Fracture 1977, Volume 2, ICF4, Waterloo, Canada, June 19 - 24, 1977

STEEL AND ALLOY THERMAL CYCLING FRACTURE

Y. F. Balandin and A. F. Malygin*

INTRODUCTION

Metal thermal fatigue is one of the basic causes of fracture damage in different equipment. Some investigators [1 - 3] have tried to estimate the strength of structural material and components by thermal cycling with hold periods at creep temperatures, on the basis of isothermal low cycle fatigue tests. However, in most cases this design approach is expected to give errors in fatigue damage assessment due to the particular characteristics of material strain and fracture by thermal cycling.

FATIGUE DAMAGE UNDER THERMAL CYCLING CONDITIONS

The difference in fatigue damage under thermal cycling and at constant temperature results from the temperature dependence of physicomechanical properties and from the strain mechanism. Let us consider some cases where a difference in cyclic strength is inevitable. The relation between number of cycles to failure and strength and ductility has been determined for isothermal low cycle fatigue by Coffin, Manson and Langer [4]. The influence of temperature on strength and ductility varies between materials and therefore it is rather difficult to find a temperature level for isothermal fatigue tests to estimate thermocyclic strength. For example, for carbon and low alloy steels ductility rises with rising temperature, but for Ni-base alloys the reverse situation is observed. As ductility greatly affects isothermal low cycle fatigue resistance of a material, thermocyclic strength estimation at constant temperature (equal to maximum cycle temperature) in the first case will give overestimated values, and in the second case underestimated. The discrepancy between estimated and observed number of cycles to failure may reach 20 times for Ni-base alloys (15Cr-75Ni) at 1073K [5]. In the case of thermal fatigue cyclic life dependence on material ductility is less distinct. For example, the study of 18Cr-10Ni-1Ti stainless steel, tested at $973 \rightleftarrows 373$K, having 4% and 40% elongation and equal ultimate strength by different heat treatments, does not reveal a great difference in thermal fatigue resistance.

The structural heterogeneity of design materials (non-metallic inclusions) may be responsible for additional stresses in thermal cycling which originate from the difference in thermal expansion coefficient and modulus of elasticity of matrix and inclusions. This is evident from thermal fatigue tests of 18Cr-9Ni steel with a nitride inclusion volume fraction of 0.05% and 0.5%. The difference in number of cycles to crack initiation was 50-1000 times, yet in low cycle fatigue tests at 973K it was 2 times.

Wide variations in cumulative damage by isothermal and non-isothermal cycling may take place by creep processes. By thermal cycling creep is increased and grain boundary shear becomes more intensive. It is well

---

*196236 Bassejnaia Street, 117-1-85 Leningrad, U.S.S.R.

known that one-side strain accumulation along grain boundaries is relevant to the material cyclic strength versus time relationship. The greatest shear irreversibility appears by thermal cycling with creep in the maximum temperature range. This comes about by virtue of the difference in material strain mechanism at the highest and lowest cyclic temperatures. In isothermal cycles with equal hold periods in tension and compression grain boundary shears are reversible and a cyclic strength versus time relationship is barely apparent [6]. The intensity of time effects varies at hold periods in tension and compression. In thermal cycling long-term cyclic strength of the material does not depend on the stress direction at hold periods. Quantitatively it may coincide with long-term cyclic strength at constant temperature only in the case of hold periods in tension (Figure 1).

Repeated sharp cooling increases the non-equilibrium vacancy concentration in metal. It favours diffusion and in particular non-metallic phase precipitation. An illustrative example is a correlation of the decarburization of welded medium carbon steel for sharp cooling 923 ⇄ 723K with prolonged exposure time at one of these temperatures and by isothermal cyclic loading. In 250 hour tests decarburization depth in the vicinity of an 18Cr-10Ni-1Ti steel fusion line after thermal cycling was 10 times greater than that at 923K and 100 times greater than at 723K. The above mentioned local decarburization and mechanical properties reduction associated with it lower the cyclic fatigue life of the steel ten times. As another example the degree of nitride precipitation in 18Cr-9Ni steel with 0.1% N_2 was compared by thermal cycling 973 ⇄ 293K and by cyclic loading for 15 hours at 973K. Titanium nitride precipitate volume fraction in thermal cycling was much higher and cyclic fatigue life 1000 times lower than under isothermal conditions. Existing macrodefects in metals may be dangerous to a different extent when isothermal and thermal fatigue processes are compared. In sharp thermal cycling temperature fields distort and defects appear to experience more strain due to loading non-uniformity. This is illustrated by a test of an 18Cr-10Ni-1Ti steel weldment, containing 3 mm diameter pores. The strain concentration factor determined from fatigue curves under thermal cycling conditions was 2 to 2.5, whereas at constant temperature it was only 1.2. Such a difference changes cyclic fatigue life by 10 times. Thermal cyclic loading is characterized by some other factors, for example, unreversible thermal ratchetting [7].

