotating bending test machine with the rotation speed of 6000 rpm. There is a closed furnace on the test machine to heat the specimen. The temperature control is maintained by a temperature control unit with a PID

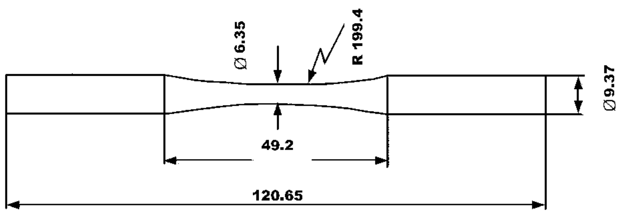

Fig. 1 B type specimen

Table 1 The Spectral Analysis Results of the Material Concerned

Element	%	Element	%	Element	%
C	0.3643	Si	1.06	Mn	0.371
P	0.0216	S	0.0012	Cr	5.55
Mo	1.18	Ni	0.250	Al	0.0329
Co	0.0304	Cu	0.11	Nb	0.00808
Ti	0.00198	V	0.583	W	0.0675
Pb	<0.0020	Sn	0.00960	Sb	<0.00200
Mg	…	Fe			

(Proportional-Integral-Derivative) system, which consists of a thermocouple replaced as close to the specimen as possible but not touching it, and a temperature control unit that controls the thermocouple. A digital display on the test machine shows the number of the rotation and total cycles.

2.3 Carrying Out the Experiments

The system was adjusted before the experiment was started and cooled with air to not only prevent the temperature increases due to the friction of the material during heavy loading from increasing environment temperature, but to protect the parts, such as bearings, sensitive to high temperature. After the system reaches a stationary condition, the loading is applied to the specimen.

The upper and lower load limits were determined first, and then the experiments were performed for seven loading steps. Then the loading was decreased from its maximum value, and this process was continued to the stress level at which the specimen did not break. The experiments were carried out with those seven-stress levels selected for each temperature, which was more intense around the infinite life region. For each stress level, 6-8 experiments were performed. The fatigue life was determined from the results taken from five specimens by eliminating one each of the specimens having the largest and smallest number of fracture. Fatigue limit was determined using the Stair Case method.[1,13].

2.4 Determining the Applied Load

While an experiment is carried out, the usual way is to apply the load calculated and to obtain the corresponding stress on the specimen surface. In this study, the stress applied to the specimen is calculated by the following equation:[14]

$$\sigma = \frac{16WL}{\pi D^3} \qquad \text{(Eq 1)}$$

in which σ is the maximum stress on the specimen surface, *W* shows the total load applied to the specimen, *L* is the distance whose value is constant and 101.6 mm, and *D* is the minimum radius shown in Figure 1. In Eq 1 in which *L* is constant, only the *W* that should be calculated for the stress to be formed for a given radius value is left. The weight of bearing and loading hook should either add to the total weight or subtract from the weight calculated; thus the loading must be applied as the net weight. The value of this constant weight is 14.8 lb (6.7 kg). The other stress values are $\sigma_m = 0$ (alternative loading) and $R = -1^3$.

3. Results

3.1 Fatigue Tests

In Fig. 2-9, the σ-N curves are given for the tests conducted at temperatures of 20, 50, 100, 200, 300, 400, 500, and 600 °C. In the experiments carried out to form the curves, the upper stress value was chosen as much as 80% of the tensile stress considering the principle in the literature, which is stated as "the magnitude of the first loading should be as much as 70-85% of the tensile stress."[2,3] The strength value at the infinite life was determined by conducting the experiments with smaller decreases in loading from the region where the slope of the curve showed a decrease until reaching the number of cycles of 2×10^6. As seen from Wöhler curves, the fatigue limit of this material does not change between 400-600 °C, while it decreases until 400 °C, depending on the increasing temperature. The changes in the value of fatigue limit with the increasing temperature are given in Fig. 10.

