Chapter 17
High-Temperature and Low-Temperature Fatigue

17.1 Introduction

Material properties are dependent on the temperature. The tensile strength, yield strength and modules of elasticity decrease with increasing temperature. It should be expected that fatigue properties are also affected by the temperature. The effect of a high temperature on mechanical properties can be associated with transformations of the material structure due to diffusion processes, aging, dislocation restructuring (softening), and recrystallization. In general, such processes imply that plastic deformation can occur more easily at an elevated temperature. This can lead to the well-known creep phenomenon defined as continued plastic deformation under sustained load. With respect to fatigue, it can imply that more plastic deformation and creep occur in the plastic zone of a fatigue crack which may apply to both microcracks and macrocracks. As a result, fatigue damage accumulation might be enhanced. Furthermore, other failure mechanisms are possible. During creep under sustained load, creep failures occur by grain boundary sliding, void formation (also often at grain boundaries), void growth and coalescence. In general, fatigue is not an intergranular but a transgranular failure mechanism. It thus is not obvious that fatigue and creep damage are simply additive. Actually, the different failure mechanisms of creep and fatigue suggest that a simple addition of damage contributions is physically not realistic. Furthermore, the combined action of cyclic load

and an increased temperature should be expected to be different for different materials and different temperature ranges.

High-temperature fatigue combined with time-dependent temperature variations applies to specific structures. As an example, turbine blades are exposed to high combustion temperatures, high centrifugal forces and vibratory bending loads. In certain cases, the severe conditions of high-temperature fatigue have necessitated the development of new materials. Another aspect of the high-temperature fatigue problem is that the temperature will not be constant. In general, the temperature varies between a high operating temperature and a low non-operational ambient temperature. As a result of the temperature profile, cyclic thermal stresses can be introduced. High-temperature fatigue conditions imply that the fatigue load and temperature vary both as a function of time. In addition to the cyclic load, two more variables are time (t) and temperature (T). It then is easily recognized that the complexity of the problem scenario in practice can be considerable.

In previous chapters, verification tests have been frequently recommended. This is also very much true for high-temperature fatigue problems, but tests with both cyclic loads and cyclic temperature profiles are far from easy. Moreover, realistic high-temperature fatigue tests require that a realistic time scale is adopted which will imply lengthy experiments. Furthermore, also the temperature must be accurately controlled since it has a large effect on creep.

In view of the complexity of the high-temperature fatigue problem and the special materials developed for high-temperature application, the problem is a very special one. Knowledge and experience of the more general problems of fatigue of structures at ambient temperatures have a limited meaning for high-temperature fatigue. Because of the particular nature of the high-temperature fatigue problem, it is briefly covered in this chapter. Two selected case histories are discussed (Section 17.2) followed by some illustrations of temperature effects on fatigue properties in Section 17.3.

Fatigue is also possible in structures operating at temperatures significantly below room temperature, e.g. structures in the open air or sea water. The problem of fatigue at low temperatures is entirely different from fatigue at high temperatures. Trends of low-temperature fatigue are summarized in Section 17.4. Some general comments on temperature effects are made in Section 17.5.

17.2 Two examples of high-temperature fatigue

Turbine blades

The turbine blades of a turbofan engine are exposed to an extreme temperature, at the present time well above 1000°C, and in the order of 70 to 80% of the melting temperature (in °K). High-temperature materials have been developed because a high operating temperature is most important for increasing the efficiency of gas turbine engines.

