Residual Stresses Induced by Surface Enhancement Processes

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Abstract The residual stress field caused by shot peening, hole cold expansion, laser shock peening and ultrosonic peening were presented and the influence of residual stresses on fatigue properties were investigated. The results show that shot peening can enhance the fatigue property, especially for high strength alloys. Moreover, hole cold expansion can increase the fatigue strength more than shot peening due to deeper residual compressive stress fields in surface strained layer and smoother surface. Laser shock peening and ultrasonic peening are the high intensity peening processes and can induce both the deeper residual compressive stress layer and the fine microstructure in surface strained layer, therefore they should have more important engineering applications in future.

Keywords residual stress, shot peening, hole cold expansion, laser shock peening, X-ray diffraction

1. Introduction

The weight objectives and aggressive performance are driving components made of advanced high strength materials and manufactured by some special surface enhancement processes to induce compressive residual stress. There are many surface enhancement processes that can introduce beneficial residual stress and improve fatigue property in localized, but critical areas. Shot peening is used on components of almost any shape due to its flexibility. Hole cold expansion is mainly employed to increase the fatigue strength and prolong fatigue life of parts with holes. Laser shock peening (also called as laser peening or shot peening) was originally developed in aeronautical industry to increase the resistance of foreign object damage (FOD) of blades, and then was employed to improve fatigue property of components with or without FOD and corrosion resistance of engine key parts (for example blisks and obturating ring). Ultrasonic peening was used to induce compressive residual stress and get fine microstructure in welded components.

Residual stress is stress present in a structure or component without any external load or any external moment and keeps itself balance. Residual compressive stress always occurs with residual tensile stress. The significance of residual stresses for fatigue is important in various practical problems. Unintentional tensile residual stress can have an adverse effect on fatigue performance, while beneficial compressive residual stress can significantly improve fatigue resistance.

Fatigue cracks generally starts at the free surfaces of components. As a consequence, the surface conditions are most significant for the fatigue behavior of a structure [1-4]. Surface enhancement to improve the fatigue resistance was developed a long time ago and now is still developing toward the high energy, deep surface layer, and complex treatments. Surface integrity is defined as surface conditions and functions for perfect or enhanced component surface and residual stress is the main aspect of surface integrity. Surface enhancement processes improve the fatigue property, stress corrosion cracking resistance and wear mainly by modifying surface integrity. Residual stress plays the important role in increase the resistance of fatigue and stress corrosion cracking.

There are many investigations on measurements and simulations of residual stresses and the role of residual stresses on fatigue crack initiation and propagation behaviors, while there are few quantitative studies on residual stress effects on fatigue strength/limits or fatigue life. Many scientific questions are not well answered and some phenomena cannot be reasonably explained. It is well known that fatigue crack usually starts subsurface where maximum tensile residual stress is for the surface enhanced specimens and fatigue strength is increased, then why can residual tensile stress improve fatigue resistance? Therefore, we should consider the influence of residual stresses on fatigue property in the view of both mechanics and materials science or other theories.

This paper focus on residual stress fields induced by surface enhancement processes and gives a brief review on the role of residual stress in the fatigue crack initiation and propagation behavior based on our many investigations.

2. Residual stress field characteristics and its effects on fatigue property for surface enhanced specimens

2.1. Residual stress field features induced by surface enhancement processes

It is important to obtain the residual stress field features before analyzing the effects of residual stress on fatigue performance. Many surface enhancement processes induce compressive residual stress in surface layer by elastic-plastic deformation, so the residual stress distribution in a material is often as a result of the retained strain of inhomogeneous plastic deformation. It should be pointed out residual stresses discussed here occur just on the macroscale. On a much smaller scale, another kind of residual stress can be present. It is well known that plastic deformation on a microscale is not a homogenous process and mainly induced by dislocation slips or twins or kinks which depend on deformation strain and strain rate as well as the tested material. Therefore, it is different from grain to grain, and even inside a single grain, the plastic deformation may be just concentrated into a few slip bands. The microresidual stresses are significant for explaining fatigue mechanism although it is not easy to obtain the precise and accurate values unless the deformation mechanism is clear. The characteristics of residual stress field induced by surface enhancement processes were briefly described as follows.

