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A summary is presented of the major findings of a program whose objective was to investigate the phenomenon of preferential heat generation around damaged regions in materials subjected to mechanical vibrations and to develop an understanding of the mechanisms involved in this process. Vibrothermography is a nondestructive inspection technique based upon the utilization of this phenomenon. It has been found that this technique has considerable potential for inspecting composite materials. A significant amount of knowledge has been gained concerning the nature of the heat generation process and the relation of the frequency dependence of the heat patterns to the mechanical excitations. In particular, we now have convincing evidence that the heat generation around a delamination-type defect occurs preferentially at frequencies corresponding to natural resonance modes of anisotropic plates having the size of the delamination and subjected to fixed-fixed boundary conditions.

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Vibrothermography: Investigation, Development & Application of a New Nondestructive Evaluation Technique

Final Report

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November 26, 1986

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Statement of Research Program

Vibrothermography is a nondestructive testing technique which utilizes a combination of mechanical vibrations and real-time video-thermography to investigate the internal state of damage in materials. The basic concept was discovered in our laboratory at Virginia Tech. It was observed that mechanical vibrations of various types, when introduced into a specimen, caused preferential dissipation of energy into heat around internal discontinuities. This technique is unique in its ability to characterize complex damage states (such as develop, for example, during the fatigue of composite materials) in a manner which is directly related to the mechanics of the defect formation and of the defect state. Because of this, the technique can be developed for quantitative nondestructive measurement of the severity and distribution of defects and damage states.

This research program was begun to specifically address the question of how heat is generated in damaged materials under vibratory excitation, and to develop an understanding of the mechanisms involved in those processes. An attempt was to be made to establish the physical parameters which control the heat generation processes, in order to enhance the efficiency of developing test methods (and choosing materials) based upon vibrothermography. In addition, the program attempted to further develop the general method of vibrothermography for a few select applications of particular importance. To be more specific, the objectives of this investigation were stated as follows:

1. To thoroughly investigate and ultimately model the mechanism of heat generation by internal flaw surface-surface interference.
2. To develop a philosophy and testing scheme that can be used to reliably establish the material properties that determine the quantitative suitability of different materials (and components) for the application of vibrothermography for defect detection, monitoring, and interpretation.
3. To develop a philosophy and experimental method for the processing of the appropriate heat pattern details in a way that will serve the purpose of analytical interpretation and, eventually, automated pattern analysis.
4. To consolidate and expand the information that we, and others, have obtained regarding all types of hysteretic energy dissipation that is known or suspected to be of significance to the further development of vibrothermography.

5. To begin the development of an understanding of the heat patterns generated by distributions of defects, especially as those patterns relate to the strength, stiffness and life of engineering materials.

The approach which was used to achieve these objectives was to conduct a systematic investigation, mostly experimental in nature, wherein certain variables were controlled and the resulting response was noted. Strain rate, stress state, defect type and shape, material type and excitation history were controlled and varied to establish the mechanism of heat generation and to determine the limitations of the method. A philosophy and understanding of these effects were sought so that results could be extended to situations which are not specifically addressed in our program. The first concern of our approach was to establish the basic nature of the vibrothermography effects and to develop an understanding and description of those effects. That understanding was tested by selecting several practical situations to examine and by comparing the results with our expectations.

Summary of Important Results

The first major objective of this research program was to determine the mechanisms of heat evolution responsible for the development of the observed thermographic heating patterns in the vicinity of damaged regions. Before this objective can be achieved, it is necessary to establish in general the heat evolution mechanisms in mechanically loaded systems. This objective was studied early and results were reported in Ref. 2 listed under Publications and Technical Reports Published. We found, to begin with, that the present state of the field of study concerning energy dissipation in solid materials is disjunct. In fact, in our opinion, the lack of a unified approach to the field has been a serious impediment to progress. In any case, examination of the literature for mechanisms which may be responsible for heat generation in the vibrothermography technique led to some conclusions about which mechanisms were <u>not</u> responsible. For example, the dissipative mechanisms associated with anelasticity are not of practical importance to the vibrothermography technique because of the low amount of heat such mechanisms produce and the low frequencies at which these mechanisms are excited. Also, examination of the literature led to some conclusions concerning which parameters are important to stress-related thermal emission processes. An example here is the fact that thermal conductivity of the material interrogated plays a dominant role in the thermographic patterns developed while the geometry dependence (region size, for example) plays a more minor role [2].