The blades are cyclically exposed to high centrifugal forces with one cycle corresponding to a single engine run-up and shutdown, which is a low-cycle fatigue condition. Because of the sustained centrifugal force and high working temperature, creep may occur. This obviously occurred to the turbine blade in Figure 17.1a. Furthermore, blade vibrations at a high frequency induce high-cycle fatigue conditions. Fatigue fractures due to these vibratory loading are shown in Figure 17.1b. A third type of load is coming from thermal stresses. During engine run-up, the blade temperature is increased very rapidly which leads to a transient inhomogeneous temperature distribution in the blade. The temperature of the thin trailing edge of the blade is increased much faster than in the bulk of the blade. This also applies to the leading edge, although to a lesser extent. During engine shutdown the cooling of the trailing and leading edge will be faster. The inhomogeneous temperature in the blade and the related thermal expansion and contraction are causing a thermal stress cycle. It has resulted in a fatigue crack in the trailing edge of the turbine blade shown in Figure 17.2 (low-cycle fatigue). Crack growth occurred along the grain boundaries. Plastic deformation in the grain boundaries is very difficult at room temperature, but at a high temperature the grain boundaries become weaker than the matrix of the grains (grain boundary sliding and cavity formation) with intergranular cracking as a result.

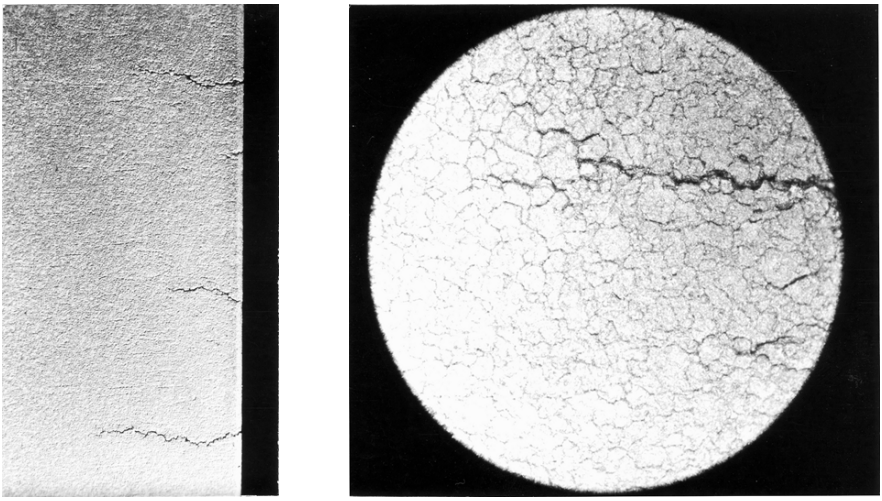
The material of the blades shown in Figures 17.1 and 17.2 is a nickel alloy (Nimonic) which was developed as a high-temperature material for turbine blades in view of the high working temperature. The failures shown in these figures occurred in the 1960s. However, a further increase of the working temperature was required for improving the efficiency of turbofan engines. This has lead to the development of new materials which also required new blade production techniques. Transverse grain boundaries were eliminated by producing turbine blades as monocrystals with a unidirectionally solidified eutectic composition [1, 2] which greatly improved the creep resistance. The eutectic structure consists of a matrix

(a) Turbine blades with large creep deformation and cracking due to overheating. Blade length 11 cm

(b) Fatigue failures in turbine blades starting at the trailing edge (blade chord 25 mm)

Fig. 17.1 Turbine blade failures.

as one phase of the eutecticum embedding long fibers as the second phase. Obviously, the directionality of the eutectic composite should be in the length direction of the blade. This is an example of designing a material and a production process for a special application. Special coatings are also applied to turbine blades in order to resist surface oxidation. Furthermore, new blade cooling systems have been introduced. As a consequence, turbine blades are highly complex and expensive [3]. The major problem is not designing against fatigue, but developing materials and blades for extremely high-temperature application. Of course, stress distributions in the blade and the joint between the blades and the turbine disk must still be considered in view of fatigue (see the wiffle tree in Figure 17.1a).



(a) Trailing edge with cracks. Length of lower crack 4 mm

(b) Intergranular character of crack. Diameter of optical field 2.5 mm

Fig. 17.2 Intergranular fatigue crack in trailing edge of a turbine blade due to thermal fatigue.

