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Experimental Considerations in Vibrothermography

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ABSTRACT

Sonic, or thermosonic nondestructive testing, which is based on the vibrothermography method introduced in the late 1970's, has attracted a great deal of recent interest as a means for detection of cracks that were previously considered to be undetectable using thermographic inspection methods. Excitation of a solid sample with bursts of high-energy (500 – 3000 Joule), low-frequency (10 – 50 kHz) acoustic energy has been demonstrated to be effective in generating transient localized heating at crack sites, making them detectable by an infrared camera. Despite the apparent simplicity of the scheme, there are a number of experimental considerations that can complicate, or in some cases even prevent, the implementation of vibrothermography-based inspection. Factors including acoustic horn location, horn-crack proximity, horn-sample coupling, and effective detection range all significantly affect the degree of excitation (or whether any excitation occurs at all) that occurs at a crack site for a given energy input. In cases where the experimental objective is precise measurement of crack length, the method used to visualize the data from the IR camera and its optic must also be taken into consideration.

Keywords: Thermography, nondestructive, vibrothermography, sonic thermography

1. INTRODUCTION

Vibrothermography was first introduced in the late 1970's, as investigators observed that as cracks or discontinuities in a solid sample were excited with high energy, low-frequency ultrasound, they generated heat and were detectable with an IR camera.[1,2] Despite this promising start, the technique remained dormant until recently, when techniques known as sonic thermography, or thermosonic testing were introduced[3]. Significant improvements in IR camera performance over the past 20 years have made it possible to detect small cracks using lower excitation energies (or short duration pulses of high energy) than the original reports suggested. As a result, there has been considerable renewed interest in implementing vibrothermography as a nondestructive crack detection method.

Although the precise physical mechanisms that give rise to heating at a crack site are still topics of active discussion by researchers in the field, it is generally agreed that frictional heating at the faces a crack contribute to the temperature rise that is detected by the infrared camera. In the basic scheme for modern vibrothermography-based testing, an acoustic horn is placed in contact with a solid sample, and a brief pulse of acoustic energy in the 10 – 50 kHz range is applied to the sample. Pulse energy is typically in the range of 500 – 3000 Joules, and duration less than a second.

The signal generation process in vibrothermography is almost entirely determined by the interaction of the injected sonic energy with the mechanical properties of the sample. The thermal and IR emission characteristics of the sample play a relatively small role. In principle, heating of the sample is minimal unless a crack or some other source of frictional heating is present. However, in practice, there is often significant localized heating at the sonic insertion point, and also at any clamping points. Nevertheless, discrimination between cracks and background features is relatively straightforward, compared to conventional pulsed thermography, where the entire sample surface is heated. In most solids, propagation of the injected sonic energy to the crack site can be taken to be nearly instantaneous, based on the distance that sound travels in the period of a single IR camera frame (e.g. the speed of sound in steel is approximately 6 mm / microsecond, so the distance traveled in a single video frame period is nearly 100 meters for a camera operating at a 60 Hz frame rate). Furthermore, the degradation of the injected pulse by dispersion or attenuation is relatively low, compared to the severity of diffusion on an injected thermal pulse. As a result, in certain materials, it is possible to effectively excite features that are relatively far from the insertion point.

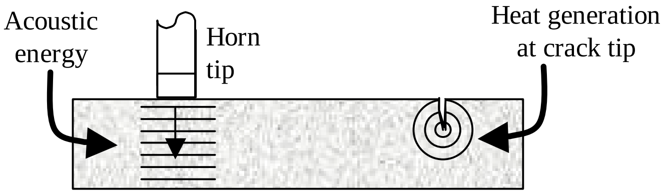

Figure 1: Sketch of basic vibrothermography interaction. Acoustic energy from a horn is injected into a solid sample, causing frictional heating at the tip, or along the faces of a crack.