The application of the vibrothermographic technique is affected by our practical ability to observe and produce heat images. We have found that, as expected, the temperature difference between heat generating regions and non-heat generating regions can be as much as three orders of magnitude greater for insulators than for good conductors. Second, the sharpness of the temperature gradients is also different, i.e., for good conductors the distance over which the temperature change is spread is less. Both of these factors affect the acuity of the heat image developed. Details of the dependence of image acuity upon these factors were presented in Ref. 2. For stress related thermal emission to be used to locate material defects and characterize the local response in the neighborhood of a defect or flaw, only certain mechanisms are of practical interest. We may categorize those mechanisms as anelastic effects, viscoelastic effects and structural dissipation. The only anelastic effect which is possibly important to the vibrothermographic technique is the dissipation produced by relaxation mechanisms in long chain molecules. If history-dependent behavior (viscoelastic effects) is present, especially plastic deformation and localized slip, very large temperature differences can be produced in both good and poor conductors. We have reported on several occassions in the past that structural dissipation on the local level due to the interference of two surfaces which rub, flap, or pound against each other under cyclic excitation may also produce considerable heating. Our experimental work has indicated that the latter two mechanisms are typically acting concurrently, especially in composite materials, and are responsible, almost entirely, for the observed heat patterns (Ref. 3, for example.) Recent experimental work has led us to alter this viewpoint, somewhat. We now believe that the majority of heat production during application of the vibrothermographic technique results from viscoelastic dissipation mechanisms which occur preferentially in the neighborhood of a flaw due to stress concentrations which are increased when a delamination-type flaw is excited in one of its resonant modes. This observation will be discussed further in a latter portion of this report.

One of the more efficient heat-producing mechanisms, according to our experimental observations, is plastic deformation in metals or polymers. For example, a bar of aluminum cycled in tension-compression fatigue to load levels above the yield stress reached a steady state temperature 140°C above ambient. A polycarbonate specimen, loaded quasi-statically at a slow rate developed deformation bands which slowly progressed through the specimen. The temperature in these deformation bands exceeded 16°C above that in undeformed regions of the bar [3]. On the other hand, in composite materials, we have made an especially large number of experimental observations under both large amplitude, fatigue loadings and low amplitude, high frequency loadings. In these materials, temperature differences in excess of 30°C have developed in regions where internal surfaces such as delaminations exist. These regions develop heat by a combination of structural dissipation and viscoelastic effects. We have been able, we believe, to show that the majority of heat evolution is a result of a viscoelastic mechanism which is stress dependent. This conclusion is based upon a series of experimental observations in our laboratory, as discussed further in subsequent paragraphs.

A major difficulty ensuing from the lack of an appropriate physical model for detailing the phenomenon of vibrothermography is the degree to which correct conclusions can be drawn from experimental observations. On the other hand, in order to develop the model, one needs to base the requirements for the model upon physical observations. For example, in an early paper (Ref. 5), we were led to state the conclusion that the thermal patterns produced by the vibrothermography technique were independent of resonances of the specimen-shaker system. Rather, we were led to believe, based upon experimental observations made up to that time, that the developed thermal patterns were caused by local resonances in the neighborhood of damage existing in composite specimens. These local resonances would depend upon the local geometry and stress fields in the damaged region and hence would be affected little by any changes in system resonances. Later observations (Ref. 12) forced us to modify this position. The later observations indicated that the heat patterns produced are dependent upon both local and system resonances. In particular, the frequencies of vibration at which a local damaged region becomes delineated by development of thermal patterns appeared, in some situations, to be frequencies of natural resonances of the specimen. There is, in some situations, an interaction between the presence of damage and the resonating condition of the specimen which causes heating in the region of damage.

