Detection of cold cracks in the cast-steels by the methods of ultrasonic and eddy-current infrared thermography

A I Cheprasov¹, S V Knyazev³, A A Usoltsev³, A E Dolgopolov³ and R O Mamedov²

¹ Department of Physical Methods and Quality Control Units, National Research Tomsk Polytechnic University, 30 Lenina Street, Tomsk, 634050, Russia
² Department of Materials Science, Foundry and Welding Engineering, Siberian State Industrial University, 42 Kirova Street, Novokuznetsk, 654007, Russia

E-mail: krookia@mail.ru

Abstract. The aim of this study was to investigate the possibility of detection of cold cracks in the massive steel products using ultrasonic and eddy-current excitation, as well as the thermal imaging method of temperature recording, that in the perspective should be completed by the development of requirements for the monitoring equipment.

1. Introduction
The essence of the proposed methods is as follows. Ultrasound (US) infrared (IR) thermography presuppose local excitation of pulse or continuous ultrasonic vibrations in the control object with the registration of the temperature field of a large part of the control object by the infrared imager. Surface and subsurface cracks appear in the form of local temperature anomalies caused by the effect of internal friction and mechanical hysteresis. The basis for the development of this method was positive experience in control of composite materials, as well as foreign experience in metals control. Eddy-current infrared thermography uses the induction excitation of eddy-currents in metal, and the temperature rises in the cracks zone as a result of the crowding of the electromagnetic field lines.

2. Discussion and results
Ultrasonic IR thermography. Famous classical methods of thermal loading under thermal nondestructive control (TNC) are applicable only to a certain category of detected defects. Typically, these techniques require thermal stimulation of all control objects which is not always acceptable. Moreover, certain categories of defects can not be detected in principle by conventional thermal stimulation, e.g., via optical heaters. The optimal stimulation method, apparently, could be the one which would not lead to the change in the temperature of defect-free zone.

At the present time this kind of stimulation of internal defects is carried out by thermo-mechanical methods.

In the 90’s of the last century the term “vibrothermography” became popular, indicating the thermal control process (TC) of the hidden structural heterogeneities of materials on their surface temperature fields under cyclic mechanical loading. A similar procedure can be performed with the acoustic or ultrasonic excitation of materials as the source of a significant increase in the temperature
is the internal friction of the defects walls under their irradiation by mechanical vibrations, i.e. a thermo-mechanical heat takes place. This method is based on the analysis of absorption and scattering of acoustic (ultrasonic vibrations) in the solid media. Ultrasonic stimulation is most frequently used, realizing the principle of optimal heating and advantages of the synchronization method of heating function and the recorded temperature readings. The method is being developed by an independent group of G. Busse (University of Stuttgart, Germany) under the name “Ultrasonic lock-in thermography” [1-4], as well as by R. Tomasom, R. Favro and others (Wayne State University, USA) [5], who use the term “Sound IR imaging”, or “Thermosonics”. In recent years in the United States to refer to the appropriate procedure the term VibroIR or SonicIR is used (Lawrence Livermore National Laboratory) [6].

![Image](image_url)

**Figure 1.** Method of heat waves (ultrasound stimulation).

The difference in surface optical methods and volumetric ultrasonic heating is illustrated in Figure 1. During the surface heating the excess temperature signal occurs not only above the defect, but also in the defect-free zones, which leads to a current noise contrast caused by the surface heterogeneities. Ultrasound stimulation produces mainly temperature signal only in the area of defect, and the temperature of defect-free zones remains close of the temperature of the environment, which was called the “dark field principle”. As a result, ceteris paribus the probability of the correct defects detection increases (the requirements for the qualification of operators are reduced). Importantly, form of the temperature signal during at ultrasonic stimulation does not always coincide with the form of a signal appearing during surface heating: in many cases only a few zones of internal defects generate significant amount of heat due to wall friction, therefore, the topography of the surface temperature signal may be associated with the zones of developing cracks and do not reflect the already “formed” defects.

The authors of the method [3, 4] describe the experimental setup in which the ultrasonic excitation of products was carried out by elastic waves of frequency 20 kHz and a power of several hundred watts, the amplitude of which was modulated with a frequency of 1 Hz. For temperature recording was the thermal imager Jade II of company CEDIP (now FLIR Systems) was used, which provided a record of thermal images of format 320x240 at a frame rates up to 200 Hz in the spectral range 3 ... 5 µm. Duration of a single test reached 3 minutes.