(1) Shot peening

Shot peening is a well-known process to introduce favorable residual stresses at the material surface of a component. This process plastically stretches the surface layer of a material and the elastic substrate material restrains this plastic deformed surface layer, therefore, residual stresses are induced. A typical residual stress field caused by shot peening is illustrated in Figure 1 and some parameters were proposed to analyze the characteristics of residual stress field by shot peening.

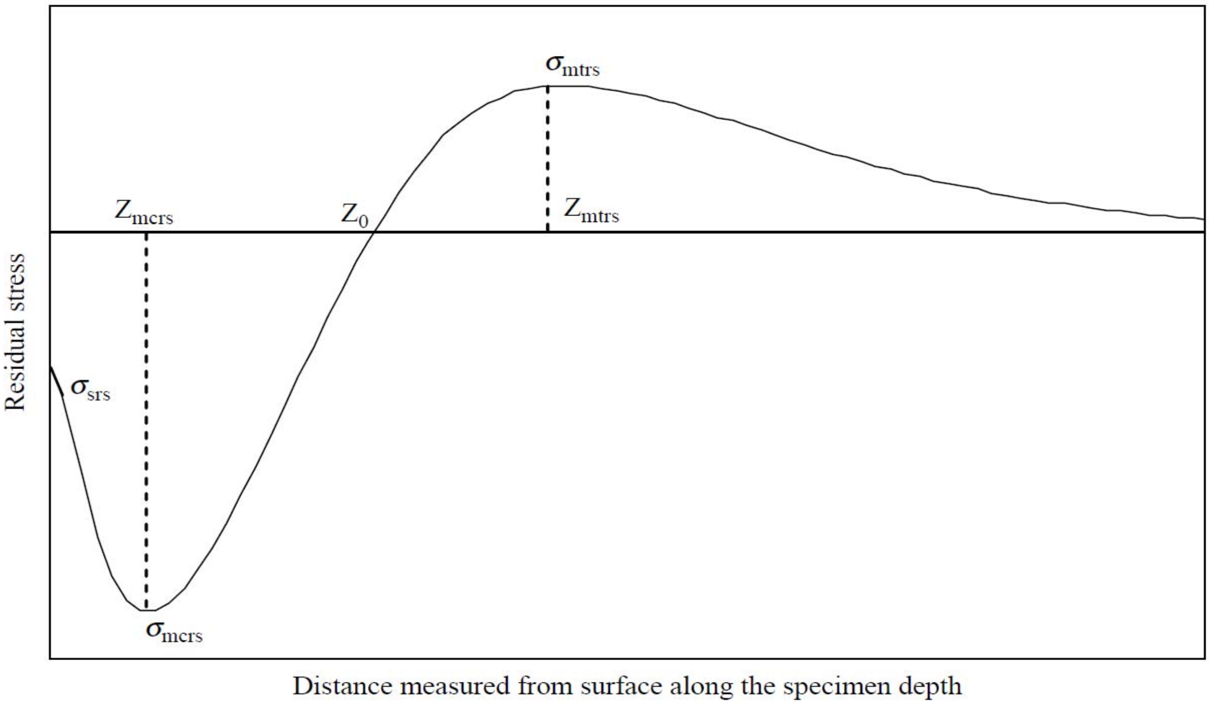

Fig. 1 Schematic residual stress field caused by shot peening

There are six parameters to show the residual stress distribution shown as in the Figure 1. σ_{srs} is the residual stress at the surface or call it as surface residual stress. σ_{mcrs} is the maximum compressive residual stress and its value is often more than half yield strength even in some cases near the yield strength for fcc crystalline metals but it is usually near the surface in the most cases. σ_{mtrs} is the maximum tensile residual stress its value is the order of tenth to half of the value of σ_{mcrs} , this depends on the thickness of specimens. Z_{mcrs} is the distance from surface where compressive residual stress is the maximum. Z_0 is the depth where residual stress becomes zero and beneath where residual stress will change from compressive to tensile. Z_{mtrs} is the distance from surface where tensile stress is the maximum one. The values of these parameters are related to shot peening process parameters (such as shot peening intensity, surface coverage, shot's size and hardness etc.) and the peened material. The relationship of the values of these parameters to process parameters and material's property is given in the references [5, 6].