2. PRACTICAL CONSIDERATIONS

Although the amplitude, frequency and duration of sonic excitation are factors in effective crack excitation, in most cases these parameters are less critical than details of the experimental setup, which can completely undermine the detection process if they are not handled properly. In attempting to implement an inspection for crack detection using vibrothermography, one must be attentive to several requirements and limiting factors:

?? ***Sonic energy from the horn should be coupled into the part as efficiently as possible.*** The horn tip should be parallel to the surface of the part, and held in place with sufficient mechanical pressure to insure constant contact throughout the sonification process. For many applications, curvature or irregularities in the sample surface may make it impossible to achieve parallel placement of the horn tip and surface. In such cases, a compliant couplant layer may be used to compensate for any misalignment. The coupling layer also serves to prevent slipping and sliding of the horn, and also protects the sample surface. However, the liquid couplant used for conventional ultrasonics do not provide these desired gripping or protective functions. Instead, a thin solid sheet of a relatively soft, yet sonically conducting material is often used as the intermediate coupling layer. Unfortunately, selection of the appropriate material is an empirical trial and error process. Couplant materials including metal foils, paper, leather and Teflon$^{?}$ have been used successfully, but no one material has proven to be a universally good couplant.

?? ***Energy inserted to the part should not be coupled to the fixtures or mounting hardware.*** Ideally, the part would be floating, i.e. unattached to any fixture, yet rigid, so that energy injected into the part remained there. In practice, some energy delivered to the part will inevitably be transferred to the mounting hardware. In the worst case, energy will simply pass through the part to the hardware, and cracks, if present, will not be properly energized. It is important that mounting and fixturing is designed to minimize energy transfer, i.e. fixture materials should be chosen to maximize the acoustic impedance mismatch with the part.

?? ***The part and horn should be mounted rigidly.*** The objective of the ultrasonic horn is to excite the lattice structure of the part. Inadvertent translation, rotation or large-scale vibration of the sample during the excitation process Similarly, the horn fixture should not allow any slippage or lateral motion of the tip.

?? ***The horn should not damage the surface of the part.*** The horn tip is often a hard metal alloy, e.g. titanium. Viewed with a high-speed camera, it becomes apparent that the action of the horn is essentially a hammering motion, i.e. the tip lifts off of the sample surface and then makes contact with each sonic period. The effect of tens of thousands of such impacts in a brief period is often some scuffing of the sample surface. In most cases, this can be avoided with the use of an appropriate couplant material. However, it also emphasizes the need to operate at the lowest possible energy levels at which reliable detection can be achieved.

Although these considerations may seem obvious, it is often the case that they cannot all be optimally achieved in a given situation. Often, factors such as the shape of a part, the delicacy of its surface finish, or limited access to appropriate insertion points necessitates that trade-offs in the considerations listed above are made. For example, inspection of a part with a delicate surface finish that must not be scratched or marred may require the use of a thicker, tougher couplant that will protect it, at the expense of coupling efficiency.

3. INSPECTION CONSIDERATIONS

In developing an inspection procedure for vibrothermography, there are additional considerations that should be addressed in order to determine that critical defects can be detected reliably. At this point in the development of vibrothermographic methods for NDE, there are no prescribed rules for addressing these considerations. Instead, they must be addressed empirically, using test samples in the laboratory, before actual testing takes place.

?? ***Field of excitation:*** In many situations, acoustic energy can excite cracks far from the insertion point (?1-2 feet). However, frictional heating at a crack diminishes in proportion to the distance between the crack and the excitation source. Thus, for a given inspection, the maximum crack-source distance for reliable heating and detection must be determined experimentally, based on a crack that is equivalent to the required critical flaw size. The field of view must then be chosen so that every point in the field of view falls within the necessary minimum distance to the source.

?? ***IR camera optics:*** Some compromise must be achieved between the desires to inspect a large area in a single sonic excitation event, to image the smallest cracks possible, and to use a relatively modestly priced, medium resolution infrared camera. As the field of view increases in size, the projection of each pixel in the infrared camera focal plane also increases in size. If an inspection requirement is based on identification of cracks greater than a particular size, precise measurement of cracks may not be possible if resolution is diminished because the field of view is too large.

?? ***Method of visualization:*** In many cases, crack indications are easily identified in the raw image from the infrared camera. In these instances, little or no additional image processing is required to detect the presence of the indication. However, measurement of the crack length, or validation that the indication is actually a crack, may require more sophisticated processing techniques. Similarly, smaller cracks may not be readily detectable in the raw image, and may require special processing.

?? ***Process control:*** At present, this is one of the most challenging aspects of implementing a vibrothermography-based inspection. Simply put, there is no straightforward way to determine that for a given excitation event, the entire field of excitation was properly sonified. In a production environment, where identical parts are to be inspected repeatedly, the situation is less severe. However, for a new, unknown part, without prior testing and characterization, it is difficult to discriminate between a null result from a defect part, and one from a part in which proper excitation was not delivered.