Supersonic transport aircraft: The Concorde [4]

In the 1960s, the supersonic passenger aircraft, the Concorde, was developed jointly by the French and English aircraft industries. The aircraft had to fly at twice the speed of sound (Ma-2) which implies that aerodynamic heating of the aircraft skin occurs up to a temperature of slightly above 100°C (212°F). The design team expected that aluminium alloys could still be used, but it was recognized that the age-hardened condition of these alloys could be affected by overaging at the elevated temperature. Some softening of the material might decrease the mechanical material properties and creep and fatigue were earmarked as potential problems. Extensive experimental programs were carried out. The Al-alloy selected for the structure was RR58[22] (composition 2.4Cu, 1.6Mg, 1.1Ni, 1.65Fe; ASM equivalent: 2618) which was artificially aged at 190°C (374°F). Because the aging temperature is significantly above the maximum in-flight temperature, it might be expected that a stable material structure is maintained in service. However, it does not guarantee that some softening does not occur and cyclic slip in the material might occur more easily. Fatigue tests were carried out on various types of specimens simulating notched elements of the aircraft

[22] RR58 was an existing Rolls Royce alloy used for compressor blades subjected to a moderately elevated temperature.

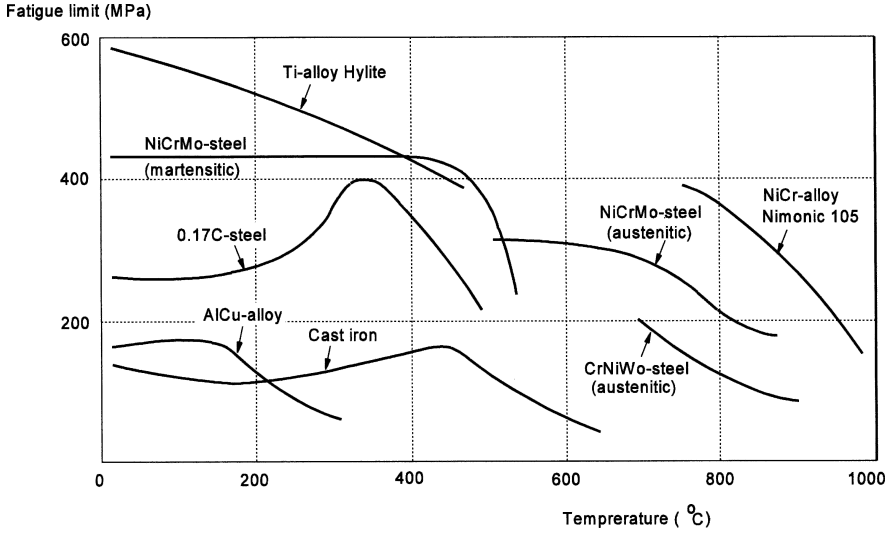


Fig. 17.3 The influence of the temperature on the fatigue limit ($N = 10^7$) of various materials. Data collected by Forrest [6] (graph after Radaj [7]).

structure. Load histories and temperature cycles relevant to supersonic flights of the Concorde were used. Significant thermal stresses are introduced in supersonic flight because aerodynamic heating starts at the outer skin of the structure while the temperature of the internal structure is lagging behind. Thermal stresses in the reversed direction occur after returning to subsonic flight. Finally, a full-scale flight-simulation test on the complete aircraft structure was considered to be necessary in order to gain sufficient confidence with respect to fatigue and creep. A complex test rig for the full-scale test included equipment for heat cycles with periodic heating and cooling of the outside of the structure by air in a kind of tunnel around the aircraft. Due to the complexity of the test and the need for periodic inspection, the test could not be run fast. Acceleration of a test with heat cycles is anyway a problem because heat effects on the material behavior are time dependent and should in principle be simulated on a real time scale. A compromise was obtained by using a slightly higher maximum in the temperature cycle (maximum 130°C) in order to accelerate the thermal damage contribution, but the test still lasted for about seven years. The Concorde fleet has accumulated some 25 years of operation in service without significant thermal fatigue problems. The Concorde was retired from service in 2003 for economic reasons.

