Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2015, 44 (116), 43–46
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/055

Received: 31.08.2015
Accepted: 06.11.2015
Published: 07.12.2015

Possibility of defect detection by eddy current thermography in marine structures

Waldemar Świderski

Military Institute of Armament Technology
7 Wyszyńskiego St., 05-220 Zielonka, Poland, e-mail: waldemar.swiderski@wp.pl

Key words: infrared thermography, non-destructive testing, marine structures, eddy current, steel, aluminum

Abstract

The main criterion for selecting materials for marine structures is the requirement of strength, which in shipbuilding is met by steels and high strength aluminum alloys. Internal and external forces acting on the hull of the ship have to be considered during the design process. There are also such factors as wave strength and sea conditions, waves hitting into the bow of the ship, vibrations, thermal differences, load displacement, loads caused by starting and landing aircraft on aircraft carriers, loads that occur upon the sudden immersion in and emerging from water in the case of submarines, effects of fatigue, corrosion cracking, etc. Eddy current thermography is a new non-destructive testing technique for detecting cracks in electro conductive materials. It combines the well-established inspection techniques of eddy current testing and thermography. The technique uses induced eddy currents to heat the sample being tested. Defects are then detected by changes in the flow(s) of induced eddy currents, which are revealed by thermal visualization and captured by an infrared (IR) camera. The paper discusses code for the numerical modeling of nondestructive testing by eddy current IR thermography and of IR testing of materials used in marine structures. The ThermoEdCur computer program developed by Vavilov was used to select suitable heating parameters of the tested metal sheet samples in order to detect subsurface defects.

Introduction

One of the basic requirements for selecting materials for warship construction is high corrosion resistance. However, not only corrosion resistance, but also an economic factor (cost) determines the kinds of materials that warship designers propose to use for a specific type of watercraft. The main criterion for selecting materials for marine structures is the requirement of strength, which in shipbuilding is met by steels and high strength aluminum alloys. Structural steel has been the traditional material used for 150 years in the shipbuilding industry because of its excellent mechanical properties and low manufacturing costs. Aluminum alloy as an alternative material has been used since 1930 (Jurczak, 2010).

Structural steels for the construction of naval ships must meet stringent requirements. Internal and external forces acting on the hull of the ship have to be considered during the design process. There are also such factors as wave strength and sea conditions, waves hitting into the bow of the ship, vibrations, thermal differences, load displacement, loads caused by starting and landing aircraft on aircraft carriers, loads that occur upon the sudden immersion in and emerging from water in the case of submarines, effects of fatigue, corrosion cracking, etc. (Bogucki, 2007). The materials used to construct vessels are subjected to cyclic fatigue loads (during operation) that are comparable to mutual bending loads (Jurczak, 2010).

The elements of warship construction of hull and superstructure are not only determined by technical parameters, but also by the combat and tactical capacities of the vessel. The construction of these elements and, first of all, the type of material used will impact its exploitation. Bulkheads are typically made of steel sheets having thicknesses from 3 to 6 mm, depending on their position within the hull. The superstructure can be made of aluminum alloy with a thickness of approx. 3 mm. Improper welding and the misuse of straightening technologies for aluminum alloys can cause intense corrosion and material losses, which increase the risk of cracks developing during use (Jurczak & Dudzik, 2012).

All rolled materials typically have much worse mechanical properties (e.g. toughness) in the thickness direction (i.e. perpendicular to the surface) than in the direction parallel and transverse to the rolling direction. This phenomenon is very detrimental to structures in which items are loaded with forces acting in the direction of material thickness. These forces can make materials get substantial stratifications parallel to the surface plate, called lamellar cracks. Most often, these cracks are found in rigid designs of highly loaded joints connecting deck bulkheads in tankers, in combinations of deck stringers with large holes in the corners of the ship, in sheer strake connections on the deck, in supporting elements of bulkheads, in the base plates of engines, etc. The main causes of these cracks are non-metallic inclusions (in the material) and a high sulfur content.