3.1.1 Fatigue Test at Room Temperature. To determine the fatigue life of the material concerned, before starting the heating the first experiment was carried out at room temperature (RT). The fatigue limit of the hot work tool steel X40CrMoV 51 at 2×10^6 cycles was found as 432 MPa. The Wöhler curve for this experiment is illustrated in Fig. 2.

3.1.2 Fatigue Test at 50 °C. The first experiment with heating was carried out at 554 MPa loading, and the numbers of cycles to fracture were obtained as being between 3300-10670. Then, the numbers of cycles to fracture were found for the decreasing loading rate, and given in Fig. 3. It was understood that the necessary cooling process must be done to prevent any increase in the system temperature that could disturb the temperature balance. The maximum loading that the material can endure without breaking was obtained as 422 MPa, which is illustrated in Fig. 3. It has been also observed that the decrease of the fatigue limit started at this temperature.

3.1.3 Fatigue Test at 100 °C. In the experiment carried out at high temperatures, the first loading level for the stress levels above 530 MPa was determined as the value lower than the maximum loading due to the excessive deformation due to temperature resulting in excessive heat. Therefore, the loading of 530 MPa was selected as the maximum loading for the temperature of 100 °C and above. In the first experiments at this stress level, the numbers of cycles to fracture were obtained as being between 2250-21000. A Wöhler curve was drawn for this temperature by inserting the numbers of cycles to fracture obtained for the decreasing stress levels into Fig. 4. The maximum loading that the material can endure without

