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THE EFFECT OF CRACK CLOSURE ON HEAT GENERATION IN VIBROTERMOMOGRAPHY

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ABSTRACT. Vibrothermography is a nondestructive evaluation (NDE) technique that has shown great promise in detecting tight cracks that can often be missed using other NDE methods. Vibration applied to a structure containing cracks forces crack faces to rub together and generates frictional heat imaged with an infrared camera. The closure state of a crack controls the locations and magnitude of heat generation in a vibrated crack. Noncontacting regions of cracks and regions under large closure stresses generally do not rub together to generate heat. Heat is generated at contacting regions of crack faces under low closure stresses. Regions along a crack that generate heat can be modulated based on externally applied stresses. The closure state of a crack, the level of applied vibration, and externally applied stresses influence the regions of a crack that will generate heat and those that will not. Due to the nature of the heat generation process, some cracks that are not detectable using other NDE methods are readily detectable using Vibrothermography.

Keywords: Vibrothermography, Sonic IR, Crack Closure, Crack Detection, Heat Generation, Thermosonics

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INTRODUCTION

Crack closure is the process by which residual stresses force crack faces into contact. Closure stresses hold crack faces together due to a variety of mechanisms including plasticity-induced closure, roughness-induced closure, oxide-induced closure, etc. [1]. Crack closure is an important parameter that affects both crack propagation rates as well as the detectability of cracks in structures. Crack closure was first observed by Elber [2] and is an important parameter in understanding crack propagation. It is equally important in nondestructive evaluation (NDE) since crack closure affects the ability of NDE techniques to detect the presence and locations of cracks in structures. NDE techniques are most sensitive to open cracks since open cracks create a larger interruption in the bulk structure of a material. Open cracks have lower amounts of closure between the crack faces than tight cracks creating an effectively larger defect volume. Larger defect volumes give increased contrast in X-ray inspections, serve as fluid reservoirs for fluorescent penetrant inspections, interrupt the magnetic fields involved in eddy current inspections, leak more magnetic flux in magnetic particle inspections, and provide reflective surfaces for ultrasonic inspections. Additionally, increased closure decreases the probability of detecting and increases the probability of undersizing a detected crack [3]. Thus, the major NDE techniques are more sensitive to open cracks than tight cracks.
Vibrothermography, also known as Thermosonics or Sonic IR, is an NDE technique gaining increasing attention due to its ability to rapidly detect cracks, delaminations, and disbonds in structures [4]. A significant advantage of Vibrothermography is that it does not rely on the presence of open defect regions to interrupt the bulk structure and trigger a detectable response as do other major NDE methods. Vibrothermography instead relies on the rubbing of crack faces to generate heat. Frictional rubbing does not depend on the presence of open regions along a crack for the inspection method to be effective. Thus, Vibrothermography has the potential to detect tighter cracks with greater reliability than is possible using other NDE methods.

The method of defect detection using Vibrothermography is shown in Figure 1. First, a part is vibrated using a transducer [5, 6]. The vibrations force opposing crack faces to rub together. Heat is generated at rubbing crack faces due to friction, increasing the temperature of the material surrounding the defect. An infrared (IR) camera is used to observe the outer surface of a sample for the presence of defects which are indicated by locations of local temperature changes on the surface. Thus cracks, disbonds, delaminations, and other defects with contacting interfaces may be observed due to friction-induced heat generation at the defect.

The amount of crack closure and the distribution of closure stresses between crack faces affect the heat generated in Vibrothermography and appear to be major factors influencing both the detectability of a crack as well as determining which crack regions, if any, will generate heat due to applied vibrational stresses. Both the amount of heat generated as well as the locations within a crack that generate heat are affected by the closure state of the crack and can be modulated by applying an external load to open or close the crack [7, 8].
**THEORY**

Crack faces may be forced into contact through a variety of mechanisms. Generally, the dominant closure mechanism is plasticity-induced closure, caused by the envelope of plastically-stretched material from the plastic zone around an advancing crack tip forcing crack faces into contact upon relaxation of the externally-applied load that grew the crack. A second important mechanism, roughness-induced closure, results from a mismatch in opposing fracture surface roughnesses giving way to additional closure stresses between crack faces. Many other closure mechanisms are possible based on the conditions to which the crack was subjected [1, 9, 10]; however, these mechanisms were not significant in the cracks studied in this paper. Closure mechanisms affect the detectability of cracks by causing crack faces to contact prematurely (under tensile or zero external load) and creating interactions between the faces of the cracks. These interactions cause closure stresses between the crack faces that can reduce or eliminate the ability of NDE techniques to detect the cracks or mask portions of the crack [3, 11].