(2) Hole cold expansion

Hole cold expansion has been developed to increase fatigue resistance of components with holes. The hole is firstly drilled to a slightly undersized one which is a few percent smaller than the design size. Then a tapered pin or a split sleeve over a mandrel pulled through the hole to expand material around hole. As a result, plastic deformation occurs and the plastic zone has been stretched tangentially because it pushed outwards in the radial direction. The plastic zone has a larger diameter than before and the elastically strained material around this plastic zone will exert a pressure on the plastic zone, therefore tangential compressive stresses around the hole are introduced. The values of residual stress depend on the interference of hole to the tapered pin or the thickness of split sleeve over mandrel as well as the cold expanded material. A typical residual stress distribution along the cold expanded hole is given in Figure 2 [7].

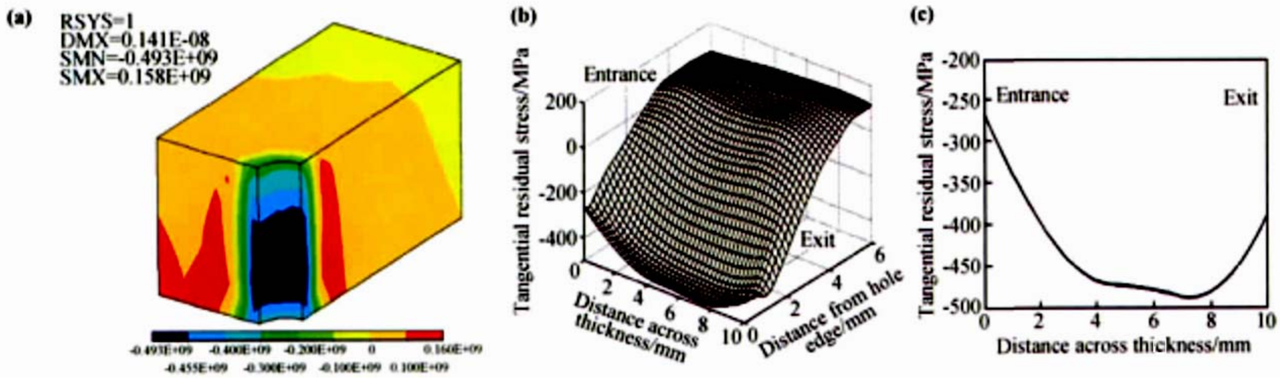

Fig.2 Tangential residual stress distribution of hole cold expanded 7050-T7451 aluminum alloy in (a) the whole component, (b) smallest cross-section plane and (c) hole edge along thickness [7]

The maximum compressive residual stress is not at the upper entrance surface or lower exit surface but the middle surface near exit surface. Moreover, the residual stress at entrance surface is less than one at the exit surface. Therefore, the 2-D residual stress could result in significantly under or overestimating fatigue life.

(3) Laser shock peening

Laser shock peening exposes the surface of a workpiece to laser pulses with pulse duration in the nanosecond range and obtains a modified surface layer on the order of millimeters. A typical residual stress distribution caused by laser shock peening is shown in Figure 3. The values of residual stresses depend on process parameters and peened material. The main parameters are pulsed energy, pulsed times and pulse duration. The mechanisms of deformation which occur in plastic shock wave deformation are highly dependent on the strain rate. It is well known that twin formation becomes particularly relevant as strain rate grows. Deformation is strongly determined by stacking fault energy, which constitutes a measure of the probability of cross slip of screw dislocations. Moreover, it is should be noted that any kind of thermal manipulation must be avoided; otherwise it will induce tensile residual stress. Consequently, the absorption layer must be thick enough to prevent thermal effects on the workpiece itself, and particularly in cases of overlapping irradiation, the absorbing layer should not have sustained damage that may result in thermal effects on the workpiece during the final irradiation. There are some differences in the values of residual stresses for different pulse times for easy plastic-deformation alloy as shown in Figure 3.