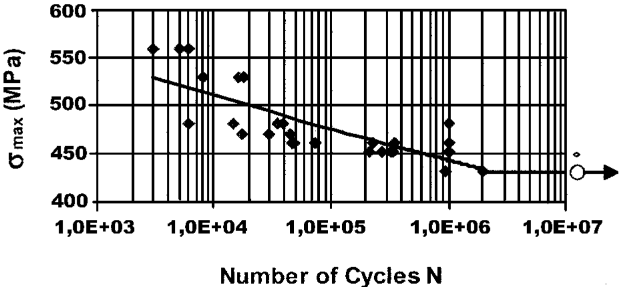

Fig. 2 σ_{max}-N curve for the fatigue test carried out at RT

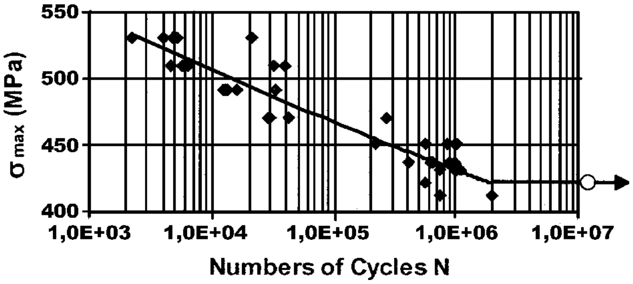

Fig. 4 σ_{max}-N curve for the test performed at 100 °C

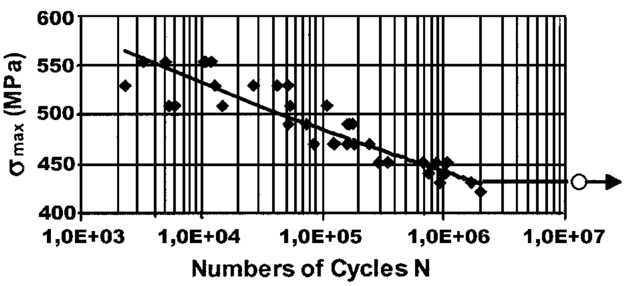

Fig. 3 σ_{max}-N curve for the test performed at 50 °C

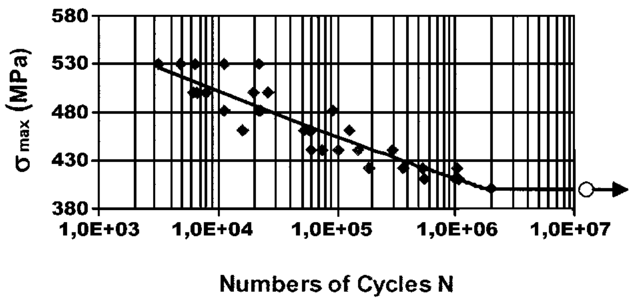

Fig. 5 σ_{max}-N curve for the test performed at 200 °C

Table 2 The Mechanical Properties of the Material Concerned

Heat Treatment	Experiment Number	Diameter, mm	σ_{yield} (Engineering), MPa	$\sigma_{ultimate}$ (Engineering), MPa	% Strain, ϵ	Hardness, HB
Prior to heat treatment	1	5	416	667	27	383
	2(a)	5	423	676	27	329
	3	5	437	688	28	312
	4	5	451	683	28	312
	5	5	432	679	27	333
With heat treatment	1	5	453	710	26	278
	2(a)	5	432	662	27	297
	3	5	453	686	27	314
	4	5	466	705	26	273

(a) Indicates the average value of 11 experiments' results that give very close values

breaking was obtained as 412 MPa in the experiments conducted until 2×10^6 cycles (Fig. 4).

3.1.4 Fatigue Test at 200 °C. For this temperature, the maximum stress level was selected as 530 MPa, and the numbers of cycles to fracture were obtained between 3180-21670 (Fig. 5). The numbers of cycles to fracture increased as the stress level decreased, and the maximum loading at which the material can endure without failure was obtained as 402 MPa.

3.1.5 Fatigue Test at 300 °C. The numbers of cycles to fracture were obtained between 1870-14250 for the stress level of 530 MPa, which was determined as the maximum stress level due to the excessive deformation at high temperatures. The decrease in the numbers of cycles to fracture eventually reached the value of 2×10^6 for the stress level of 392 MPa as the values of stress were decreased (Fig. 6).

3.1.6 Fatigue Test at 400 °C. For this temperature, the maximum stress level was selected as 559 MPa, and the numbers of cycles to fracture were obtained between 2000-6000. The maximum loading at which the material can endure without breaking was obtained as 383 MPa for the temperature of 400 °C at 2×10^6 cycles. The stress-number of cycle curve is given in Fig. 7. The number of the rotation selected for this experiment was 5500 rpm, and it took 6 h to reach 2×10^6 cycles.

3.1.7 Fatigue Test at 500 °C. The first loading for this experiment was applied at the stress level of 530 MPa, and the numbers of cycles to fracture were observed between 2000-6000. The loading level at which the material can endure without breaking at 2×10^6 cycles was determined as 383 MPa by conducting the experiments by decreasing the stress level as it approached the infinite fatigue life. The results are illustrated in Fig. 8. The fractures occurring at the stress level of 373 MPa are due to defects in the material. Those results indicate that there is no decrease in the fatigue limit of the material for the