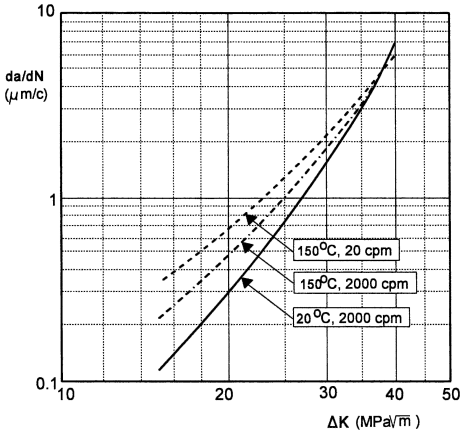
17.3 Fatigue properties at high temperatures

Test results of the fatigue limit of various materials as affected by temperature were collected by Forrest [5], see Figure 17.3. The data were obtained under cyclic bending at frequencies in the order of 40 to 50 Hz. For several materials, the fatigue limit above a certain temperature is considerably reduced, which indicates that the material can no longer be used at higher temperatures. A comparison between different materials in Figure 17.3 indicates a relatively high-fatigue strength of the Ti-alloy at temperatures up to about 400°C. Titanium alloys are still used for several high-temperature applications, particularly in several components of turbofan engines. Figure 17.3 also shows that the austenitic steels are superior to the martensitic steels. The superior material in Figure 17.3 is the nickel alloy Nimonic 105.

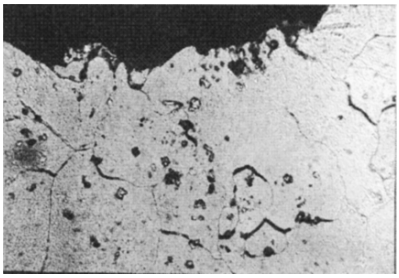
A remarkable behavior is exhibited by the 0.17C steel (mild steel). The fatigue limit apparently increases at elevated temperatures until a maximum of about 350°C. According to Forrest [5], this should be associated with strain aging due to enhanced diffusion of carbon atoms to dislocations which then are restricted in slip movements.

The reduction of the fatigue limit of the aluminium alloy (Al-Cu) at elevated temperature is a result of overaging of the precipitation hardened material structure. Also, the martensitic structure of the low-alloy high-strength steel is not stable at high temperatures. If the material structure is not stable at a high temperature, time-dependent phenomena can occur in the material, and an effect on fatigue properties should occur. Effects of the frequency and wave shape have been observed. Creep, either on a microscale or a macrolevel, will contribute to the failure mechanism. Creep resistance is essential for the fatigue strength at high temperatures which requires a stable material structure.

The fatigue notch effect at high temperatures can be significantly different from the notch effect at room temperature. If creep is possible, the peak stress at the root of the notch may be relaxed as result of plastic creep deformation. Obviously, life predictions accounting for creep deformation will be complex because the temperature-time history is an additional and relevant variable to be considered. Moreover, retrieving of material data to account for the time-dependent material behavior is not a simple task. Actually, design efforts for a structure operating in a high-temperature environment should be supplemented by experiments which faithfully include all relevant conditions.



(a) The effect of the temperature and frequency on the fatigue crack growth rate



(b) Intergranular crack growth and grain boundary voids during creep at $S = 200$ MPa and $T = 150°C$ (width of picture 200 μm).

Fig. 17.4 Fatigue and creep crack growth in an Al-alloy (2024-T3) [8].

Most basic material data on the temperature effect were obtained as low-cycle fatigue results of tests on unnotched specimens. Such tests can indicate a safe upper temperature limit which precludes creep deformation, in most cases a criterion to be satisfied. Fatigue crack growth at an elevated but still acceptable temperature is then of interest. Fatigue crack growth data for elevated temperatures were essential for the development of the Concorde. Some results of an old elementary test program on an aluminium alloy are presented in Figure 17.4. Tests were carried out on center cracked specimens at room temperature and 150°C. For the elevated temperature tests, frequencies of 2000 and 20 cycles per minute were used. Crack growth was faster at the elevated temperature, and at this temperature, it was again faster for the lower frequency. Crack growth under all three conditions was still transgranular. Tests at 150°C on precracked specimens ($a_0 = 12$ mm) were also carried out under sustained load. Crack growth by creep until $a = 20$ mm occurred in 32 hours, while crack growth now was intergranular and grain boundary voids were also observed in the wake of the crack, see the illustration in Figure 17.4b. The difference between the fracture mechanisms of fatigue and creep is confirmed.

