Positive effect of indentation on fatigue crack growth of mild steel

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Abstract. A number of cold work processes have been attempted to improve the fatigue performance of metallic materials. A competent indentation may have a positive effect on increasing the fatigue property of metals, and it was expected to strength mild steel with outstanding ductility but relatively weak strength. Indentation was introduced by a round steel indenter with a diameter of 5 mm. Fatigue crack growth behaviour and hardness distribution of both as-received specimen and specimen with indentations were studied systematically together with relevant microscope observations on fatigue-fractured surfaces. The results show that indentation could significantly improve the fatigue property of specimen because of the generation of compressive residual stress, and considerable increase the hardness near the location of indentation due to increase of material density.

1. Introduction

The cold working processes, e.g. shot peening and tensile overload, have been widely studied to improve the mechanical properties of metallic materials, especial fatigue behaviour. Competent shot peening can improve the fatigue resistance due to the incorporation of compressive residual stresses in the surface layer because the plastic deformation is constrained by adjacent deeper material [1-3]. However, shot peening influence is closely related to the process parameters applied (e.g. peening intensity, particle size and material, and nozzle distance) [4]. This indicates that this style of cold working process may improve or deteriorate the fatigue performance, which depends on the parameters applied and material properties. Additionally, the increase of surface roughness due to the application of shot peening also decrease the fatigue property because of the stress concentration at the surfaces of specimen [5]. Residual stress relaxation in shot-peened specimen during fatigue cycling is inevitable problem, especial in high stress amplitude fatigue testing [6]. As for the application of a single tensile overload, the fatigue life extension is limited significantly due to the initial acceleration of fatigue crack growth rate da/dN during the subsequent fatigue cycling [7-13].

The aim of this paper was to address the improvement of the fatigue performance of mild steel, which is commonly used in engineering industries. The effect of indentation on the fatigue crack growth behaviour and hardness profiles of mild steel were investigated together with the fatigue fracture mechanism.
2. Material and experimental details
The material used in this study was mild steel, and the chemical compositions are listed in Table 1. A standard extended-compact tension (E-CT) specimen with a U-notch and with a thickness of 10 mm was adopted for fatigue testing, as illustrated in Figure 1(a). All specimens were machined from the same plate using wire-electrode cutting. Four specimens in total were machined: two as-received specimens (one for fatigue measurement, and the other for hardness test), and two specimens had three indentations each (one for fatigue measurement, and the other for hardness test). The indentations were incorporated by a round steel indenter with a diameter of 5 mm using a servo-hydraulic universal machine (TENSON-WDW-T100) with a crosshead speed of 5 kN/min. The location and size of indentations are shown in Figure 1(b). The Vickers hardness tests were carried out along the path of Mode I fatigue crack growth.

Table 1. Chemical compositions of mild steel (wt.%).

| Material       | C   | Si  | Mn  | P  | S  | Fe  |
|----------------|-----|-----|-----|----|----|-----|
| Mild steel     | 0.17| 0.38| 1.05| 0.025| 0.03| balance |

![Figure 1](image-url)

Figure 1. (a) E-CT specimen, and (b) the size and location of indentations (in mm).

Fatigue crack growth tests were performed on the as-received specimen and the specimen with three indentations using a servo-hydraulic fatigue test machine with a capacity of 100 kN. Paris curves, \( \frac{da}{dN} - \Delta K \) curves, are shown in the following sections, in which the \( \Delta K \) is calculated with the following standard formula [14]:

\[
K = \frac{P(B\sqrt{W})}{[(1-a)^{3/2} \times (1-d/W)^{1/2}] \times (1.15 + 0.94\alpha - 2.48\alpha^2 + 2.95\alpha^3 - 1.24\alpha^4)} (1)
\]

where \( P = \) the applied maximum load, \( B = \) thickness, \( W = \) width of E-CT specimen, \( a = \) crack length from the loading line, \( d = \) distance from edge to loading line, \( \alpha = a/(W-d) \), and \( 0.1 \leq (a + d)/W < 1 \).

After fatigue test, fracture surfaces were examined with a scanning electron microscopy (SEM) to characterize the fracture characteristics. SEM specimens were cut from the fractured specimens, and were washed in ethanol using an ultrasonic cleaner for 5 mins before examination.

3. Result and discussion
Vickers-hardness profile of the as-received specimen is shown in Figure 2, and compared with that of the specimen with three indentations. The hardness of as-received specimen is very tiny, which provides a reference to study the effect of indentation on hardness distributions. It is evident that the indentation increases the hardness because of strain hardening and increase of density, and the maximum occurs in the bottom of each indentation.
The Paris curves are plotted in terms of $da/dN$ as a function of the applied $\Delta K$ for the specimen with indentations, and compared with that of the as-received specimen, as shown in figure 3. It is clear that, with indentation, the $da/dN$ decelerated immediately by showing lower $da/dN$ in comparison to that of the as-received specimen, and then tried to recover to the normal value. That is, the presence of indentation has a significant influence on improving fatigue resistance of the selected material. This is because indentation can result in plastic deformation, which generates compressive residual stresses nearby.

The fracture surfaces after fatigue testing were observed using SEM. The typical micrograph observations are shown in figure 4 for the as-received specimen, and in figure 5 for the specimen with indentations, respectively. To compare, the SEM observations from the two studied specimens are carried out at the corresponding locations or similar crack lengths. Comparison of figures 4 & 5 shows that the secondary cracks in the fracture surface of as-received specimen is more and sever than those of the specimen with indentation. After careful comparison, it can be found that the characteristic of fractured surface near indentation is distinctly different from that at the centre of specimen (in the direction of thickness of specimen). That is, the application of indentation also generates severe deformation of material nearby. Combined with fatigue performance as discussed above, it should be pointed out that the indentation-induced residual stress is beneficial to improvement of fatigue resistance, but excessive deformation is harmful.
Figure 4. Typical fatigue-fractured surface of the as-received specimen at crack length $a \approx 21$ mm: (a) near the dent surface, and (b) at the centre of the sample thickness.

Figure 5. Typical fatigue-fractured surface of the specimen with three indentations at crack length $a \approx 21$ mm: (a) near the dent surface, and (b) at the centre of the sample thickness.

4. Conclusions

4.1. Indentation influence on hardness and $da/dN$
The effects of indentation on the fatigue crack growth, hardness distribution and fracture characteristic of E-CT specimen made from mild steel were studied experimentally in this study. Indentation incorporated in a specimen could provide considerable reduction of $da/dN$ in the specimen, and could increase hardness near the location of indentation.

4.2. Indentation is to improve the fatigue resistance
According to the discussion above, indentation is sure to improve the fatigue resistance. Compressive residual stress and strain hardening were the predominant factors for improvement of fatigue property. Similar peening method such as induction hardening has been widely and successfully used into railway axles with considerable advantages [15, 16].

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