This frequency related behavior of laminated fiber reinforced composite structures with delaminations during vibrothermographic inspection has been studied thoroughly (Ref. 12). Two models were proposed to explain the frequency-related heat patterns developed during vibrothermography. First, a local resonance model was postulated using an analytical dynamic examination of a delamination in an infinite medium. In this case, the delamination was modeled as two anisotropic plates, one on either side of the delaminated region, tied together along the boundary of the delamination. The natural modes of resonance for these plates were then calculated and used to predict frequencies of heating, assuming that heating would occur when these plates of the size of the delamination were excited in a resonance mode. When in a resonance mode, the assumption was that either the plates would excite heating by rubbing, clapping or otherwise interacting with one another, or by increasing the stress in the region around the delamination and thereby increasing the degree of heating via some viscoelastic mechanism.

Second, a structural resonance model was proposed. Here, the natural modes of resonance were calculated for the entire specimen. For the first model, as already noted, it was assumed that heating would preferentially occur at the delamination site when the local plates began resonating. For the second model, it was assumed that heating would occur preferentially when local strain fields increased in value due to structural resonating conditions. That is, the frequency dependence of the heating is assumed to occur because the stress-amplitude in the region of the damage is dependent on the resonance frequencies of the structure. During a structural resonance, a damage region may or may not develop heating, depending upon the location of the damage in the structure. The standing waves or mode shapes in the structure determine where the strain energy is distributed and hence determine if a particular damage region in a certain location will develop heating to an extent detectable by the thermographic camera. Our most recent experimental observations indicate that both models are basically correct if heating results from the transformation of mechanical energy into thermal energy via some viscoelastic mechanism. Such heating will preferentially occur in regions of stress concentrations introduced by an interaction of damage and mechanical resonance.

Both of the postulated models were tested experimentally and compared to the predictions, as reported earlier (Ref. 12). Composite panels having a thickness of two plies, with delaminations between the plies, developed heat pattern-frequency relations as predicted by the local resonance model. However, thicker laminates did not develop heat patterns at predicted frequencies. For these thicker laminates, the heat patterns developed at frequencies corresponding to the structural resonance model, as reported in Ref. 12. A very careful and more complete experimental study performed over the past two years has verified that the local resonance model is indeed also appropriate for predicting frequencies at which delaminations will develop preferential heating in thicker laminates.

For example, a five-plies thick, unidirectional graphite epoxy laminate was constructed with simulated delaminations between the second and third plies. This resulted in two anisotropic plates of different thickness above and below the delamination (a three-plies thick plate and a two-plies thick plate). The local resonance model was used to calculate the first several natural modes for each of these plates, and the specimen was tested vibrothermographically. Table 1 shows a comparison of the predicted and experimentally observed results. As can be seen, the correlation between the natural modes of resonance of each of the plates, and the temperatures at which heating was observed is quite close. Furthermore, careful measurement of the degree of heating has been obtained for each frequency. We wished to test the following hypothesis: If the heat generation is due to delamination surface interactions (clapping, rubbing, etc.), then we would expect the degree of heating to be always greater on the side of the laminate corresponding to the thinner plate, each time a frequency corresponding to a resonance of either the two-ply or three-ply plate is applied to the laminate. This hypothesis is based upon the idea that if heat generation is due to some surface friction phenomenon, then, since the delaminated surface is closer to the laminate surface on the side of the laminate corresponding to the two-ply thick plate, this side should always appear hotter than the other side at a resonance frequency of either the two-ply or the three-ply plate. On the other hand, if heating is caused by a viscoelastic phenomenon dependent upon local stresses, the side of the laminate containing the plate which is undergoing a natural resonance should heat up more than the side which is not resonating at a particular applied frequency. Recent experimental observations show that there is indeed preferential heating of the side of the laminate corresponding to the particular thickness of plate which is being excited by application of a frequency corresponding to a natural mode for that thickness plate.