James [8] reported on fatigue crack growth at 538°C (1000°F) in an austenitic stainless steel (type AISI 304), which was a potential material for a breeder reactor. He carried out crack growth tests at several load

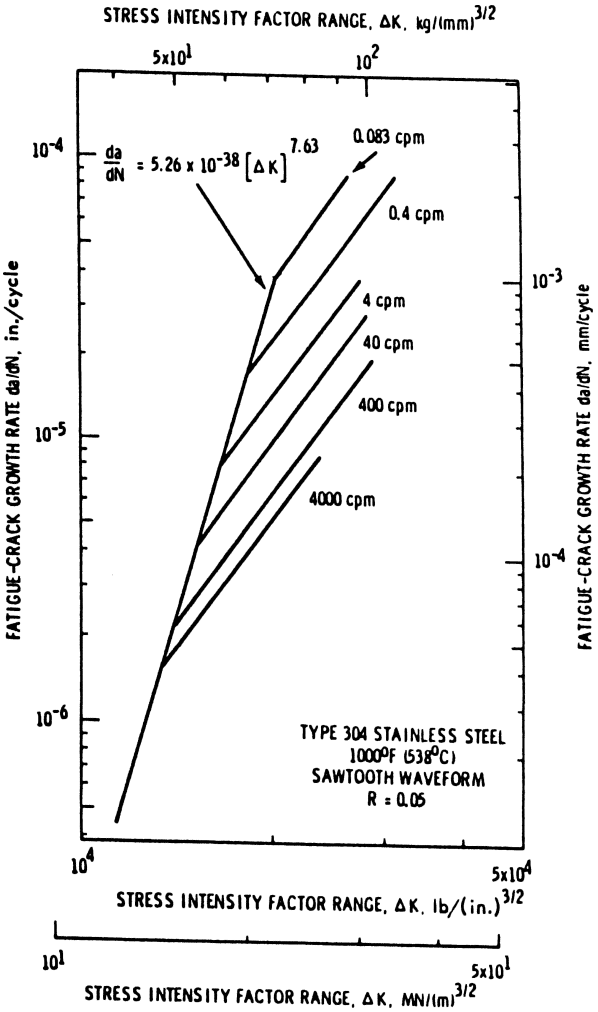


Fig. 17.5 The effect of the frequency on the crack growth rate in annealed stainless steel (AISI 304) [9].

frequencies varying from fast (4000 cpm = 67 Hz) to rather slow (0.083 cpm or 1 cycle in 12 minutes), see Figure 17.5. At low ΔK-values, a frequency effect was not yet observed, but at higher ΔK-values a systematic effect occurred with higher crack growth rates at a lower frequency. Crack growth in most of these tests was still transgranular. James also carried out tests with two different wave shapes: (1) a positive saw tooth, and (2) a trapezoid wave shape with holding at $S_{\max}$ for the major part of the load cycle, both at three frequencies of 4, 0.333 and 0.083 cpm respectively. At the

first two frequencies, a systematic wave shape effect was not evident, but at the lowest frequency of 0.083 cpm, the crack growth rate was lower for the trapezoid wave shape with holding at $S_{\max}$. Moreover, the fracture mechanism being predominantly transgranular for the saw tooth wave shape changed to predominantly intergranular crack growth. In the latter case, the crack growth path was more irregular while also more secondary cracks were observed. Recall a similar observation in Chapter 16 (see Figure 16.8) where a more complex cracking mechanism under corrosion fatigue due to holding at $S_{\max}$ also led to a lower $\mathrm{d}a/\mathrm{d}N$.

The results of James cannot simply be transferred to other materials. However, it should be recognized that a high-temperature fatigue crack growth problem requires similar research to explore the effect of temperature, loading rates and hold times corresponding to load and temperature profiles occurring under service conditions.