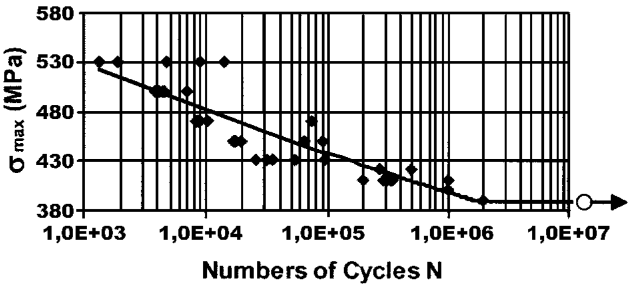

Fig. 6 σ_{max}-N curve for the test performed at 300 °C

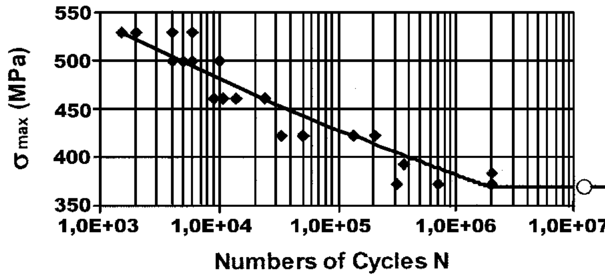

Fig. 8 σ_{max}-N curve for the test performed at 500 °C

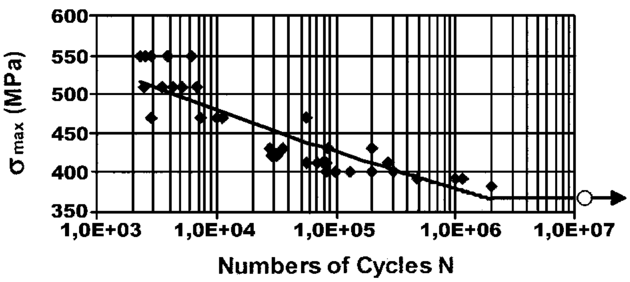

Fig. 7 σ_{max}-N curve for the test performed at 400 °C

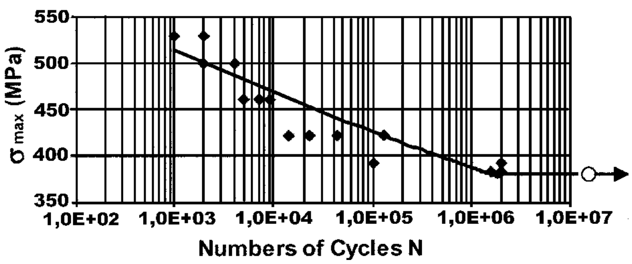

Fig. 9 σ_{max}-N curve for the test performed at 600 °C

temperatures between 400-500 °C at 2 × 10^6 cycles. The period for 2 × 10^6 cycles is about 6 h for 5500 rpm.

3.1.8 Fatigue Test at 600 °C. In the fatigue test at 600 °C, the first loading was selected as 530 MPa, as was done in most of the experiments, and the number of cycles to fracture were observed between 2000-6000. The fatigue limit of this material for 2 × 10^6 cycles was obtained as 383 MPa with the decreasing loading, which was the same result obtained in the tests conducted at 400 and 500 °C. The Wöhler curve is drawn in Fig. 9. In accordance with the experimental results, it can be said that the fatigue life of the material at the stress level of 383 MPa does not show a significant decrease at the temperature levels of 400, 500, and 600 °C. The experiment took 6 h.

When the values of the fatigue limit at 2 × 10^6 cycles are compared for the experiments carried out at the temperatures between RT and 600 °C, it shows a decrease of 50 MPa in the fatigue limit of that material for the temperatures up to 400 °C (Fig. 10). However, this is a decrease of 10 MPa for each 100 °C, which is slightly low. The decrease observed between RT and 400 °C is relatively low. There was no decrease in the fatigue limit of the material at the temperature between 400-600 °C, and it stayed constant at 383 MPa. Figure 10 shows that the fatigue limit of the hot work tool steel X40CrMoV 51 at 2 × 10^6 cycles decreased slightly between RT and 400 °C, but remained constant for the temperatures between 400-600 °C.

4. Discussion

When the values of the fatigue limit at 2 × 10^6 cycles are compared for the experiments carried out at the temperatures between RT and 600 °C (Fig. 10), it showed a decrease of 50 MPa in the fatigue limit of that material for the temperature up to 400 °C. However, it was a decrease of 10 MPa for each 100 °C, which is slightly lower than that of non-alloyed steels.[15] There was not any decrease in the fatigue limit of the material concerned; namely it remained constant at 383 MPa for this temperature level. The variation of the fatigue limit at the temperatures between the RT and 600 °C decreased until the temperature of 400 °C, as was expected,[14-16] but the decrease ceased after that temperature value. The reason is that the material includes the elements forming strong carbides such as V, Mo, and Cr, which prevent the decrease of the fatigue limit due to higher temperatures by forming carbides such as V-C, Mo-C, Fe-Cr-V-Mo, and Cr-C. As seen in Fig. 11, which shows the x-ray spectrum obtained by using an x-ray diffractometer (wavelength-dispersive spectrometry), the sample contains several carbides that explain why the decrease of the fatigue limit ceased at 400 °C.

