- Pin material and lubrication
- Pin bending

A square-shaped lug head has a lower K_t than a rounded lug head. However, head shape has little effect at large values of D/d. Reducing the lug width on its loaded side (i.e., waisting) increases K_t. As the clearance between the pin and hole increases, K_t also increases. Interference fit reduces K_t, but this reduction varies inversely with load. It has been suggested that $K_t = 3$ is near optimum for fatigue strength design. The proportions for this K_t would be $D/d = 2$, $H/d = 1$, and $t/d = 1$.

Fatigue in Welded Joints

As shown in Fig. 13, attaching a weld to a load-carrying member cannot only reduce the fatigue strength substantially but also lower the fatigue limit. In this example, the fatigue limit of the welded component is one-tenth that of the plain component. As a consequence of this phenomenon, it is frequently found that in cyclically loaded welded components, the design stresses are limited by the fatigue strength of the welded joints.

There are several reasons why a weld reduces the fatigue strength of a component. These reasons fall into the following categories:

- Stress concentration due to weld shape and joint geometry
- Stress concentration due to weld imperfections
- Welding residual stresses

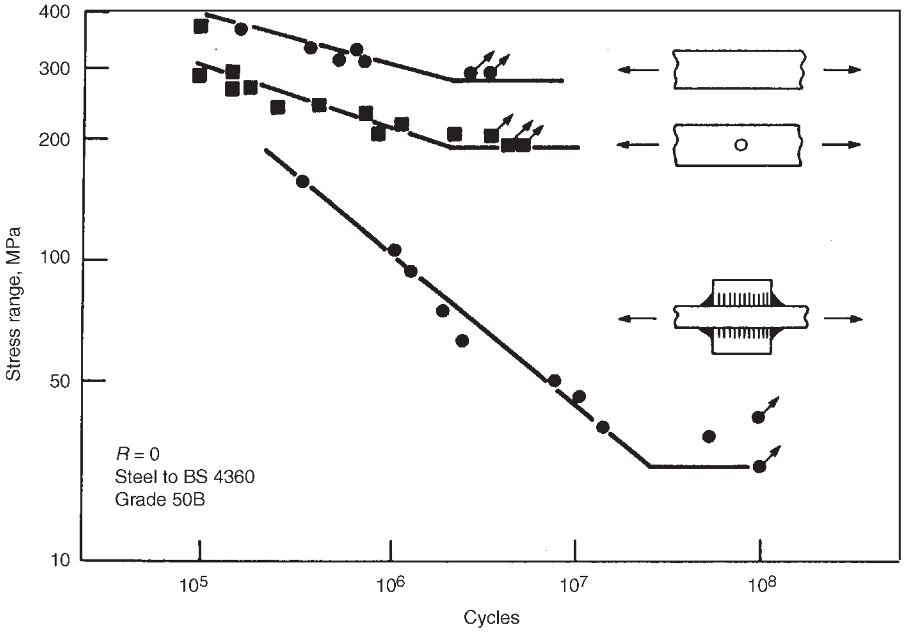

Fig. 13 Comparison of fatigue behavior of a welded joint and parent metal. Source: Ref 16

To be able to design against fatigue in welded structures, it is important to understand the influence of these factors on the performance of welded joints.

Stress Concentrations due to Weld Shape and Joint Geometry

Making a welded joint either increases or decreases the local cross-sectional dimensions where the parent metal meets the weld. Generally, any change in cross-sectional dimensions in a loaded member will lead to a concentration of stress. Thus, it is inevitable that the introduction of a weld will produce an increase in the local stress. The precise location and the magnitude of stress concentration in welded joints depends on the design of the joint and on the direction of the load.

Some examples of stress concentrations in butt welds and fillet welds are given in Fig. 14. The weld toe is often the primary location for fatigue cracking in joints that have good root penetration. In situations where the root penetration is poor or the root gap is excessive, or in load-carrying fillet welds where the weld throat is insufficient, the root area can become the region of highest stress concentration. Fatigue cracks in these situations start from the root of the weld and generally propagate through the weld (Fig. 15).