17.4 Fatigue at low temperatures

Low temperatures can change the material fatigue behavior for two reasons. First, the mechanical response of the material is different. In general, the yield strength and tensile strength are higher than at room temperature. This trend is associated with an increasing resistance against plastic deformation (lower mobility of dislocations). Second, environmental effects on fatigue are reduced at a low temperature because reaction rates of chemical processes and diffusion are lower. Forrest [5] collected fatigue strength data from the literature and averaged the results of various sources for different groups of materials. He presented results for three low temperatures as the ratio between the fatigue strength ($N = 10^6$) at a low temperature ($S_{N,T}$) and the fatigue strength at room temperature ($S_{N,RT}$) see Figure 17.6. The ratios in Figure 17.6 are all larger than 1. Apparently, the fatigue strength at low temperatures is larger than at room temperature, the more so for a lower temperature. The results in Figure 17.6 indicate that the fatigue strength of notched specimens is also increased by a lower temperature.

Effects of low temperatures on fatigue crack growth are also reported in the literature, see e.g. [9]. In general, fatigue crack growth occurs more slowly at low temperatures if small to moderate ΔK-values are applicable, whereas faster crack growth has been observed for larger ΔK-values with $K_{\max}$ close to K_c or K_{Ic}. The increased crack growth rate for large ΔK-values can be understood because of the reduced ductility

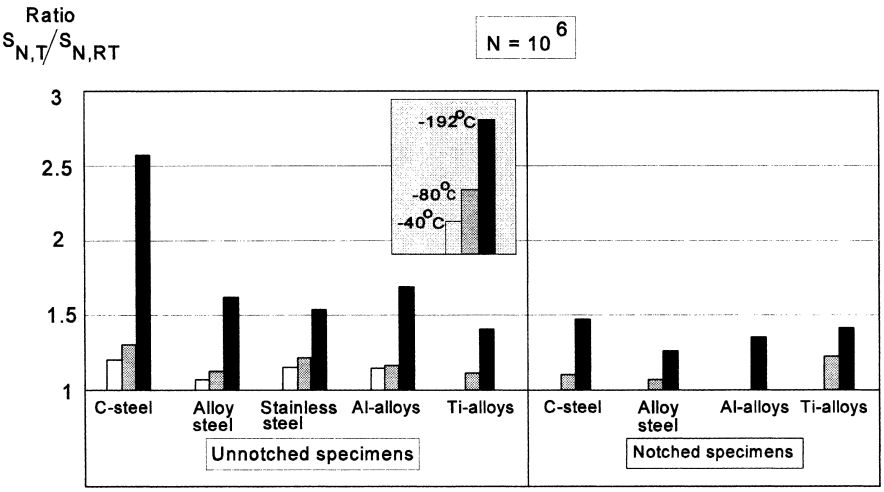


Fig. 17.6 The low-temperature fatigue strength ($S_{N,T}$) divided by the fatigue strength at room temperature ($S_{N,RT}$) for unnotched and notched specimens of different material groups. Data compiled by Forrest [6].

at lower temperatures. However, why should crack growth be slower at low ΔK-values, i.e. in the threshold and Paris region; regions I and II in Figure 8.6. This could be due to reduced cyclic plasticity at the crack tip, but also to some environmental contribution which may be less detrimental at a lower temperature. As discussed in Chapter 16, the water vapor contents of air can affect the crack growth rate. A lower crack growth rate has been observed for a lower water vapor pressure, and the pressure is reduced by a low temperature. Broek carried out crack growth tests on two aluminium alloys (2024-T3 and 7075-T6) at room temperature and at 0, −25, −50 and −75°C respectively [10]. The results in Figure 17.7 confirm that crack growth is slower at lower temperatures. Broek explained this trend as a result of the lower water vapor content of the air at low temperatures. He confirmed the favorable effect of a low water vapor pressure by supplemental tests at room temperature in very dry air, see the crack growth curve for these conditions in Figure 17.7.