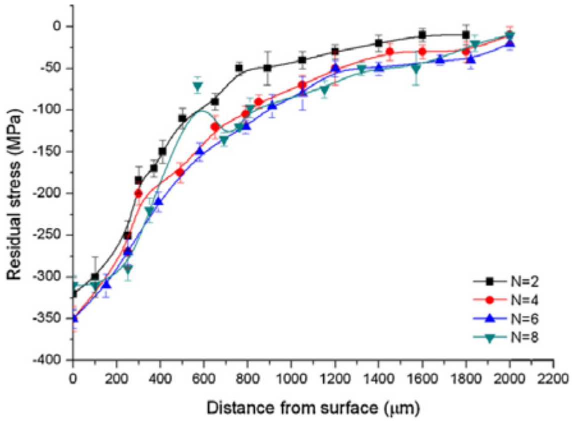

Fig.3 Residual stresses caused by laser shock peening in 7050-T7451 aluminum alloy [8]

(4) Ultrasonic peening

Ultrasonic peening induces deeper residual stress surface layer than conventional shot peening [9], as illustrated in Figure 4. Compared with shot peening, the value of surface residual stress for ultrasonic peened specimens is almost same as shot-peened one, while the maximum residual stresses of compressive and tensile are larger than shot-peened ones.

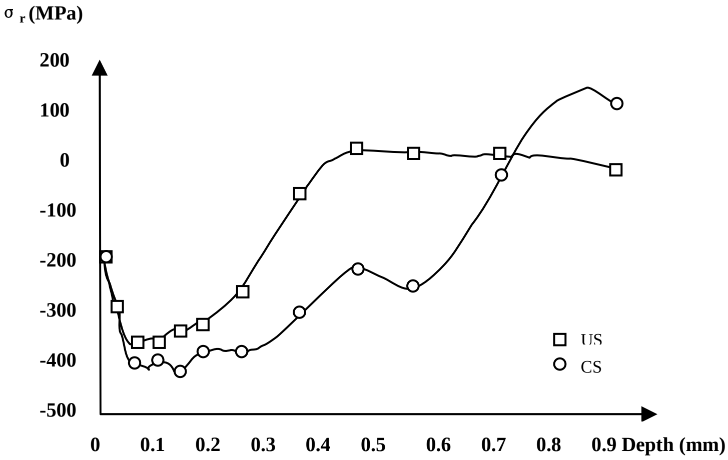

Fig.4 In-depth profile of residual stress in 2014-T6 aluminum alloy produced by conventional shot peening (CS) and ultrasonic peening (US) [9]

2.2. Effects of residual stress on fatigue crack initiation behavior

There are many investigations on residual stress on fatigue performance, and now we just provide some results of our studies. The rotating bending fatigue tests (stress ratio R=-1) were conducted for some aeronautical metallic materials including high strength steels, aluminum alloys, and titanium alloys. A total of 20 specimens were tested as a group to determine the fatigue strengths/limits for each alloy at 1×10^7 cycles by staircase method [10]. The experimental results are shown in Table 1. The apparent or nominal fatigue strength or limit, σ_{app}, is determined by the applied stress range, σ_a, for rotating bending fatigue tests. The local strength or limit, σ_{loc}, is calculated as the critical stress for fatigue crack initiation by combing the local applied stress, σ_{locapp}, with the local residual stress, σ_{locrs}, that is $\sigma_{loc} = \sigma_{locapp} + \sigma_{locrs}$. Moreover, the effect of surface enhancement is illustrated in the fatigue strengthens/limits increase of surface-enhanced specimens compared with unenhanced ones by as given in Table 1. The fatigue crack sources were determined by scanning electron microscope (SEM) and the locations of fatigue crack sources were determined by the distance from surface [11]. Some typical fatigue crack sources are shown in Figure 5. The fatigue crack sources always locate at the surface for unenhanced specimens, whereas for those surface-enhanced ones, they are located beneath the surface-enhanced layer where residual stress is tensile.