The objects of study were composite materials (carbon and glass-fibre plastics) and ceramics, which demonstrated such advantages of ultrasonic stimulation as selectivity for defects and the effective use of excitation energy. In particular, detection of cracks and stratifications in the stringer
ailerons, made of carbon fiber, on the modulating frequency of 0.4 Hz proved to be very effective. Another controlled material was silicon carbide reinforced with carbon fibers, which is used in space shuttles, high speed train brakes, etc., where it is necessary to resist the fast and powerful changes in temperature. The authors of study [3] suggest that ultrasound stimulation can detect those zones, where cracks develop, while the surface optical excitation reveals relatively large areas with anomalous TPC. With respect to the riveted joints of aluminum sheets, widely used in aviation, it was found that the conventional thermal images reflect the influence of the rivets on the heat-transfer and are insensitive to cracks. The temperature field pattern under a modulated ultrasonic load is more bound to the relative movement of interconnected sheets under load. In particular, when checking the data of the eddy-current control detecting a crack along a row of rivets, the ultrasound thermography showed that the same crack is detected at a frequency of 0.06 Hz (power of ultrasonic stimulation 600 W), and compared to the eddy-current control its mark has a greater length on the phasegram and on the ampligram.

A further increase in the competitiveness of the ultrasound thermography method is associated with the increased energy input and, consequently, the expansion of the control zone, which is currently about 1 m². Choosing the ultrasonic heater parameters it is necessary to prevent the formation of standing waves, in the nodes of which the defects can be overlooked (on the thermograms the standing waves can be seen as regular strips).

One of the main drawbacks of the periodic ultrasound stimulation method is a need to maintain good contact between the product and the ultrasonic stimulator for a few minutes required to reveal sufficiently deep defects. To solve this problem, in analogy to optical excitation it is proposed to use for products heating short ultrasound pulses (with a certain carrier frequency), and the surface temperature field to investigate using the thermal imager at the cooling stage (phase angle thermography with ultrasound burst excitation) [1, 4]. The experimental results were obtained during detection of a crack in the row of rivets in the aluminum aircraft stringer panel. The duration of the ultrasonic pulse with power 2 kW was 100 ms. The cooling stage was investigated for 3 seconds at a frequency of thermal images recording of 15 Hz. The crack was visible in 270 ms due to its walls friction of its walls, but the interpretation of the initial thermograms was hampered by the presence of noise, as well as product heating near the ultrasound system.

In [4] a comparative data on the optical and pulse ultrasonic excitation during testings of aerospace products are provided. Ultrasonic pulses with the power up to 600 W and duration 100 ms (the carrier frequency 20 kHz) were used. The results of ultrasound thermography were recognized as the most informative in the control of composite materials, ceramic coatings on the turbine blades and riveted joints.

Research at Wayne State University is focused on the detection of cracks under pulsed ultrasonic excitation [5]. The authors use the “ultrasonic gun” for welding produced by the company “Branson”, which generates a pulse with power of 1 kW and a duration of 30...200 ms with a carrier frequency of 20 kHz. The pulse is introduced by the direct contact through a steel horn of diameter 1.3 cm, using an immersion paste; the temperature development process is observed for a few seconds. The sub-surface cracks appear in the form of local temperature increase in the background of almost “cold” product (Figure 2a). Most clearly the effects of heat generation in the crack zone are revealed during recording the sequences of thermal images and viewing them in the form of a IR film (example of thermograms of a growing crack 1 mm in length is given in Figure 2b). The example of detection of a fatigue crack in the turbine blade is shown in Figure 3.

The Lawrence Livermore National Laboratory performed studies on the use of ultrasound vibrothermography for detecting defects of welded joints in the products of complex shape, in particular, in the zone of tubes and plates joints. It was found that the defective welded joints exhibit specific signatures of a thermal field under loading the product for 0.1 sec by a package of ultrasound pulses with power 300 W at a frequency of 30 kHz [6]. The advantage of the method is the weak dependence of the results on the ultrasound entry point. The disadvantage is the possibility of inducing new defects at sufficiently high power of ultrasonic pulses. In the same laboratory the comparative
tests of acoustic microscopy, radiography, ultrasonic method and vibrothermography for detection of various defects in the nose panel of a space shuttle, made of 36-layer carbon fiber and coated with silicon carbide, were conducted. The results of vibrothermography turned out to be very promising.

**Figure 2.** Pulse ultrasonic infrared thermography (results obtained by the foreign partner of the Contractor – Wayne State University, Detroit, USA): a – thermogram of numerous cracks (bright zones) in the aluminum panel of the internal combustion engine cylinder; b – development of cracks in the cutting zone in the aluminum plate 3 mm thick (the crack length is less than 1 mm).

In general, it should be stated that the infrared thermography method with ultrasonic stimulation is promising, but its features are still poorly understood; for example, in many cases, where intuitively the emergence of dynamic temperature signals were anticipated, such signals were not registered. The dynamic response of the control object depends on the excitation energy, the method of fixing the control object, in particular, thin products, and material properties. The frequency of the ultrasonic stimulation needs to be close to the natural frequencies of products in order to increase the heat generating efficiency.