A reduced environmental effect on fatigue crack growth at low temperatures may also apply to several materials for crack growth in a liquid environment. If low-temperature conditions should be considered for structures in service, it is advisable to carry out exploratory tests. This requires a careful simulation of the service conditions also with respect to the load frequency.

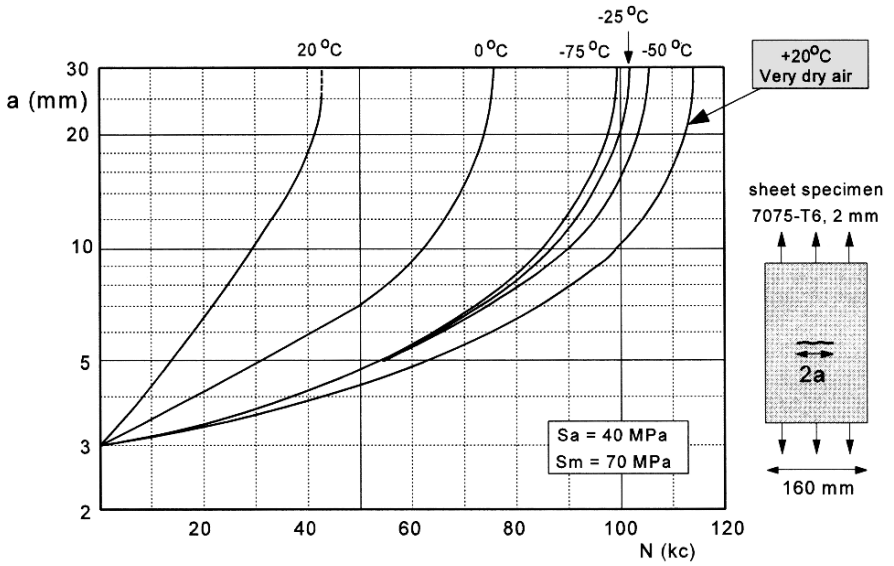


Fig. 17.7 The effect of low temperatures on fatigue crack growth in specimens of an aluminium alloy [11].

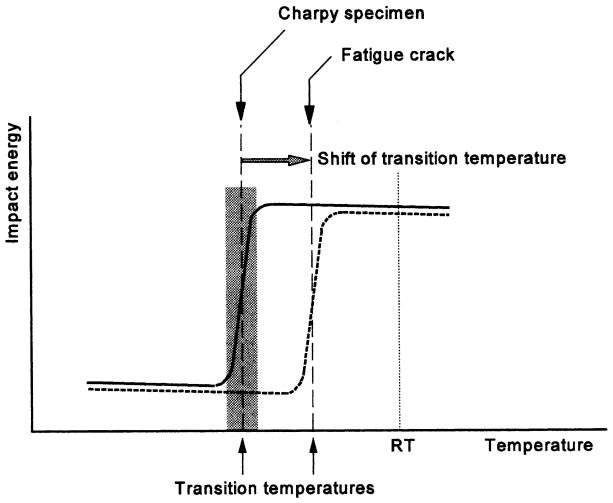


Fig. 17.8 The transition temperature revealed by impact tests on Charpy V-notched specimens of low-carbon steel. A higher transition temperature for fatigue cracks.

Transition from ductile failures to brittle failures

In general, less plastic deformation occurs during static failures at low temperatures. The material ductility is reduced and this is manifest