Table 1 Rotating bending fatigue strengths/limits of high strength aeronautical structural materials

Material	Surface condition	σ_{app}/MPa	σ_{loc}/MPa	σ_{sur}/MPa	σ_{int}/MPa	$\sigma_{int}/\sigma_{sur}$
40CrNi2SiMoVA steel	Machining	718	750	750	1065	1.42
	Shot peening	1040	1065			
16Co14Ni10Cr2Mo steel	Machining	720	720	720	966	1.34
	Shot peening	835	966			
0Cr13Ni8Mo2Al steel	Machining	763	738	738	997	1.35
	Shot peening	887	997			
2121-T851 aluminum alloy	Machining	160	160	160	224	1.40
	Shot peening	206	224			
7050-T7451 aluminum alloy	Machining	185	185	185	261	1.41
	Shot peening	223	252			
	Laser peening	263	261			
7475-T7351 aluminum alloy	Machining	170	150	150	206	1.37
	Shot peening	202	206			
TC21 titanium alloy	Machining	420	400	400	560	1.40
	Shot peening	550	560			
Ti60 titanium alloy	Machining	416	430	430	594	1.38
	Shot peening	580	594			

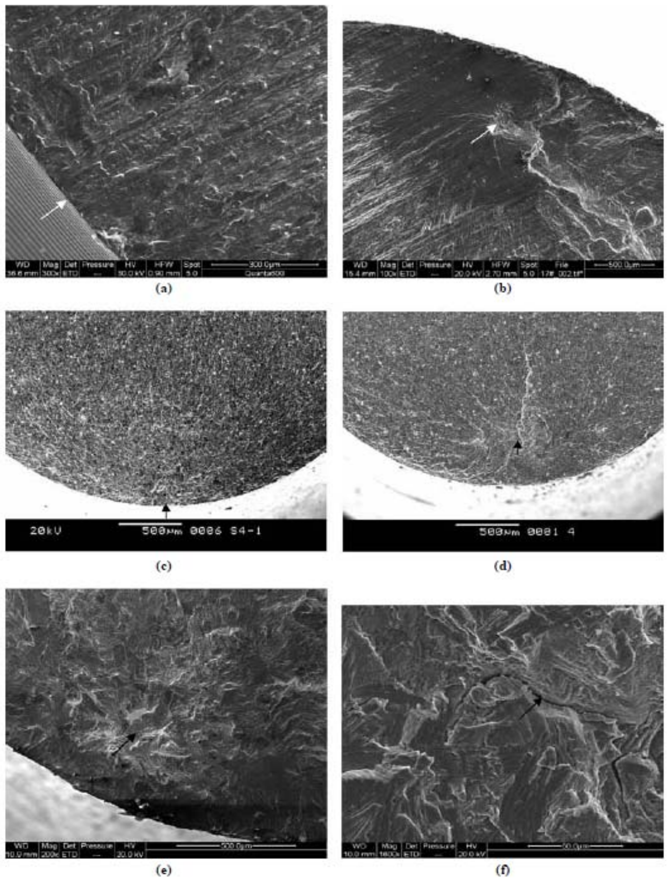

Fig.5 Typical fatigue crack sources (a) Machined specimens of 7050-T7451 aluminum alloy, (b) shot-peened specimens of 7050-T7451 aluminum alloy, (c) machined specimens of Ti60 titanium alloy, (d) shot-peened specimens of Ti60 titanium alloy, (e) shot-peened specimens of TC21 titanium alloy, (f) fatigue cracks in the fatigue crack sources of shot-peened specimens of TC21 titanium alloy

2.3. Influence of residual stress on fatigue crack propagation performance

The effect of shot peening on small crack growth was investigated in a 7475-T7351 aluminum alloy [12]. A single edge notch tensile specimen was employed and the notches were shot peened. Small crack growth fatigue testing was performed in an MTS fatigue tester using constant amplitude loading (stress ratio R=0.06 and maximum stress σ_{max} =160MPa) in a frequency of 10Hz at room temperature under laboratory air conditions. The plastic replica method was used to record small crack data at the notch root. To acquire accurate small crack lengths, acetyl cellulose plastic replicas (often called AC paper) were employed to monitor the small crack length as a function of the number of load cycles. Stress intensity factors for small cracks subjected both to external loads and to shot peening induced residual stresses were determined using weight function methods [12, 13]. The fatigue small crack growth rate was analyzed by FASTRAN software [14] and the crack propagation behavior of unpeened and shot-peened specimens is shown in Figure 6 and Figure 7, respectively.