Heat is generated in contacting regions of the crack that are under low, but nonzero closure stress. The regions of the crack that are held together too tightly to be rubbed together due to the applied vibration are referred to as locked asperities. Locked asperity regions do not generate heat since the crack faces are not free to rub against each other. Similarly, regions of the crack that do not contact due to the applied vibration, but remain open do not heat and are referred to as open regions. Thus, heating asperities are those regions of the crack where asperities are in contact and rub due to the applied vibration which generates frictional heating. Heat generated in cracks is not uniformly generated along the surface of a crack. Different regions along a crack will heat up to varying degrees and in many cases, certain regions of a crack will not generate any heat. It is possible that heat can be generated both at the surface as well as below the surface. Figure 2 shows a depth profile of a semielliptical surface crack with a schematic of the crack heating as a function of the crack length and depth. Figure 2 shows that heat generation can occur both at the surface and below the surface, often giving rise to complicated surface heating profiles as shown in Figure 3. These heating profiles can be very complex depending on the amount and type of closure mechanisms acting along the crack faces; however, due to heat diffusion, these regions often blur together and create difficulties in imaging individual regions of heat generation.

![Figure 2. A schematic of heat generation in a vibrating crack. The figure shows a cross-sectional view of a bar containing a surface crack with a semielliptical depth profile.](image)
Removing the effects of diffusion is not a trivial process. Heat is generated at different contacting regions of the crack and separated by small regions devoid of contact. Additionally, the contact between asperity regions is very complex and heat that is generated by these asperity regions is generated at different amounts along contacting regions. Finally, only temperature changes at the surface of a structure can be imaged, so solutions to back out specific heat generating regions and amounts of heat generated can quickly diverge. Holland and Renshaw [12] have developed a method to remove diffusion effects in the plane of the sample surface by means of a second-order spatial derivative and two-dimensional spatial filtering. This method does not give accurate measurements of heat generation rates, but does eliminate the effects of diffusion due to surface heat propagation. Subsurface heat generation is generally lower than heat generation at the surface due to reduced crack face mobility and the additional heat diffusion length from the subsurface heat source to the surface of the part. This image enhancement method was used on a 13 mm crack as shown in Figure 3. The method effectively isolated regions of heat generation. It can be seen that heat is not uniformly generated along the surface of the crack. More importantly, the heat generating length of the crack shown in Figure 3 is 6.64 mm but the crack length is 13.51 mm. Heat generation was centered between the two crack tips but did not occur near the crack tips. This means that a large portion of the crack did not generate heat due to locking of crack face asperities from the higher closure stresses present near the crack tips. These higher closure stresses resulted from plastic deformations that occurred during the crack growth process.

**EXPERIMENTAL PROCEDURE**

Cracks were grown in Titanium 6Al-4V (Ti 6-4) samples to a length of about 13.0 mm under different conditions designed to grow cracks with different closure states to compare the effect of closure on the positions of heat generating regions of the cracks. The crack in Sample A was grown to have a lower closure stress than the crack in Sample B. After unloading these samples from the servohydraulic testing machine used to grow the cracks, they were placed in a bending fixture to modify the closure state on the crack faces by introducing external tensile loads to counteract the plastic closure stresses. Mounting points were se-
FIGURE 4. Images of infrared crack heating locations as an increasing tensile stress is applied.

lected to correspond to nodal locations of the excited vibrational resonance to minimize their effect on the sample vibration [13]. An external tensile load was applied using the bending fixture to peel open the cracks as the samples were vibrated to generate heat on portions of the contacting crack faces. Regions of heat generation were compared versus the closure state on the cracks to determine the influence of crack closure on the regions of the crack that generated heat.

RESULTS

Figure 4 shows the regions of heat generation as a function of the applied tensile loads for the two cracks. The regions of heat generation move towards the crack tips as the load is increased and away from the tips as the load is decreased. Figure 4 shows that as the closure state of the crack changes, so do the primary regions of heat generation along the cracks. The heat-generating regions of Sample B are closer together than those of Sample A due to the higher crack closure stresses present in Sample B.