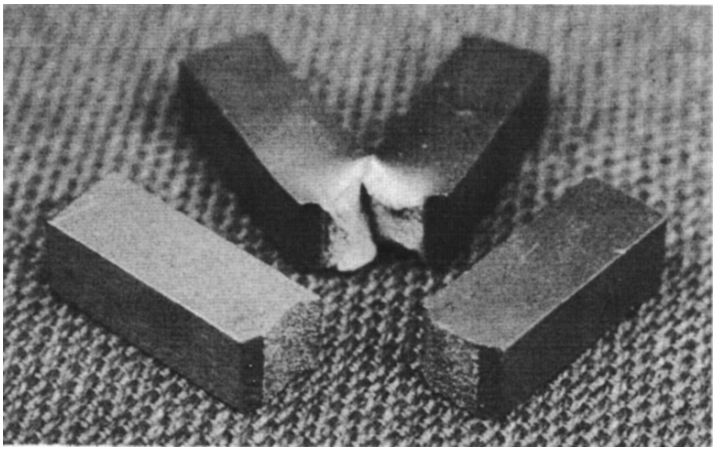


Fig. 17.9 Two Charpy V-notch specimens, thickness 10 mm. Brittle failure in the front specimen tested below the transition temperature, and ductile failure in the rear specimen tested above the transition temperature.

during fatigue crack growth under severe load cycles with a high $K_{\max}$. Fractographic observations have shown that ductile striations may disappear at low temperatures, while indications of crack extension by a cleavage mechanism have been found depending on the type of material [9]. However, an exceptional transition from ductile to brittle failure is exhibited by low-carbon steels (mild steel). This phenomenon is usually studied by impact tests on Charpy V-notch specimens. The tests are carried out at different temperatures and the impact energy for breaking the specimen is measured. If the temperature is decreased, the impact energy suddenly drops to a substantially lower level within a fairly narrow temperature range, see Figure 17.8. The range is characterized by the transition temperature, T_{trans}. For $T > T_{\text{trans}}$, the failure of the Charpy specimen is a ductile failure with much plastic deformation and without separating the specimen in two pieces, see Figure 17.9. However, for $T < T_{\text{trans}}$, a brittle failure occurs without apparent plastic deformation also shown in Figure 17.9. Microscopic investigation have revealed that the failure for $T > T_{\text{trans}}$ occurs as a quasi-static type of failure by void formation and coalescence. For $T < T_{\text{trans}}$, a cleavage type of failure occurs. Although the Charpy test is useful to indicate whether a material is sensitive to cold-brittleness, it should be understood that the transition temperature is not a material constant. In general, T_{trans} will move to a higher temperature if plastic deformation at the tip of the notch of the Charpy specimen is more restrained. A smaller plastic zone and a higher peak stress in this zone are then obtained (see Section 5.8).

This will promote the brittle type of fracture. Plane strain conditions with a triaxial stress distribution at the root of the notch enhance the restraint on plastic deformation. The plane strain character is further promoted by a larger thickness of the specimen, but also by a sharper notch and even more by a fatigue crack. As a consequence, the transition temperature can be higher for a fatigue crack than indicated by tests on Charpy V-notch specimens, see Figure 17.8. Because of the restraint on plastic deformation, the transition temperature is also increased by a higher yield stress, which implies that the risk of brittle failures in structures of mild steel is larger if the hardness of the material is higher. The increased hardness can be due to a higher carbon content or the heat treatment of the steel. A most dramatic example of brittle failures occurred during World War II and also afterwards, when welded Liberty ships in cold water broke in two parts by brittle failures in welded joints [11].

17.5 Some general comments

High-temperature fatigue is in the first place a problem associated with the stability of the material structure. Essential information is related to the load- and temperature-time histories. Where ambient temperature fatigue problems can considerably benefit from stress analysis calculations, material research is more essential for high-temperature fatigue. Temperature limits beyond which the material stability deteriorates should be determined, and fundamental understanding of the material behavior is important. As an example, it has occasionally been overlooked that the creep resistance can significantly depend on the strain-hardening (dislocation structure) of the original material. High-temperature fatigue problems require experimental research while knowledge of material science is indispensable for planning the research.

Low-temperature fatigue is a fully different problem. Plastic deformation at low temperatures is more difficult than at room temperature which has consequences with respect to fracture toughness and fatigue crack growth at high ΔK-values. These aspects should be recognized if the operational environment of the structure includes low temperatures. Designing for fatigue durability in terms of avoiding stress concentrations and limitations on allowable stress levels still remain relevant. The transition from ductile failures to brittle failures at low temperature, especially of low-carbon steels, is a special issue to be considered for (welded) structures of these materials.

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