The geometry/shape parameters that influence fatigue of welded joints by affecting the local stress concentration include plate thickness (T), attachment toe-to-toe length (L), attachment thickness (t), weld toe radius (r), weld angle (θ), and the profile of the weld surface (convex versus concave) (Fig. 16). It is generally found that the fatigue strength of a welded joint decreases with increasing plate thickness (Fig.17a), increas-

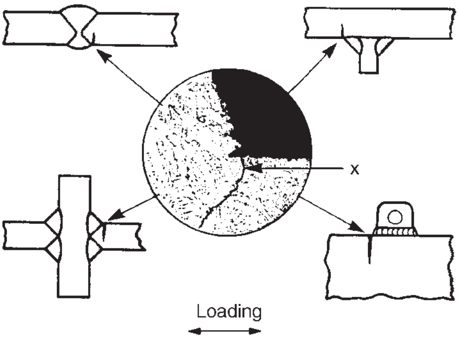

Fig. 14 Examples of stress concentrations in welded joints. Source: Ref 16

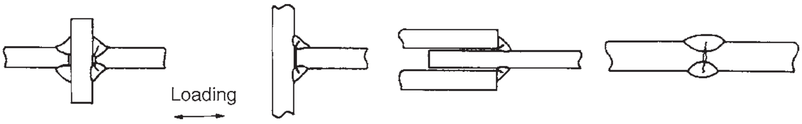

Fig. 15 Fatigue cracking from the weld root. Source: Ref 16

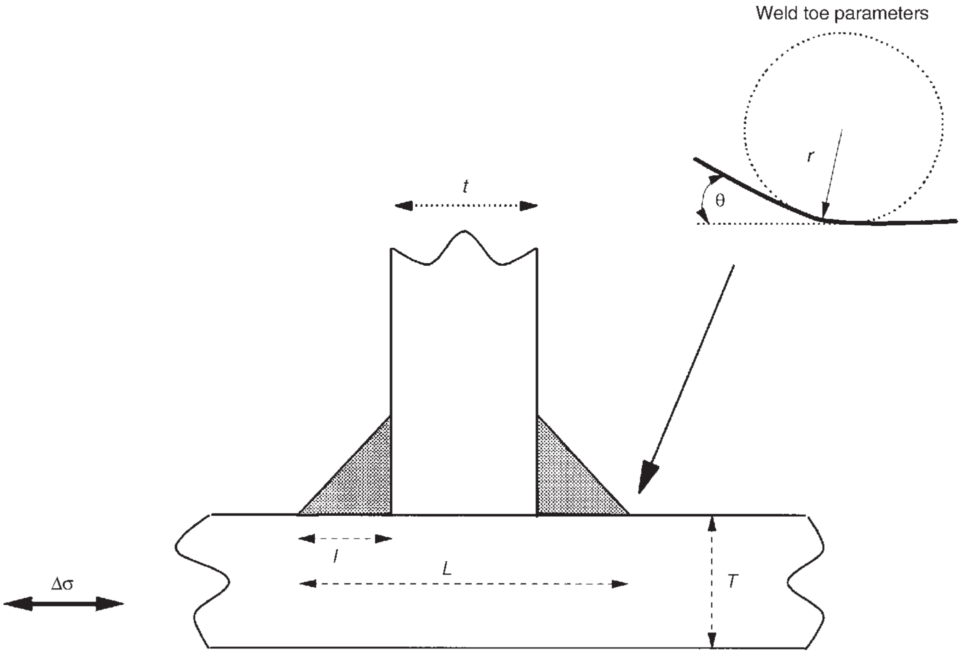

Fig. 16 Geometry parameters that affect weld toe stress concentration. r, weld toe root radius; θ, weld angle; L, toe-to-toe weld length. Source: Ref 16

ing attachment length (Fig. 17b), increasing weld angle (Fig. 17e), decreasing toe radius (Fig. 17f), and misalignment (Fig. 17c). The results given in Fig. 17 are experimental but have been confirmed by finite-element stress analysis of the local weld area. Decreasing the ratio of attachment length to thickness (L/T) from 2.0 to 0.375 will increase the relative fatigue strength by a factor of approximately 1.2. Similar results are obtained for changing the weld angle from 90° to 22.5°. By far the largest influencing parameter is the weld toe radius, which, for example, can increase the fatigue strength over the range $r = 1.0$ to 8.0 mm (0.04 to 0.3 in.) by a factor of 1.3, effectively doubling the life. The weld toe stress-concentration factor (K_t) is a function of all these geometry variables, and a number of formulas are available for butt welds and cruciform joints subjected to bending or tensile load. As an example, the following formula is for a T-joint subjected to bending load:

$$K_t = 1 + \left[\frac{1 - \exp\left(-0.98\sqrt{\frac{T}{2l} + 1} \right)}{1 - \exp\left(-0.45\pi\sqrt{\frac{T}{2l} + 1} \right)} \right] \cdot \left[\frac{0.13 + 0.65\left(1 - \frac{r}{T}\right)^4}{\left(\frac{r}{T}\right)^{1/3}} \right] \tanh\left[\frac{\left(\frac{2l}{T}\right)^{1/4}}{1 - \frac{r}{T}} \right] \quad \text{(Eq 8)}$$

with the validity boundaries $r/T = 0.02$ to 0.2, $l/T = 0.5$ to 1.2, and $\theta = 30$ to 80°.

Misalignment is another geometry-related parameter that can influence the fatigue performance of a welded joint. Misalignment can manifest itself in several ways, with angular and axial misalignments being the most common. Generally, fatigue strength decreases with increasing misalign-

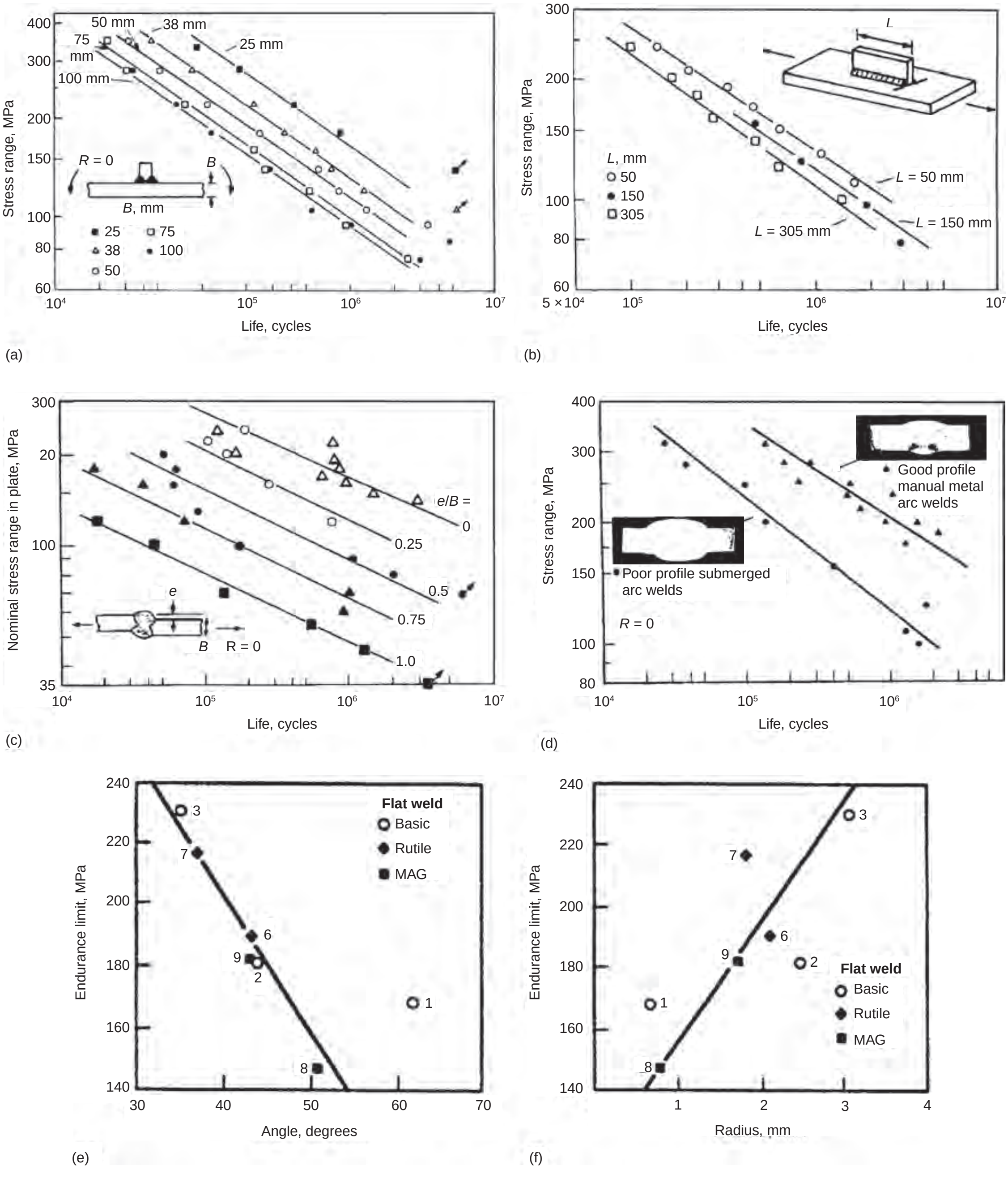

Fig. 17 Geometry factors affecting fatigue in welded joints. (a) Effect of plate thickness. (b) Effect of attachment length. (c) Effect of misalignment. (d) Effect of weld profile. (e) Effect of weld toe angle. Source: Ref 17. (f) Effect of weld toe radius. Source: Ref 16, 17

ment, as shown in Fig. 17(c). Formulas to calculate the local weld stress-concentration factor due to misalignment are now well established.

Stress Concentrations due to Weld Discontinuities

Stress analysis of an idealized model of a fillet weld loaded in the transverse direction shows that the stress-concentration factor (K_t) at the weld toe is approximately 3. This is comparable to K_t for a hole in a plate. In view of this, it would be reasonable to expect that the fatigue behavior of a fillet weld is similar to that of a plate with a hole. However, as shown in Fig. 13, the fatigue performance of the welded joint is substantially lower, implying that other factors come into play for welded joints.