Proposed method of non-destructive testing

Infrared thermography is a non-destructive testing (NDT) technique allowing fast inspection of large surfaces (Maldague, 2001; Dragan & Świderski, 2010). There are different techniques depending on the stimulation source, basically: pulsed, stepped or modulated. The specimen is stimulated with an energy source, which can be of many types, such as optical, mechanical or electromagnetic (Ibarra-Castanedo et al., 2008; Świderski, 2003). One of these sources is eddy currents.

Eddy currents are externally induced into the material and heat is produced internally from the circulation of these currents in the material. Pulsed eddy current thermography is technique that uses pulses of eddy currents induced in conducting media to generate local heating inside the material. The transient diffusion of the heat inside the material, induced by pulsed induction heating, is imaged by measuring the transient temperature profiles on the surface of the material. The presence and characteristics of the defects inside the materials changes the surface temperature transients. Thus these transients can be used for the nondestructive evaluation (NDE) of conducting materials (Kumar et al., 2008).

The distribution of eddy currents while testing objects depends on the number of characteristics describing these objects. The most important of these are (Lewińska-Romicka, 1997):

- electrical conductivity, γ;
- magnetic permeability, μ;
- operating frequency of a transducer, f.

Structural elements of warships made of metal sheets meet the requirements of using pulsed eddy current thermography to detect defects.

Modeling eddy current thermography

The ThermoEdCur computer program developed by Vavilov was used to select suitable heating parameters of the tested metal sheet samples in order to detect subsurface defects.

ThermoEdCur is the thermal NDT modeling software intended for solving a three-dimensional heat conduction problem for heating a 6-layer solid body containing subsurface defects. Similar problems can be solved by some commercial software packages, such as Femlab, Ansys/Multiphysics, Samsef/Thermal, MatLab/PDE, etc. A universal characteristic of these programs is an advantage but also a drawback. These programs are convenient for modeling sophisticated object geometries due to the technique of finite element analysis (FEA). However, to develop and use programs by implementing the above-mentioned software packages, special knowledge and training are required. ThermoEdCur is not universal, but tailored to solve some specific problems of thermal NDT, particularly, those involving eddy current (inductive) heating. ThermoEdCur implements a finite differential method that typically provides better accuracy than FEA in solving thermal NDT problems. ThermoEdCur is good for analyzing short heat pulse heating that is usually difficult or a bit tedious to do by using the above-mentioned commercial programs. Moreover the computational accuracy provided by ThermoEdCur for most practical thermal NDT cases can hardly be achieved by using other programs (ThermoEdCur, 2014).

A special test case allowed by ThermoCalcEdCur is heating by means of eddy currents. In this case, the stimulating heat energy, Q, penetrates in-depth with attenuation being described by the following formula:

$$\mathrm{d}Q = Q_0 e^{\gamma \,\mathrm{d}z} \tag{1}$$

where dQ is the energy absorbed within the dz distance, and γ is the eddy current absorption coefficient defined by:

$$\gamma = \frac{\sqrt{\pi f \sigma \mu_0 \mu}}{2} \tag{2}$$

Here f is the eddy current frequency, σ is the electrical conductivity, [S/m], $\mu_0 = 1.257\cdot10^{-6}$ N/m is the magnetic permeability of free space, [H/m], and μ is the relative magnetic permeability of the material. Therefore, eddy current energy absorption is characterized by the following parameters: f, σ, μ.

Figure 1 shows the principles of a heating line, which are often used in heating by eddy currents to search all surfaces of the object with even heating. Important parameters are speed of heating line, V, and line width, S.