A large number of experiments conducted throughout this program have produced results which continue to indicate the usefulness and advantages of vibrothermography as a nondestructive inspection technique. Thermographic methods are field techniques and hence can interrogate large areas of structural components or even large structures. This is in contrast to most of the more widely used nondestructive test methods which interrogate such small regions of material as to be practically point techniques. Furthermore, little preparation is required to perform the vibrothermographic test. Vibrothermography is especially advantageous for locating delaminations in composites. We have used it for detecting damage caused by static, fatigue, and impact (dynamic) loadings. Evidence has also been collected which shows that the maximum temperature observed during the vibrothermographic inspection of graphite epoxy laminates increases with the size of the damaged region caused by impact loading (Ref. 12). At this time, knowledge of failure mechanisms in composite materials is insufficient to be able to relate the size of damage to mechanical strength. However, other work in our laboratory has shown a direct relation between laminate stiffness and the degree of damage.

A limited number of tests have indicated the potential for using vibrothermography measurements to obtain experimental correlation with specimen damage and hence, possibly specimen stiffness. A composite structure composed of several layers of honeycomb sandwiched between two layers of a graphite epoxy laminate was impacted by blunt end rods at three energy levels: 5, 10 and 15 ft.-lbs. The panels were than subjected to vibrothermography. Only that damage produced by the two higher energy impacts (10 and 15 ft-lbs.) was detected by the vibrothermography technique. Also, there was a distinctive difference between the amount of heating in each damaged region. The damage induced by the 15 ft.-lbs. energy impact produced a higher steady state temperature than the 10 ft.-lbs. energy impacted region. Specimens were machined from the panels so that the regions of damage were located in the geometrical center of each. These specimens (including control specimens with no impact damage) were subjected to four point bending tests. The results of these tests are given in Table 2. Despite the statistically small number of specimens tested, a trend can be observed which indicates a correlation between damage observed by vibrothermography, flexural stiffness of the specimen, and load at failure. The flexural stiffness is related to the deflection at the beam center at 100 lbs. applied load, the greater the deflection the lower the stiffness. As can be seen in Table 2, there is apparently a better correlation between failure load and impact energy levels than between stiffness and energy levels for these tests. However, more tests would need to be run to determine if this is the case or whether there is sufficient in-panel variation of material properties to account for these differences.

Related tests were performed on graphite epoxy laminates impacted with a spherical ball dropped from several different heights. The specimens were then subjected to the vibrothermography technique at various frequencies. The damaged regions were detectable only at specific values of applied mechanical vibration frequencies. The amount of heating at the damaged region, expressed in terms of degrees AGA (that is, the thermal degrees as measured by the AGA thermovision camera-- approximately equal to degrees Celsius) varied approximately linearly with impact energy. A second set of tests run at a later time showed non-linear variation of amount of heating with impact energy. Figure 1 presents the difference between the temperature of the damaged impact region and ambient temperature, versus the impact energy in joules. For each mechanical vibration frequency, the damaged region produces more heat for the larger impact energies. The greater the impact energy, the greater the amount of damage. However, it is difficult to quantify the amount of damage since this consists of a number of different modes, including delamination and intraply cracking. Sectioning studies have shown that only delamination occurs at the lower impact energies while multiple delamination and intraply cracking occurs at the higher impact energies. Also shown in Figure 1 is the fact that the higher frequency produces a greater heating. The minimum temperature detectable by our thermographic system is also shown on the figure. The fact that both lines converge to this point is consistent with the idea that, with this technique, there is a minimum detectable damage level. Results indicate that low levels of damage (caused by low impact energies) make no measurable difference in mechanical properties. Thus, a minimum level of damage detectable by the vibrothermographic technique is positive in the sense that inconsequential damage is not detected by the technique. The fact that such low levels of damage is inconsequential may need to be proven in each specific case, of course; but for the graphite epoxy material used in this case, this has been shown to be true.