As stated previously, weld imperfections are, to some extent, controllable and can be avoided during fabrication, or their effects can be included in the design. The difference observed in Fig. 13 has been attributed to the presence of microscopic features at the weld toe. These features are small, sharp, nonmetallic intrusions and are present in most, if not all, welds. The extent and distribution of these features varies with the welding process and also possibly with the quality of the steel plate and its surface condition. The exact source of these intrusions is not precisely known, but it is believed that slag, surface scale, and nonmetallic stringers from a dirty steel are the primary causes. An example of a weld toe intrusion is given in Fig. 18. The combined effect of these sharp, cracklike features and concentration of stress due to the weld geometry is that fatigue cracks initiate very early on, and most of the life is spent in crack propagation.

Planar weld imperfections (e.g., hydrogen cracks, lack of side-wall fusion) are clearly to be avoided because they will substantially reduce the fatigue life. Volumetric imperfections such as slag inclusions and porosity can be tolerated to some extent, because the notch effect of these imperfections is generally lower than that of the weld toe (Fig. 19).

Welding Residual Stresses

In welded structures, it is normally found that residual stresses are present in the weldment area, and these can be high enough to approach the yield strength of the material. These stresses occur as a result of the thermal expansion and contraction during welding, due to the constraint provided by the fabrication or by the fixtures, and due to the distortion in the structure during fabrication (often referred to as reaction stresses). These stresses are localized to the weld zone and are self-balancing (i.e., both tensile and compressive stresses are present). Transverse to the weld toe, the residual stress is typically tensile and can approach yield point. When a load cycle is applied to the structure, it is superimposed onto the residual-stress field, and the effective stresses acting at the weld joint can fluctuate down from yield level (Fig. 20). The range of each cycle remains