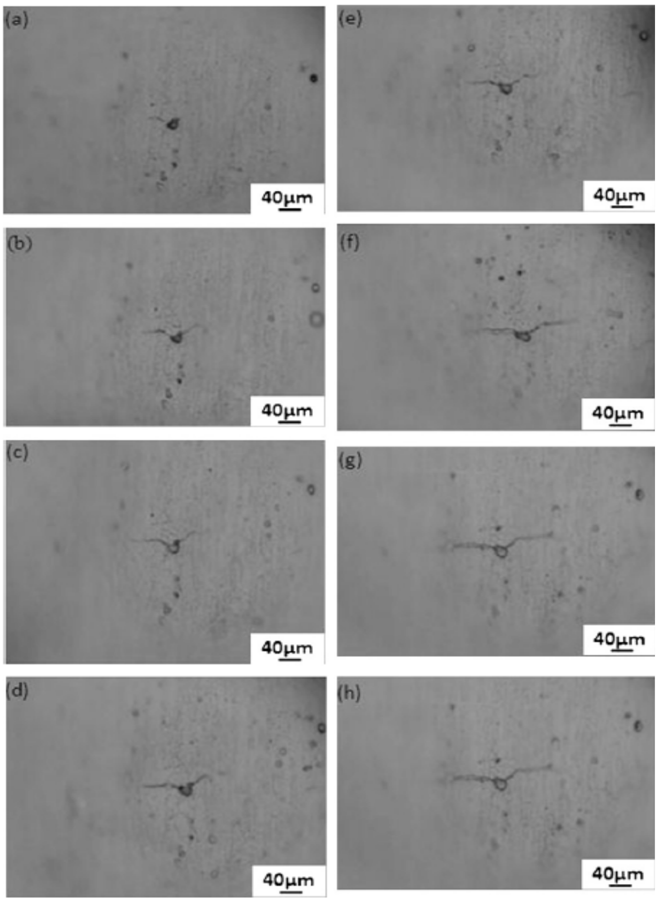

Fig.6 Replica SEM images showing small crack growth in an unpeened specimen of 7475-T7351 aluminum alloy for N cyles: (a) N=3000, (b)N= 6000, (c) N=9000, (d) N=10000, (e) N=11000, (f)N=13000, (g) N=15000, (h) N=18000. Finial failure occurred at 28000 cycles.

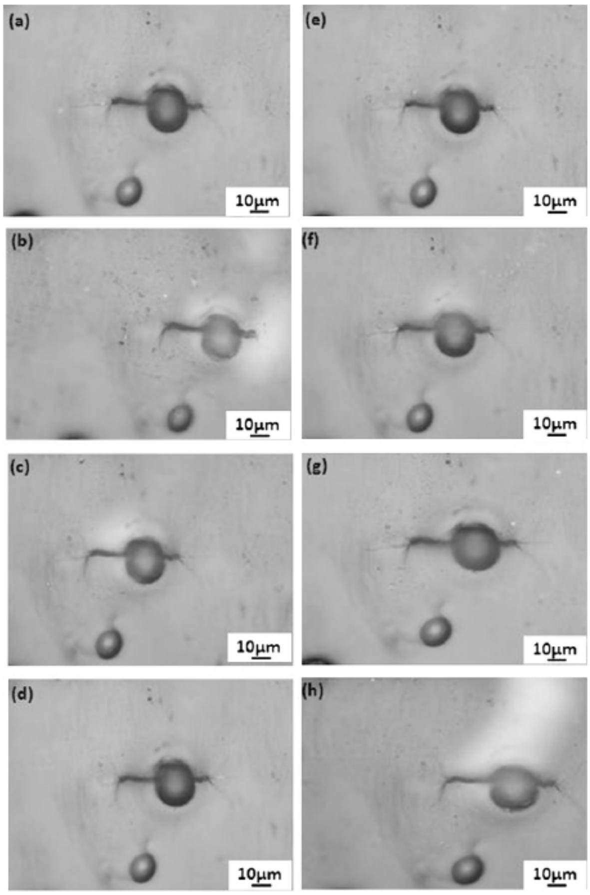

Fig.7 Replica SEM images showing small crack growth in an peened specimen of 7475-T7351 aluminum alloy for N cyles: (a) N=6000, (b)N= 7000, (c) N=8000, (d) N=10000, (e)N=12000,(f) N=14000, (g) N=16000, (h) N=19000. Finial failure occurred at 84000 cycles.