A series of fatigue tests was performed on graphite epoxy laminates having two quasi-isotropic stacking sequences, $[0,+45,-45,90]_S$ and $[45,0,90,-45]_S$. A center, circular hole was machined in each specimen. The tests were run using a new machine control technique developed in our laboratory. Normally, fatigue tests are run using either load control or strain control. These tests were performed using strain energy control. That is, the energy under the stress-strain curve is computed during each load cycle and the load is changed to maintain a constant strain energy. A major advantage of this type of machine control is that the damage levels in the specimen can be increased without catastrophically failing the specimen. The fatigue tests were run at a cycle rate 10 Hz and with a maximum load approximately 50% of ultimate. During these fatigue tests, monitoring of the secant stiffness is also performed. The stiffness generally decreases in a three stage process as the load cycles increase. Very early in the test, there is a large and rapid reduction in the stiffness (the first stage).

The second stage lasts during most of the specimen life. The second stage is evidenced by no change or a very slight decrease in specimen stiffness. The third and final stage indicates incipient failure and is evidenced again by a rapid decrease in stiffness.

Thermographic heat patterns were continuously monitored during these fatigue tests. Very early in the test, a symmetric heat pattern developed around the center notch in the specimen with temperatures slightly larger than temperatures in the far field, due to stress concentrations. As the stiffness degraded during the initial stage one, the heat pattern showed a gradual change with higher temperatures being developed. During most of stage two, which shows little stiffness change, there was also little apparent change in the thermographic patterns. Heating began to increase and asymmetric heat patterns developed around the hole during the final stage three of stiffness degradation which precedes final failure. The asymmetry and temperature levels around the notch continued to increase with decreasing stiffness. The asymmetrical heating pattern corresponded closely with damage development and with the final catastrophic failure surface. Also, the correlation between the thermographic patterns and decreasing stiffness was remarkably close.

Another series of fatigue tests was performed on $[0,90_3]_S$ graphite poly(phenylene sulfide) (PPS) laminates. During the fatigue tests vibrothermographs, acoustic emission and laminate stiffness were simultaneously recorded. The fatigue loading was at a maximum applied stress of 85% of the static ultimate strength and at a stress loading ratio of $R = 0.1$. The stiffness degraded in the three stage process discussed earlier. After the formation of matrix cracks and delaminations in the specimens as a result of the fatigue loading, thermographs indicated several local hot regions where damage was preferentially forming because of local material properties. It was noted that each time a sudden discontinuous change occurred in the laminate stiffness, one or more of the local hot spots would suddenly show an increase in temperature. X-ray radiographs were taken of the specimens and it was noted that, in the regions of heating, multiple localized delaminations had formed. Vibrothermography will detect the integrated effect of such regions, but, at least with the non-magnification optical system used on our camera, it can not resolve the individual delaminated regions. We believe that this is, in some respects, an advantage of the vibrothermography technique. The effect of damage on the mechanical behavior of composite laminates is, from all of our observations, a global effect rather than a local one. Hence, an NDT method which reacts to a global effect has a different potential for providing an evaluation of the mechanical state of the material than an NDT method which provides all of the fine microstructural damage details. Both types of methods are equally important in understanding material behavior. Acoustic emission tic emission count rate , which was recorded during the fatigue tests also, increased discontinuously at each point where there was a discontinuous change in the stiffness, again indicating a correlation with damage development.

During the last year of this contract, a successful DoD equipment grant proposal provided us with a SPATE thermographic system (Stress Pattern Analysis by Thermoelasticity) that detects and processes heat images that result from adiabatic temperature changes which are point-wise proportional to the strain field induced by rapid (cyclic) loading. Since this technique is capable of dynamic strain measurement, it is ideally suited to the purpose of the present contract in that it can be used to follow the changes in stress (strain) distribution carsed by damage development in composite laminates. This information is the key to accurate estimates of remaining strength and life and to other interpretations of damage.