STRUCTURAL MATERIAL THERMAL CYCLIC STRENGTH ESTIMATION

The above mentioned peculiar materials behaviour and failure by thermal cycling necessitates thermal fatigue life assessment on the basis of fatigue tests. The experimental methods employed may be various [8, 9] but in any case it is particularly necessary to determine the value of applied cyclic strain and to provide long hold periods at test temperatures. The load parameters are T_{max}, T_{min} (extreme of cyclic temperature), $\Delta\varepsilon$, t_c (hold period duration in cycle at creep temperature). Crack depth to 0.5 mm is taken as critical. Material thermocyclic strength decrease is most prominent in thermal cycling with a mean creep rate (Figure 2). Thermal fatigue time effects are also associated with annealing and oxidation processes. Oxidation at 1173-1273K reduces by a factor of 10 the cyclic fatigue life of heat resistant alloys. However, in the temperature range of 1273-1373K the detrimental corrosion effect is compensated by the beneficial effect of fatigue flaws annealing.

Long-term thermal fatigue based on a non-linear fatigue and static damage accumulation mechanism by thermal cycling is expressed by

$$N_f = \left(\gamma/\Delta\varepsilon\right)^{\alpha}\cdot\left(t_o/t_c\right)^{\beta}$$

(1

where γ, α, β are thermal fatigue parameters. For low and high cycle fatigue ranges parameters γ and α at T_{max} are estimated from a strain relation which for $N_f < 10^6$ may be approximated by two straight lines. Parameter β which measures the curve slope to time coordinate at T_{max} or T_{min} depends on material type (β_o), cyclic strain level (β_ε) and on hold time duration (β_t). It is determined as

$$\beta = \beta_o\cdot\beta_\varepsilon\cdot\beta_t$$

(2

A change of thermal fatigue time relation from cyclic strain is plotted in Figure 3 and expressed as

$$\beta_\varepsilon = \left(\Delta\varepsilon/\Delta\varepsilon_e\right)^{\omega}\cdot\exp\left[\omega\left(1 - \Delta\varepsilon/\Delta\varepsilon_e\right)\right].$$

(3

In this case $\Delta\varepsilon_e$ is the critical elastic strain range, ω is a material parameter determined from long-time thermal fatigue tests, conducted at hold times of the order of 1 hour. The greatest damage appears when $\Delta\varepsilon \approx \Delta\varepsilon_e$ at the expense of creep strains in long hold periods. When $\Delta\varepsilon < \Delta\varepsilon_e$ creep processes are reduced but at $\Delta\varepsilon > \Delta\varepsilon_e$ they are not changed, however short-term loading damage is increased. Thermal fatigue time effects versus hold periods are a maximum for short hold periods and decrease when cycle hold periods increase. In limiting cases β_t value varie from 1 to 0.5; its intermediate value when $t_f > t_c > t_o$ is defined in the following equation:

$$\beta_t = 1 - \frac{\ell n t_c/t_o}{2\ell n t_f/t_o}\ .$$

(4

When applying equation (1) to thermocyclic strength evaluation of structural components consideration must be given to operation factors. The influence of geometric stress concentration is considered by cyclic strain and elastic concentration factor multiplication. Thermal fatigue estimation for zones of different strength (weldments) should be performed with regard to structure concentration set up by strain redistribution under plastic loading. The thermocyclic strength of materials with structural non-uniformity depends on additional damage produced by variations in matrix and non-metallic inclusion properties. In some thermal cycling processes the conditions for irreversible thermal ratchetting may exist [10]. Thermocyclic strength estimation in ratchetting is based on a linear summation of thermal fatigue and quasi-static damage by using a strain criterion.

Crack propagation kinetics in thermal cycling differ from isothermal cycli processes described by Paris [11]. As the cracks grow in depth K_{IC} value does not increase. Cyclic fatigue life may be approximately expressed as

$$N_a = \left(a + 0.1\right)N_f/0.6.$$

(5

The application of equations (1,5) is bounded by 1173K for Cr-Ni steels and 873K for low alloy steels.