**Eddy-current infrared thermography.** Method of non-destructive testing that combines thermal imaging principle of temperature recording and eddy-current (induction) heating principle, has recently acquired a certain popularity in the metal control. Metals often have a low coefficient of electromagnetic radiation absorption, which hampers their optical heating by lamps and lasers. During induction stimulation in the surface layer of the control object the eddy-currents are induced, and material heating is due to Joule heating. Stimulation is performed either by pulsed or by periodically-modulated waves, and the test results are analyzed using the principle of synchronous detection or phase analysis.

The eddy currents are generated only in the surface layer of the material (skin layer), the thickness of which depends on the excitation frequency, magnetic conductivity, and electrical conduction of the material. In magnetic materials, such as steel, the penetration depth is very small, for example, about 0.03 mm for the excitation frequency of 200 kHz. The eddy-currents in the skin layer, round the crack and concentrate on its corners increasing the Joule heating rate and, hence, the temperature by several degrees. The temperature is higher as deeper the crack. In the non-magnetic materials the penetration depth of eddy-currents is much higher than in the magnetic ones, thus, in the crack zones their density can decrease leading to the temperature drop. The effectiveness of the eddy-current simulation depends on the orientation of the magnetic field relative to the revealed cracks, so, it is necessary to revolve the control object during practical control.

For example, the Austrian researchers [7] investigated cast steels having surface defects with the depth of several millimeters. For heating the high frequency (HF) generator with power 10 kW, pulse duration 0.1-1 s was used, and the control object was placed inside the coil. A uniform magnetic field was created by the Helmholtz coils placed apart at a distance of the radius. The texture of the temperature field can be made sharper using Fourier analysis. It was found that in the phasegram the defective marks weakly depend on the depth of cracks, so to assess the parameters of defects the initial
data of infrared thermograms and phasegram should be jointly analyzed. The advantage of phase analysis is that the phase of the signal varies considerably in the zone of cracks and weakly depends on the geometry of the control object, even if it leads to significant temperature anomalies.

In [8] the eddy-current thermal control of castings is described. It is shown that in the thin-walled pipes the through cracks are characterized by the increase in temperature only in the mouths of cracks. The scheme of full automatic control is offered, in which the product falls through the heating coil, and three infrared cameras record the product temperature field in the process of their falling. For the analysis of the test results a set of algorithms, eliminating the distortions of thermograms due to falling and segmenting the image of defects, was developed.

3. Conclusions
In the field of ultrasonic and eddy-current infrared thermography to date in the TPU the following studies have been performed:

- Experimental studies on continuous ultrasonic excitation (ultrasound frequency 22 kHz, electric power up to 300 watts have been carried out.
- Taking into account the international experience an pulsed ultrasound device for ultrasound materials stimulation was assembled (ultrasonic frequency of 22 kHz, pulse duration 0.1 s, electric power up to 2000 W).
- Due to the fact that for the input of ultrasound into the massive steel products, which are the parts of the bogies, special equipment is required, for the present moment, a number of preliminary experimental studies on the samples was conducted. These studies have shown that the main problem is the low efficiency of the ultrasound input into the metal, that does not provide the necessary temperature signals in the zone of cracks.
- For further experiments aiming at more efficient input of powerful ultrasonic vibrations into the product the equipment was designed.
- To perform an eddy-current heating of metal products with cracks a standard unit for induction hardening of metals is used, operating at a frequency of 30 kHz at an electric power of 10 kW or more.
- In the initial IR thermograms the cracks are not found on the background of a significant heating of the sample directly under the inductor coil. During the processing of the recorded sequence of infrared images, in particular, according to the so-called method of principal component analysis, the cracks are weakly detected at any mutual orientation of the cracks and coil. Apparently, in the experiments the IR camera was placed too far from the sample, as a result, a crack appears in the form of a very narrow strip.
- The research in the field of ultrasonic and eddy-current thermography should be continued. Further research is needed to optimize the frequency ranges for the two methods, the method of powerful ultrasound input into the metal and the choice of an effective inductor form.

4. References
[1] Dillenz A, Zweschper Th and Busse G. 2000 Insight 42 (12) Dec. 815–817
[2] Zweschper Th, Dillenz A and Busse G. 2001 Insight 43 (3) March 173–179
[3] Zweschper Th, Dillenz A and Busse G. 2000 Proc. Eurotherm Seminar No. 64 on Quant. IR Thermography (Reims, France) pp 212–217
[4] Dillenz A, Zweschper Th and Busse G. 2000 Proc. Eurotherm Seminar No. 64 on Quant. IR Thermography (Reims, France) pp 247–252
[5] Favro L D, Han X, Ouyang Z et al. 2000 Proc. SPIE “Thermosense-XXII” 4020 pp 182–185
[6] Burke M W and Miller W O 2004 Proc. SPIE “Thermosense-XXVI” 5405 pp 313–321
[7] Oswald-Tranta B and Sorger M. 2010 Proc. QIRT 2010 Conference pp 162–167
[8] Oswald-Tranta B, Sorger M and O’Leary P. 2010 J. Electronic Imaging 19 (3) 1–6