Compared with unpeened specimens, the small crack growth rates are very much lower for shot peened specimens. It is obvious that the small crack growth will show lower curves rate than large one if the residual stress effect is not considered, while it is normal rate if the effect of residual stress is considered, as shown in Figure 8. Therefore, the influence of residual stress on fatigue crack propagation behaviors or growth rates should be considered.

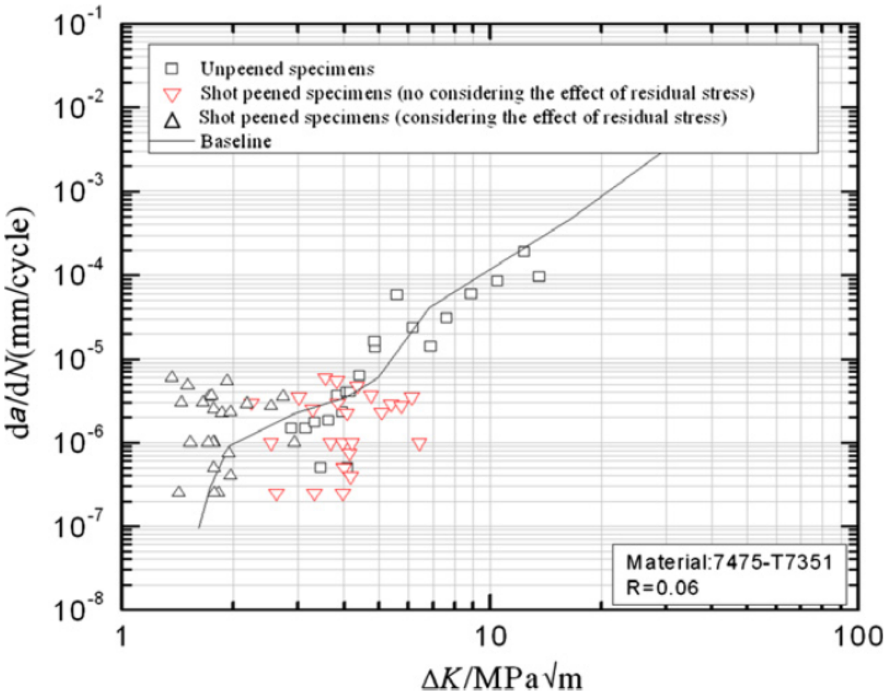

Fig.8 da/dN-△K curves for 7475-T7351 aluminum alloy

3. Conclusions and Recommendations

Residual stress has a significant effect on fatigue, stress corrosion cracking and other fracture performances. The residual stress distribution should be investigated quantitatively by experimental measurements or simulations and obtain the three dimensional characteristics.

(1) Surface enhancement processes introduce compressive residual stresses in surface layer and there are some parameters to describe the features of residual stress fields caused by surface enhancement treatments.

(2) Compressive residual stress can be measured by X-ray diffraction or neutron scatting and simulated by finite element methods or boundary element methods, therefore its effects on fatigue and fracture can be analyzed quantitatively.

(3) The fatigue crack can be initiated beneath compressive residual stress filed for surface enhanced specimens and the effect of residual stress should be considered both in the view of mechanics and materials science. Fatigue strengths/limits are increased by compressive residual stresses and surface cold worked layer for surface enhanced specimens.

(4) Fatigue crack growth rate is lower in the compressive residual stress filed for surface enhanced specimens compared to unenhanced ones; the effect of residual stress can be quantitatively analyzed by weight function methods and FASTRAN software.

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