4. EXAMPLE

To illustrate the effects and considerations discussed above, a 0.050” thick 7075 aluminum plate sample with a prefabricated crack was inspected using a commercial vibrothermography system. No surface preparation was applied to the sample. The camera was located off axis in order to minimize reflection of the camera optics off of the sample surface. A half second sonic pulse from a 2.2 kilojoule horn operating at 50% amplitude was applied to the plate, which was clamped on all sides. Teflon tape was applied to the horn tip to protect the sample surface. In a typical image from the IR camera (Fig. 2, left) in which the pre-excitation image has been subtracted, several indications of anomalous heating appear, as a result of a) heating of the sample, horn and tape at the insertion point, b) friction at various clamping points, c) reflection of heat generated at the insertion point by a hole drilled in the sample, d) the actual crack. Blooming of the heat generated around the crack indication obscures the actual shape and size of the crack. However, the 2nd time derivative of the identical data yields an image in which the actual crack shape is more clearly discerned, and discriminated from the non-crack heat sources, which appear with opposite polarity.

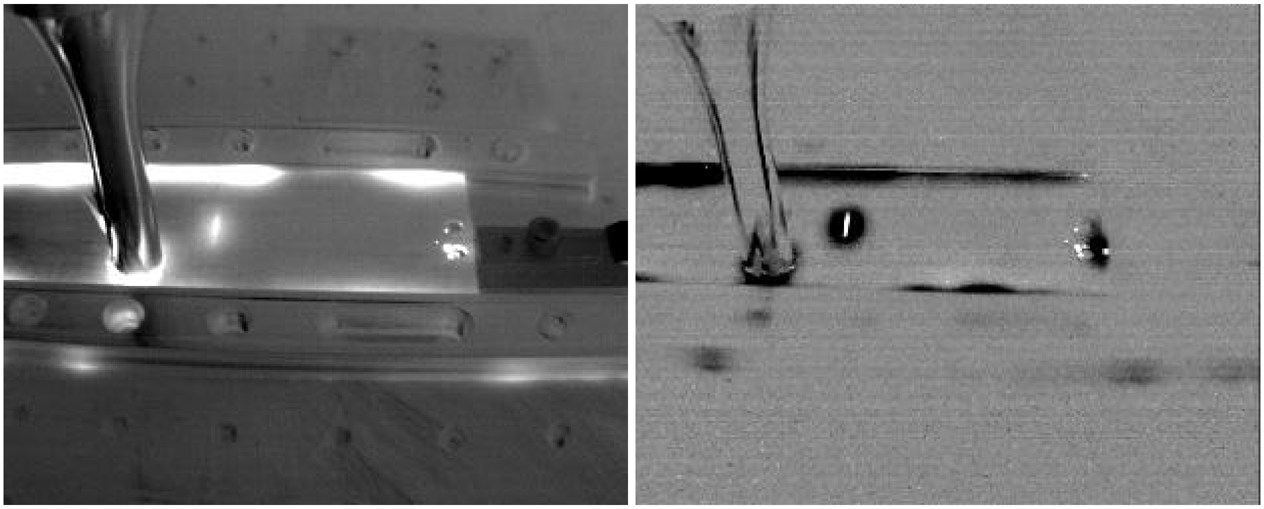

Figure 2: (left) Image with pre-excitation subtraction shows anomalous heating due to the horn tip, friction at various clamping sites, reflection from a hole at the right edge of the sample, and the actual crack. (right) In the 2nd time derivative image of the identical data, only the actual crack appears white. All other features due to non-crack heating appear with the opposite polarity.

5. CONCLUSION

Vibrothermography-based inspection methods have the potential to facilitate extremely sensitive detection of small, tightly-closed cracks that are undetectable using other thermographic methods. However, development and implementation of an inspection procedure requires extensive validation in order to establish limits of detectability, field of excitation, and appropriate fixturing for samples. Additional work is required to determine the appropriate insertion point(s) that will allow reliable and repeatable excitation of the part. These requirements suggest that at present, the technique is best suited for manufacturing quality control type situations, where identical parts are to be tested, and not for applications where unknown parts must be tested without the opportunity for pretest planning and configuration.

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