However, an understanding of thermoelastic effects in anisotropic, inhomogeneous materials has not previously been developed. In fact, the mechanics of thermoelastic temperature changes in such materials had not been stated when we began our work at least as far as we can find by careful study of the literature. Experimental experience indicated that such temperature changes are highly dependent upon the nature and details of the inhomogeneity and anisotropy of the material, not only of the laminates under study, but also of the individual plies (laminae), especially the surface plies.

Because of these facts, the influence of material inhomogeneity and anisotropy on the reversible, adiabatic, thermoelastic behavior of fibrous composite laminates containing an elliptical hole is being investigated analytically and experimentally. A closed-form, approximate solution for the two-dimensional strain field has been combined with a simple micromechanics description of a fiber-reinforced lamina to evaluate the isentropic temperature change of a lamina at an arbitrary location and orientation in a laminate subjected to an arbitrary load. Results indicate that material parameters such as the volume fraction and thermoelastic constants of the constituent materials of the lamina, and the orientation of the lamina within the laminate, affect the thermoelastic response of that particular lamina. The analysis has been checked by comparing predicted temperature change patterns with those produced by cyclic (fatigue) loading of coupon specimens with center holes. Specimens made from isotropic homogeneous materials as well as a variety of composite laminates have been tested. Analytical predictions match the experimental observations well in every case. To our knowledge, this is the first time a micromechanical thermoelastic analysis of inhomogeneous anisotropic materials has been achieved. It opens the door to a new field of NDT for composite materials for exploitation at the basic and applied levels.

Summary

It would appear that all of the objectives of the research program were met. A sound understanding of the manner in which laminated continuous-fiber reinforced materials dissipate energy under cyclic excitation was established and analytical models of those dissipation mechanisms were constructed and validated. These representations and an extensive data base developed in our laboratory were used to determine the manner in which vibrothermography works, its limitations and controlling parameters, and the appropriate techniques for the application of the method to nondestructive evaluation. In addition to this steady-state method, a new isentropic thermoelastic thermographic device and associated method of testing was investigated near the end of the program. That method is capable of measuring strain distributions under cyclic loading by measuring the pattern of thermoelastic temperature excursions caused by the field strain distribution. That technique complements the vibrothermographic method and offers unique capabilities such as the dynamic time-resolved measurement of stress relaxation associated with damage initiation and growth.

In general, a firm foundation for the use of thermal nondestructive testing and evaluation techniques has been laid by this program. Much has yet to be done to bring these techniques to bear on specific applications in the engineering world. And many opportunities for their use in fundamental studies await exploitation. Both avenues for continued work should be explored.

Table 1: Comparison of Predicted and Observed Frequencies at Which Local Maximum Heating Occurs

Delamination Size (in.)	Predicted Frequencies 2-Ply Thickness (kHz)	3-Ply Thickness (kHz)	Observed Frequencies (kHz)
0.370 x 0.355	7.25		
		10.88	10.9
	12.3		12.3
			14.7*
	17.16		17.8
		18.45	18.3
	20.86		20.9
	21.17		21.3
			24.7*
		25.74	25.6
0.460 x 0.430	4.76		
		7.15	
	8.26		
	11.15		11.1
		12.39	11.95
	13.73		13.3
	14.34		14.4
		16.72	16.3
	18.86		18.6
			19.5*
		20.6	20.3
	21.10		21.1
		21.5	21.4
0.525 x 0.480	3.71		
		5.57	
	6.55		
	8.59		
		9.82	9.7
	10.70		10.9
	11.45		11.6
		12.89	13.1
	14.86		14.6
		16.05	16.0
	16.22		16.4
		17.17	17.3
	17.94		
	18.20		18.8-19.2
			20.4*
	21.12		21.2

* These frequencies appeared to be specimen resonances.