REFERENCES

1. BRINKMAN, C. R., et al., Nucl. Tech., 16, 1972.
2. TAIRA, S., ASTM STP, 520, 1973.
3. SERENSEN, S. V., Mat. of Symp. on Low Cycle Fatigue at High Temperature, 4, Cheljabinsk, 1974.
4. MANSON, S. S., "Thermal Stresses and Low Cycle Fatigue", Mashinostroenie, 1974.
5. GETSOV., L. B., MALYGIN, A. F., et al., Mat. and Structure. Comp. Thermal Fatigue Strength, S.V. Kiev, 1969.
6. BELING, I. T. and CONWAY, I. B., Proc. First International Conference on Pressure Vessel Tech., University of Delft, Holland pt2, 1969.
7. LISENKOV, A. A. and MALYGIN, A. F., Voprosy Sudostroenia, S.Metallovedenie, 21, 1975.
8. BALANDIN, Y. F., Mat. Thermal Fatigue in Power Shipbuilding, Sudostroenie, 1967.
9. COFFIN, L. and WESLEY, R., Trans ASME, 76, N6, 1954.
10. MALYGIN, A. F., Metallovedenie, Sudostroenie, 16, 1972.
11. PARIS, P. C. and ERDOGAN, F., Technicheskaja Mekhanica, S.D., N4, 1963.

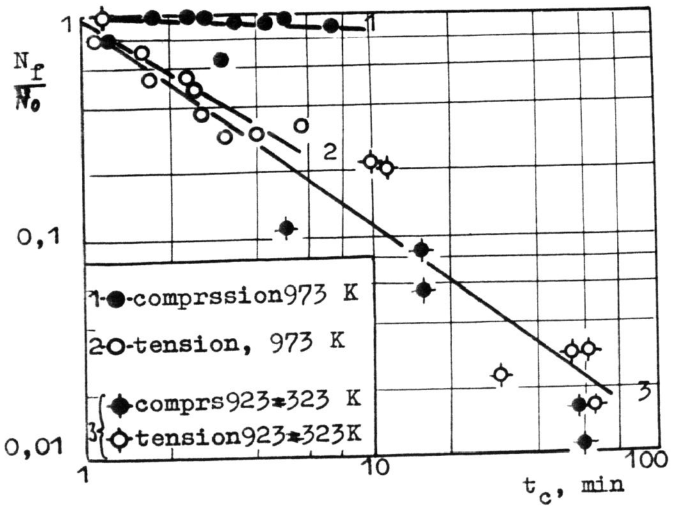

Figure 1 Time Effects of Isothermal (1,2) and Thermal Fatigue (3) of 18Cr-9Ni Steel with Hold Periods in Tension or Compression at T_{max}. (N_0 - Number of Cycles to Failure Without Hold Periods)

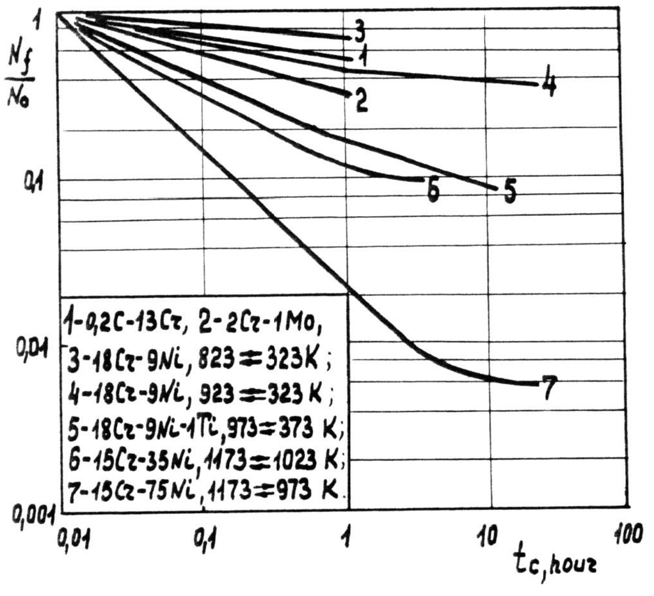

Figure 2 Thermal Fatigue versus Time Relation of Martensitic (1), Pearlitic (2), Austenitic (3 - 6) Steels and Ni-Base Alloys (7) with Hold Periods at T_{max}

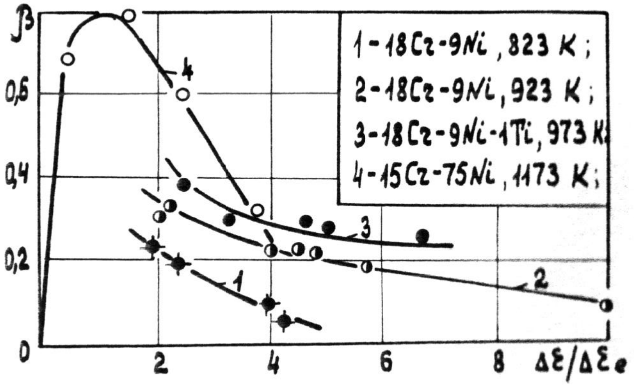

Figure 3 The Cyclic Strain Range Influence on Thermal Fatigue Time Effects Intensity of Austenitic Steels (1 - 3) and Ni-Base Alloys (4) at Creep Temperature