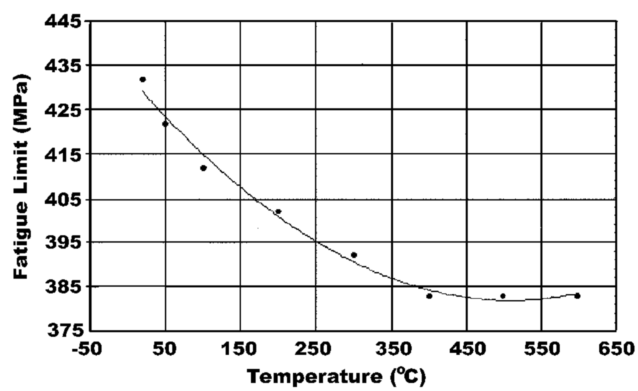

Fig. 10 The variation of the fatigue limit of the hot work tool steel X40CrMoV 51 at the temperatures between RT and 600 °C at 2 × 10^6 cycles

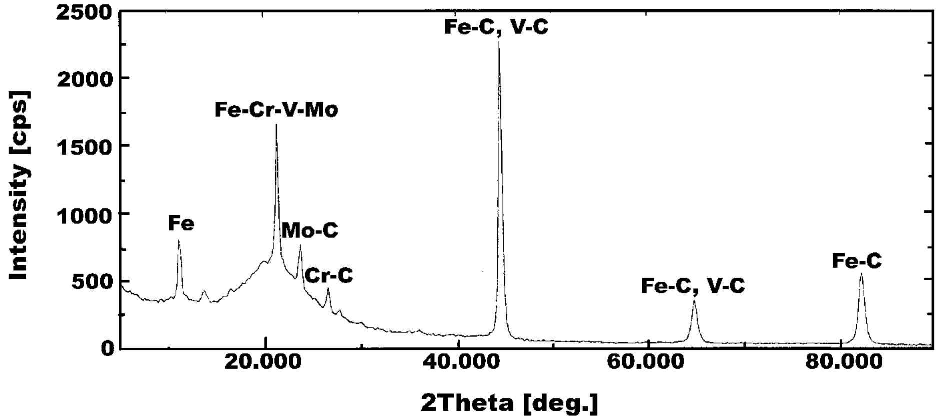

Fig. 11 X-ray photographs of the specimen in the experiment at the temperature of 500 °C

The fatigue limit of the material concerned occurred around the yield strength of that material, even a little higher than the yield strength of that material for the low temperature levels. This is because the yield point and tensile strength obtained by the axial tensile are lower than the yield point and tensile strength obtained by a bending loading. The reason is that the values of yield strength given in Ref. 2 were obtained by axial tensile loadings. In the literature, while the value of the axial tensile strength was 799 MPa and fatigue limit was 338 MPa, the tensile strength and fatigue limit obtained by bending loading was 965 and 489 MPa, respectively. The loading acting on the material in the experiment was a rotating bending loading, and the results were consistent with those in the literature.[2].

5. Results

The following results were obtained from the experiments conducted at the temperatures between RT and 600 °C:

1. The fatigue limit of the hot work tool steel X40CrMoV 51 was found as 432 MPa.
2. The maximum stress level at which the material endures without breaking at 2×10^6 cycles was observed as 422, 412, 402, and 392 MPa, at temperatures of 50, 100, 200, and 300 °C, respectively. These results can be increased by hardening or tempering the steel.
3. The decrease of 50 MPa in the fatigue limit of the material was observed in the experiments performed at 2×10^6 at the temperatures between RT and 400 °C whereas there was no change at the temperatures between 400-600 °C, which was a linear relationship at the stress level of 383 MPa. It can be accepted that the fatigue limit of the hot work tool steel X40CrMoV 51 slightly decreases at the temperatures between RT and 400 °C, but it remains almost constant at the temperature between 400-600 °C.
4. The maximum loading at which the hot work tool steel X40CrMoV 51 can endure without breaking was found at 383 MPa
5. The decrease in the fatigue limit as the temperature decreases is less than that of non-alloyed steels. It can be explained that X40CrMoV 51 includes some elements that strongly form carbides such as Mo, V, and Cr. The carbides formed in the structure prevent the strength of the material at high temperature from decreasing.