Table 2: Results of Impact Tests on Graphite Epoxy Honeycomb Panels

Specimen		Deflection at Beam Center at 100 lb Load	Avg.	Failure Load, lbs	Avg
Undamaged	1	0.0155 in.		197	
Undamaged	2	0.0155 in.	.0155	200	199
5 ft.-lbs.	1	0.0165 in.		227	
Impact Damaged	2	0.0170 in.		230	
	3	0.0173 in.	.0169	180	212
10 ft.-lbs.*	1	0.0165 in.		210	
Impact Damaged	2	0.0160 in.		197	
	3	0.0160 in.	.0162	190	199
15 ft.-lbs.*	1	0.0180 in.		191	
Impact Damaged	2	0.0180 in.		160	
	3	0.0170 in.	.0177	192	181

* Only the damage induced by these loads was detected by vibrothermography

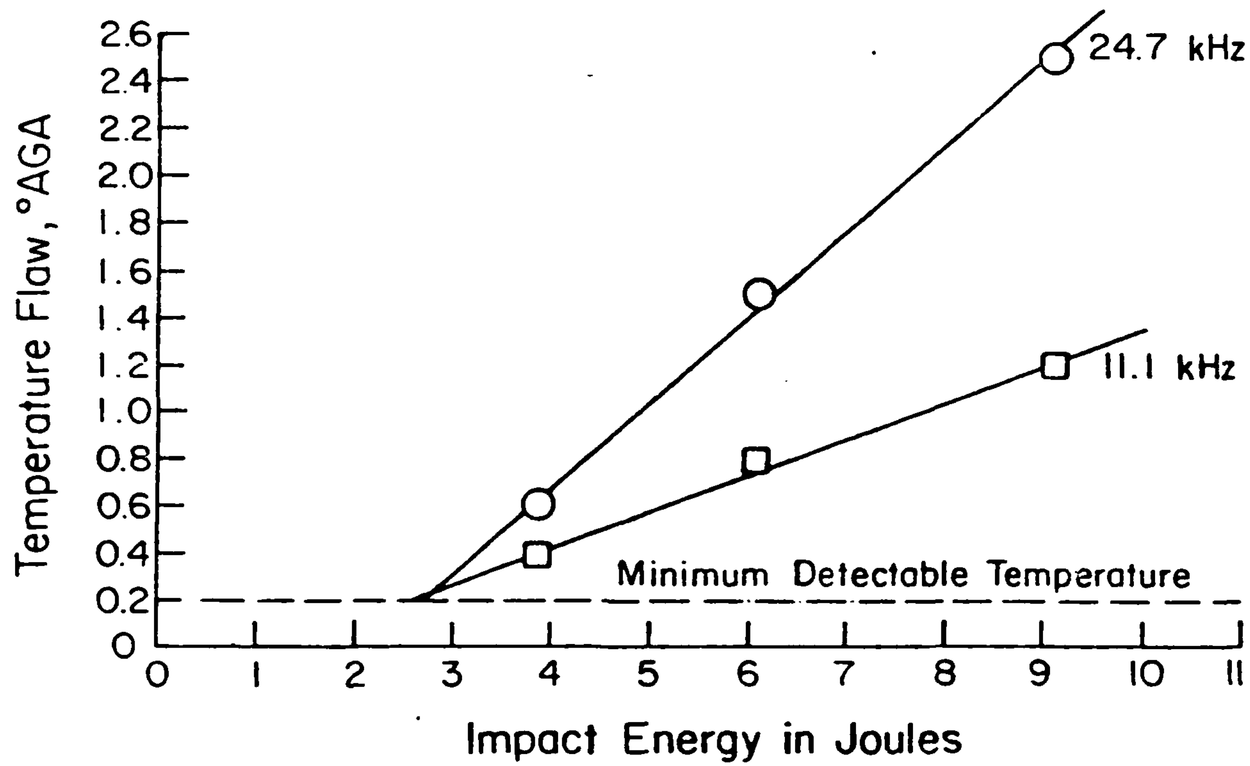

Figure 1. Temperature increase at damage site versus impact energy causing the damage.

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