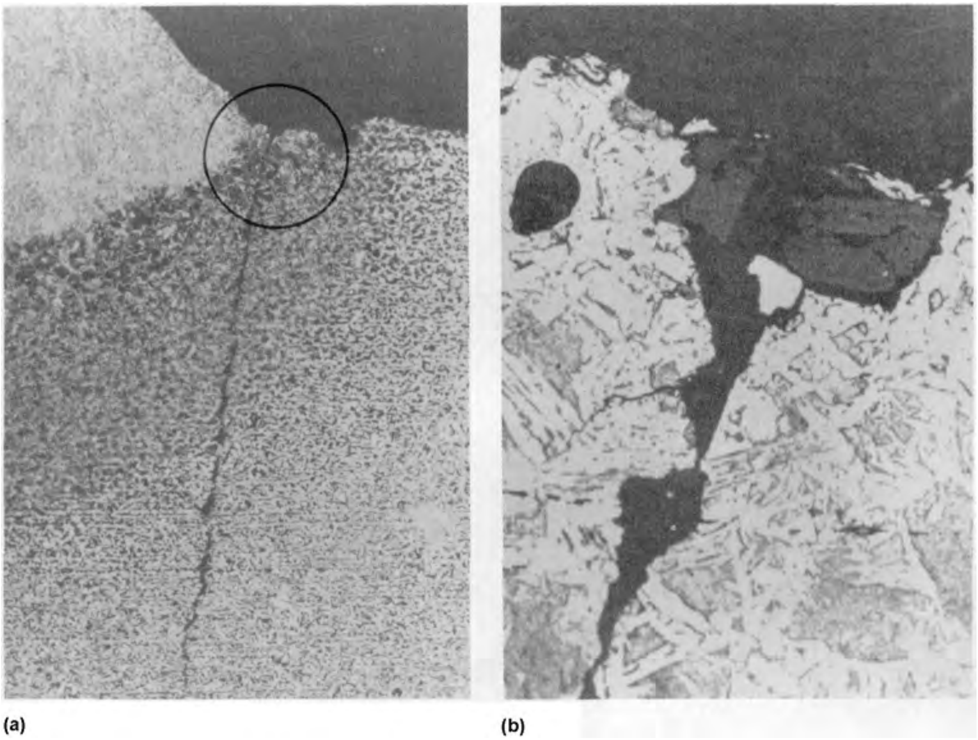

Fig. 18 Example of weld toe intrusions. Source: Ref 16

unchanged, but the effective mean stress can be significantly different from the applied mean stress. Because of the dominance of crack propagation in welded joints and the presence of high residual tensile stresses, the mean stress effect is negligible, and fatigue life is controlled by the stress range.

Reducing residual stresses using postweld heat treatment can improve fatigue life, but only if the applied load cycles are partially or fully compressive. For fully applied tensile loads, postweld heat treatment does not improve the fatigue life (Fig. 21b). Thus, it is important to know the exact nature of applied loads before a decision is made on the need to heat treat a welded structure. Indeed, it should be noted that stress relief of welded joints is never fully effective. Residual stresses up to yield point have been measured in stress-relieved pressure vessels and up to 75% of yield in stress-relieved nodes in offshore structures. Due consideration must be given to the complexity of the overall structure when stress relieving and to the time and temperature of the process.

Effect of Material Properties

Because crack propagation dominates the fatigue life of welded joints, material properties have no effect on fatigue strength. This is illustrated in