References

1. J.A. Collins: *Failure of Materials in Mechanical Design*, John Wiley and Sons, New York, NY, 1981.
2. J.E. Shigley: *Mechanical Engineering Design,* McGraw-Hill, London, UK, 1986.
3. S.H. Avner: *Introduction to Physical Metallurgy,* McGraw-Hill, 1986.
4. M.W. Brown and K.J Miller: "A Biaxial Fatigue Machine for Elevated Temperature Testing," *J. Testing Evaluation,* 1981, *19*(4), pp. 202-08.
5. L.A. Dobrzansk, J. Mazurkewicz, E. Hajduczek, and J. Madejski: "Comparison of the Thermal Fatigue Resistance and Structure of the 47CrMoWVCeZr16-26-8 Hot Work Tool Steel With X40CrMoV5-1 Type One," *J. Mater. Proc. Technol.,* 2001, *113*, pp. 527-38.
6. S.A. Bashu, K. Sing, and M.S. Rawat: "Effect of Heat Treatment on Mechanical Properties and Fracture Behaviour of a 12CrMoV Steel," *Mater. Sci. Eng.,* 1990, *A127,* pp. 7-15.
7. M. Sakane, M. Ohnami, and M. Sawada: "Fracture Modes and Low Cycle Biaxial Fatigue Life at Elevated Temperature," *J. Eng. Mater. Technol., Trans. ASME,* 1987, *109*(7), pp. 236-43.
8. M. Okazaki, T. Yada, and T. Endoh: "Surface Small Crack Growth Behaviour in Low-Cycle Fatigue at Elevated Temperature and Application Limit of Macroscopic Crack Growth Law," *Nucl. Eng. Des.,* 1989, *111*, pp. 123-34.
9. J. Wenping and P. Molian: "Nanocrystalline TiC Powder Alloying and Glazing of H13 Steel Using a CO_2 Laser for Improved Life of Die-Casting Dies," *Surf. Coat. Technol.,* 2001, *135*, pp. 139-51.
10. Q.C. Jiang, J.R. Fang, and Q.F. Guan: "Thermomechanical Fatigue Behaviour of Cr-Ni-Mo Cast Hot Work Die Steel," *Scripta Mater.,* 2001, *45*, pp. 199-204.
11. R.S. Swanson: *Handbook of Fatigue Testing*, ASTM, Philadelphia, PA, 1974, p. 4.
12. S. Preston: "Bending Fatigue Strength of Carburizing Steel SS 2506," *Mater. Sci. Technol.,* 1991, *7*(2), pp. 105-14.
13. M.A.S. Torres and H.I.C. Vodveald: *Int. J. Fatigue* (In press).
14. J. Comer and J. Handrock: *Fundamentals of Metal Fatigue Analysis*, Prentice-Hall Inc., NJ, 1990.
15. F.D. Fischer and F.G. Rammerstorfer: "Fatigue and Fracture of High-Alloyed Steel Specimens Subjected to Purely Thermal Cycling," *Metall. Trans. A*, 1990, *21A*, pp. 935-43.
16. V.S. Srinivasan, R. Sandhya, K.B.S. Rao, S.L. Mannan, and K.S. Raghavan: "Effects of Temperature on the Low Cycle Fatigue Behaviour of Nitrogen Alloyed Type 316L Stainless Steel," *Int. J. Fatigue*, 1991, *13*(6), p. 471.