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Dependence of fatigue limit on step height for stepped 0.45% carbon steel with singular stress field

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ABSTRACT

A method was proposed for evaluating the relationship between the fatigue limit and the step height for a stepped plate with a sharp corner. With reference to a small crack size dependence of fatigue limit, step heights were divided into three levels, and a new evaluation method was proposed for representing the singular stress field intensity around the corner tip. An intensity factor of the singular stress field of the corner was introduced and correlated with the step height. The fatigue limit for stepped plates was represented by the threshold value of the range of the intensity factor. Moreover, the fatigue limits for extra-low stepped plates and high stepped plates, which could not be directly measured, were estimated based on the fatigue phenomena at these conditions.

1. Introduction

The stepped shape with a corner is common in welded structures, such as the lap joint illustrated in Fig. 1(a). In such parts with corners, fatigue cracking is likely to occur under repeated loads because of stress concentration at the corner tip [1–4]. Fig. 1(b) shows an example of a weld toe in which a fatigue crack has been initiated, and Fig. 2 shows a schematic diagram of the corner shape analyzed in this study. Such corners also occur in fillets of several mechanical elements [1,4]. It is necessary to consider the fatigue limit of such parts with the stepped shape in order to ensure the safety of the overall structure [5,6]. The fatigue limit of a material with a stress concentration is determined by the fatigue crack initiation limit σ_{w1} or the fatigue crack propagation limit σ_{w2} [7,8]. Fig. 2 shows the schematic diagram of the corner shape. In this study, sufficiently sharp corners ($\rho = 0$, $\alpha = 90°$), as shown in Fig. 2(b), are investigated; therefore, σ_{w2} is taken as the fatigue limit.

For corners of various shapes, elasticity analyses of the stress field singularity and stress concentration factor have been conducted [9–13]. However, in principle, elastic singularities can only be utilized to explain the fracture phenomena of brittle materials with a crack, to which the Griffith theory [14] is applicable. On the order hand, the fracture of ductile materials occurs as a discrete phenomenon, for example, by growth and coalescence of micro-cavities, and therefore cannot be described by continuum mechanics.

Although many studies have investigated the residual stress, microstructure change, and phase change in the corners of actual welded structures, only a few studies have been conducted on the fatigue strength characteristics of sufficiently sharp corners ($\rho = 0$), which are not influenced by residual stress, microstructure change and phase change [15–17].

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Nomenclature

a	step height
A	intensity factor of singular stress field near the step root
ΔA_{th}	value of the range of A at fatigue limit
K	stress intensity factor
K_e	equivalent stress intensity factor
r	distance from the corner tip
R	stress ratio
σ_{w1}	fatigue crack initiation limit
σ_{w2}	fatigue crack propagation limit
ρ	notch root radius
σ_n	nominal stress amplitude
σ_θ	the stress in the θ direction around the 90° corner

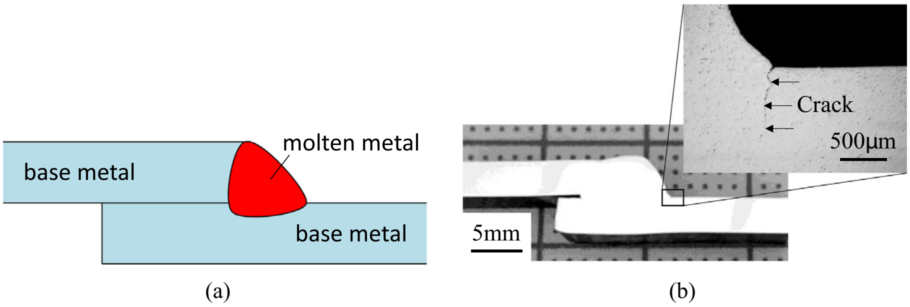

Fig. 1. Schematic diagram and fatigue crack of lap joint. (a) Schematic diagram (b) The initiated fatigue crack.

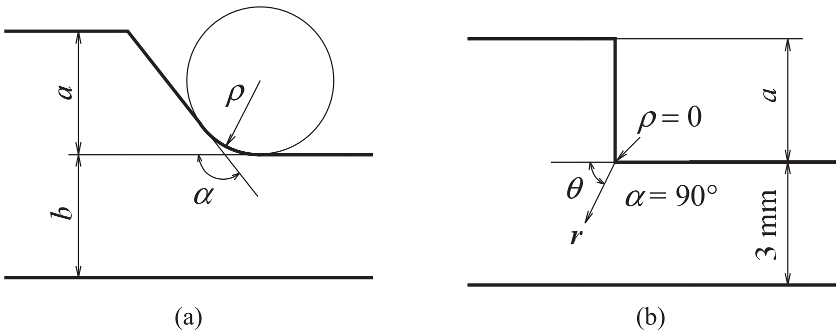

Fig. 2. Schematic diagram of the corner shape. (a) Definition of the symbols (b) Corner shape investigated in this study and definition of r-θ coordinate system.

Kihara et al. [15] proposed an equivalent stress intensity factor K_e that extends the concept of stress intensity factor for a crack and represents the singular stress field around a corner. K_e is defined by the following equation

$$K_e = (m/m_0)^\gamma K, \quad K = \sigma_0\sqrt{2\pi r_0} \tag{1}$$

where m is the gradient of stress distribution near the sharp corner tip, m_0 is the gradient of stress distribution near the crack tip, σ_0 is the nominal stress, r_0 is the notch-affected length, and γ is a constant confirmed experimentally to be two. r_0 represents the notch size and is determined by the intersection of the extrapolations of the stress distribution and nominal stress lines. Kihara et al. performed fatigue tests for specimens with several opening angles (α in Fig. 2(a)) and defined the crack initiation life based on when the crack length on the specimen side becomes 200 μm. They concluded that the crack initiation life could be expressed in terms of K_e, independent of the opening angle. However, the meaning of the equivalent stress intensity factor is unclear, and there is a possibility that material characteristics are included in γ, which is determined experimentally. In the fatigue test, the radius of curvature of the corner was reduced to ρ = 0.1 mm only on the crack obser-