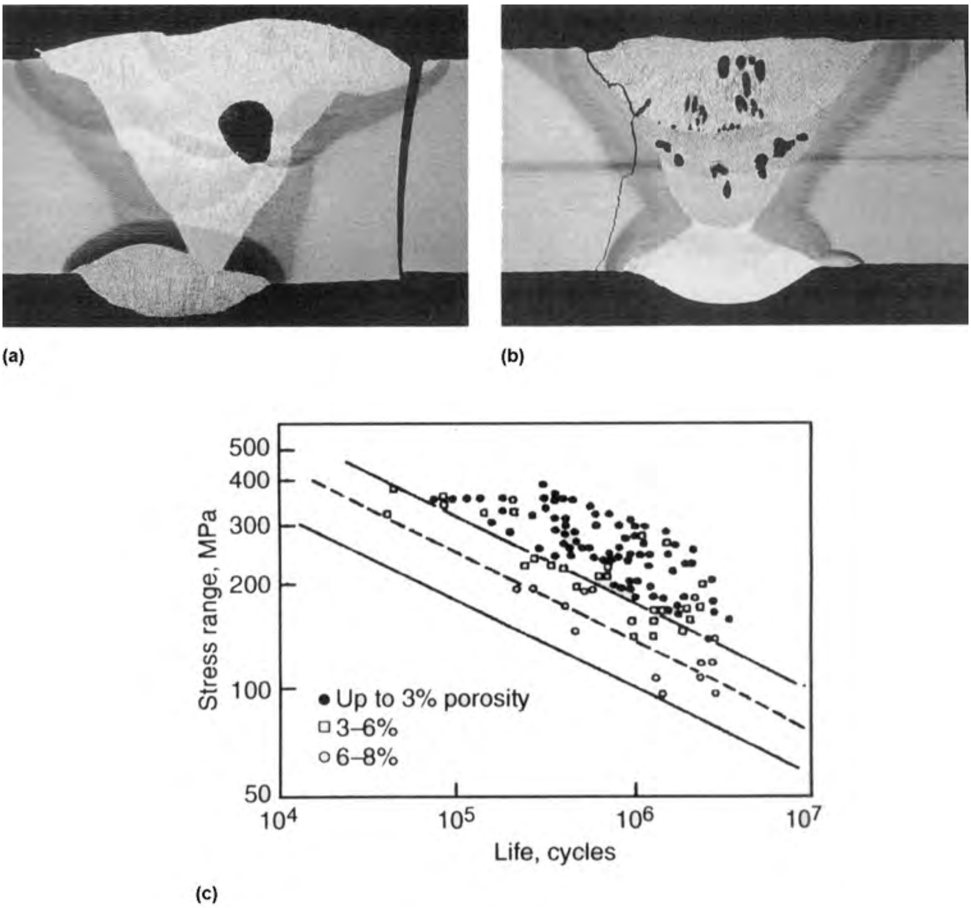

Fig. 19 Effect of volumetric defects on fatigue. (a) Slag inclusion in butt weld. Cracking from weld toe. (b) Porosity in butt weld. Cracking from weld toe. (c) Transverse groove welds containing porosity. Source: Ref 16

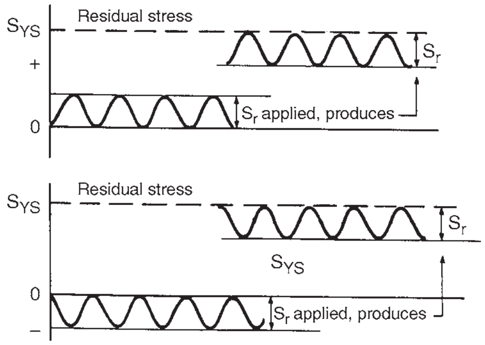

Fig. 20 Superposition effect of applied and local welding residual stresses. Source: Ref 16

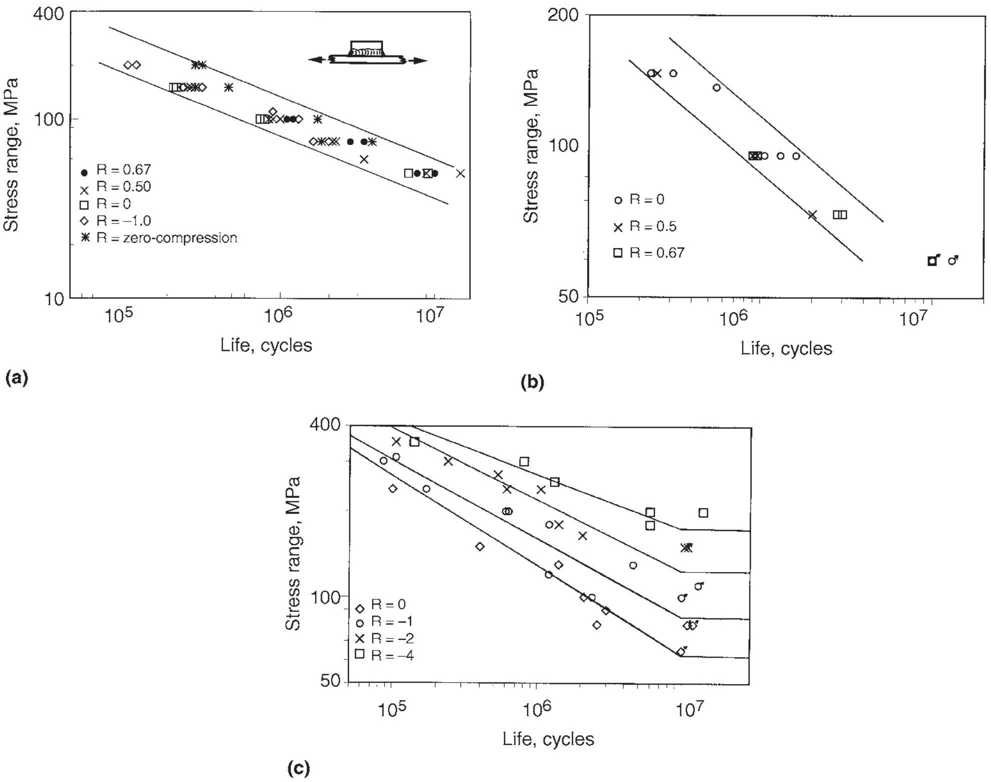

Fig. 21 Influence of welding residual stress on fatigue. (a) Effect of applied stress ratio on as-welded joints. (b) Effect of stress relief as a function of tensile load cycle. All specimens stress relieved. (c) Effect of stress relief as a function of tension-compression load cycle. All specimens stress relieved. Source: Ref 16

Fig. 22, where it can be seen that data points for steels with different strengths fall within the same scatter band. Thus, using a high-strength steel to improve fatigue life will not be beneficial for welded structures.