Using the regions of heat generation shown in Figure 4, the closure stress profile along a crack can be determined [7]. Regions of heat generation indicate which portions of the crack have been opened and which portions remain locked. Figure 5 shows the heating regions of two cracks as a function of the applied opening stress with the crack length normalized by the total crack length, $2a$, from $-a$ to $+a$. The portion of the crack length that has been opened at a given stress level is the distance between two heat generating regions in Figure 4 or the portion of the crack length between two points at equal applied opening stresses on the graph in Figure 5. The portion of the crack that remains closed, or locked, at a given opening stress is the portion of the crack length beyond the same two points in either figure. The two horizontal lines on the graph in Figure 5 are measures of the crack opening stresses, or the stresses required to fully open each of the cracks. No heat is generated at the crack opening stress level since the cracks have fully opened and the opposing crack faces are no longer able to rub together to generate heat. These data have been used to measure crack opening stresses and crack closure stress profiles of cracks [7]. These data also show that the locked asperities will not generate heat until a sufficient stress is applied to overcome the static frictional forces locking the asperities together.
Comparing the two cracks shown in Figure 4 shows that the regions of heat generation in a tight crack occur further from the tips than in open cracks. This means that tighter cracks have a larger portion of the crack faces locked together than open cracks. These results show that the crack closure stress on a crack affects the regions along a crack that generate heat and that these locations can be modified by applying an external load on the crack. The most important parameters affecting crack detectability in a vibrothermographic inspection are the closure stress along a crack, effects of static loads, and the applied vibrational or dynamic stress level. If the applied vibrational and static stresses on a crack dominate the locking stresses - due to closure stress and static friction on the crack faces - then the crack face asperities will rub against one another and generate heat creating a detectable infrared indication. If the closure stresses and static friction dominate the vibrational and static stresses, however, crack face asperities will remain locked and will not generate heat, causing the crack to be undetectable using Vibrothermography. The presence of both open and locked regions along a crack gives rise to heating asperities as shown in Figure 2 and significantly increases the probability of detection of a crack. Thus, cracks with both open and locked regions will likely also have asperities that are able to vibrate and generate heat. Such cracks exhibit heat generation at lower vibrational stresses. A fully open or fully locked crack is less likely to have asperities able to generate frictional heat and are more likely to be undetectable unless very high vibrational stresses are applied. A crack that is fully open along its length, however, is rare in an NDE inspection.

Smaller cracks have lower crack opening stresses than larger cracks that are grown under identical conditions in constant amplitude (CA) loading, though the crack opening stress is only a measure of the closure at the crack tip. Therefore, small cracks may have a sufficient closure stress along the length of the crack to lock all of the asperities together and prevent heating. Larger cracks are more likely to have larger variations in closure stresses and open regions, making them easier to find. Also, larger cracks have have more mobility and a larger fracture surface area available for heat generation. The larger surface area, larger mobility, and larger variation in closure stresses increase the probability of detection of larger cracks. Thus, defect detection with Vibrothermography is dependent on the applied vibration level, the size of the crack, and the closure profile of the two opposing crack faces. These
FIGURE 6. A tight 3.9 mm crack in a titanium sample heats up significantly due to vibration (above). The same crack was not detected with multiple inspections using fluorescent penetrants.

factors are important in explaining why smaller cracks are generally harder to detect with Vibrothermography than large cracks and thus have lower probabilities of detection [14]. It also explains why some cracks that can be missed with FPI and other methods (due to the lack of open regions) can be easily detected using Vibrothermography, as shown in Figure 6.

Figure 6 shows a 3.9 mm crack with a very small crack opening displacement, giving it a very low defect volume. This crack remained undetectable after multiple fluorescent penetrant inspections, but readily generated heat during a vibrothermographic inspection. Despite the fact that the entire surface of the crack remained in contact, the applied vibrational stress was able to rub the crack faces together and generate heat, making the crack easily detectable. Thus, some cracks that may be missed using FPI or other inspection techniques can be detected using Vibrothermography.

CONCLUSIONS

Cracks of the same size may heat differently depending on the closure stresses on the cracks as well as the influence of externally applied loads. More open cracks generate heat closer to the crack tips than tight cracks and have larger open regions that can aid crack detectability.

This paper shows how closure stresses on a crack affect the heat generation from and detectability of a crack. Larger cracks or more open cracks are generally easier to detect using NDE methods. Smaller cracks or tighter cracks are more difficult to detect with NDE methods, including Vibrothermography. Vibrothermography has, however, shown great promise in its ability to detect tight cracks that cannot be detected using other methods. The detectability of a crack using Vibrothermography is dependent on the amount of heat that the crack can generate. The amount of heat that is generated is related to the crack size, the crack mobility, the level of applied vibrational stress, and the interaction of the closure stresses on the crack with any externally applied loads. A deeper understanding of the heat generation process is needed to develop methods to generate more heat on crack surfaces and increase the probability of detection of cracks as well as understand the limitations associated with this NDE method. Understanding the physics of the heat generation process will help to create more accurate models of heat generation at contacting crack asperities and help Vi-
brothermography to become a better understood and more utilized NDE tool.

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