Microstructure. A fatigue crack starting at the weld toe will immediately grow into the heat-affected zone (HAZ) and then into the base metal. During this period, it will propagate through a variety of microstructures, and, as shown in Fig. 23, its growth rate will not be influenced in any way. Thus, the variety of HAZ microstructures (and hardness levels) in the weldment area have little or no effect on the rate at which the crack grows.

Fracture Toughness. As with tensile strength, the fracture toughness of the weld metal, the HAZ, or the base metal does not influence the crack growth rate. This can be deduced from Fig. 23, which represents a variety of materials with different strength levels and toughness values. The only influence of fracture toughness is limiting the size the fatigue crack could reach before the material fails in an unstable manner, because tougher materials are able to tolerate bigger fatigue cracks.

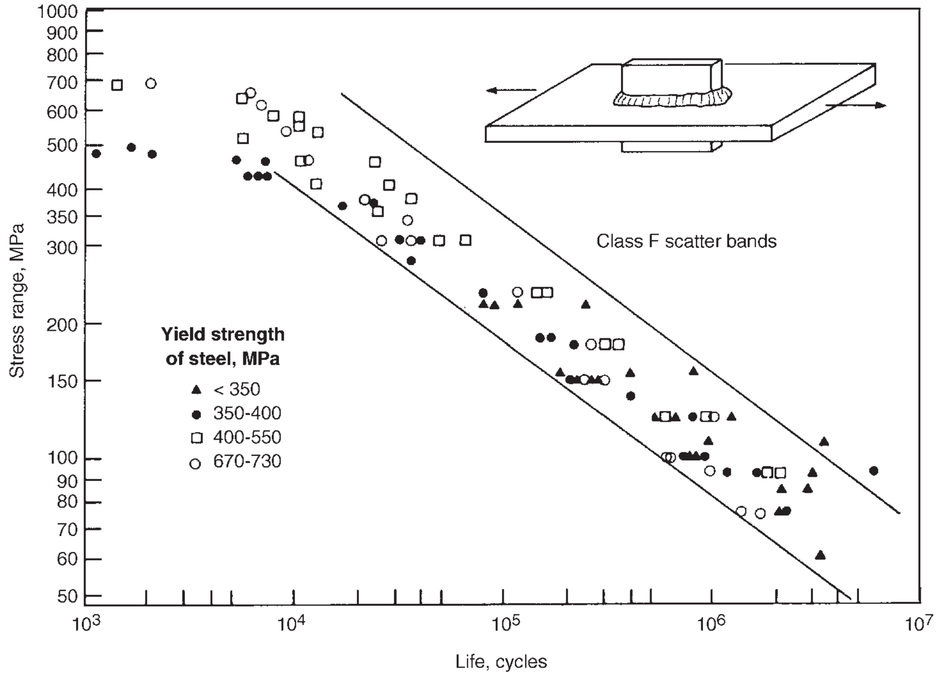

Fig. 22 Fatigue test results from fillet welds in various strengths of steel. Source: Ref 16

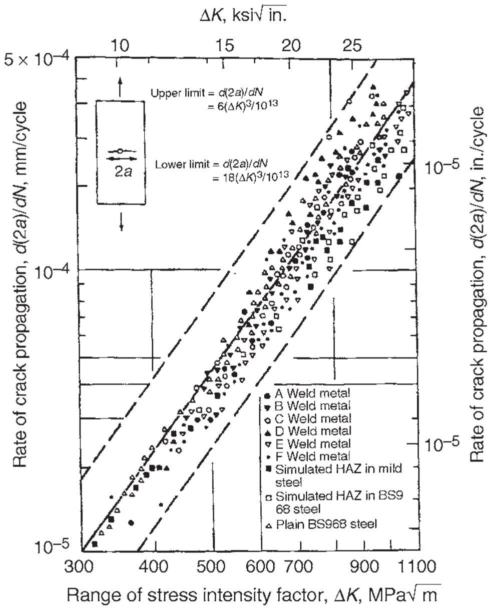

Fig. 23 Crack growth rate data showing no influence of weld metal, heat-affected zone (HAZ), or base metal. Source: Ref 16