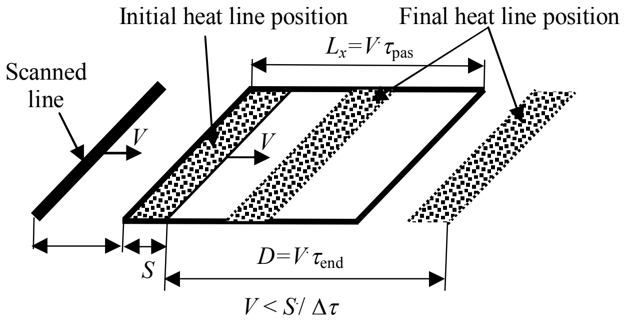

Figure 1. Heating a sample with a heating line

Models

To verify the possibilities of detecting cracks and corrosion areas in metal sheets by eddy current infrared thermography, two models of samples were used for computer simulation (Figures 2 and 3).

In Model 1 (Figure 2) metal sheet samples with dimensions of 100×200 mm and 6 mm thickness for steel and 3 mm for aluminum sheets are assumed to have three subsurface cracks (thicknesses of 0.1 mm each) filled with air and located at various depths below the surface. The steel plate has defects positioned below the surface at the following depths: Defect 1: 0.5 mm, Defect 2: 3 mm, and Defect 3: 5 mm. The aluminum sheet has the following defects positioned below the surface: Defect 1: 0.5 mm, Defect 2: 1.5 mm, and Defect 3: 2.5 mm.

In Model 2 (Figure 3) metal sheet samples with dimensions of 100×200 mm and 6 mm thickness for steel and 3 mm for aluminum sheets are assumed to have three corrosion areas of different thicknesses: Defect 4: 0.5 mm, Defect 5: 1 mm, and Defect 6: 2 mm.

Table 1 shows the thermal properties of materials used in the models.

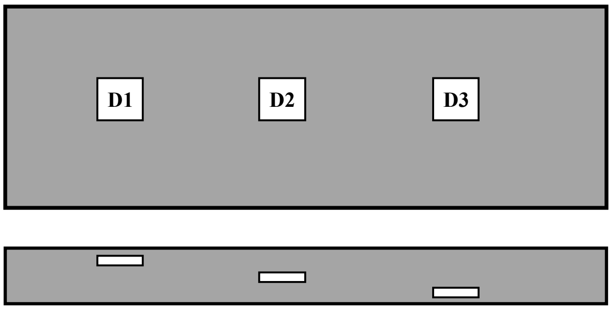

Figure 2. Model 1

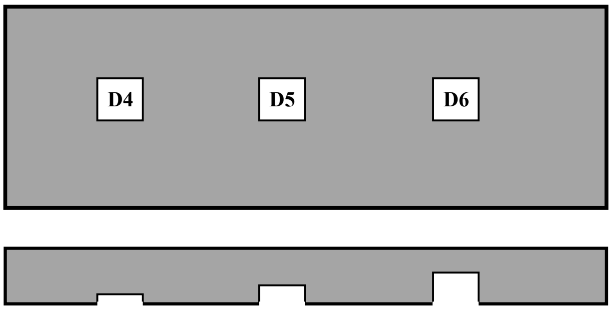

Figure 3. Model 2

Table 1. Thermal properties of materials

Material	Specific heat [J/kg·K]	Thermal conductivity [W/m·K]	Density [kg/m^3]
Air (as defect)	1005	0.07	1.2
Steel	440	25	7900
Aluminum	880	230	2700

Table 2 shows parameters the defining penetration depth of eddy currents in materials used the in models.

Table 2. Material parameters defining penetration depth of eddy currents

Material	Electrical conductivity σ [S/m]	Relative magnetic permeability μ [H/m]
Steel	$6.99\cdot10^6$	100
Aluminum	$3.5\cdot10^7$	1.000022

Results

The simulation was performed using the ThermoEdCur program by heating the samples (Models 1 and 2) with a heat flux density of 10^4 W/m^2 using the following simulated eddy current heating characteristics: width of heating line 10 mm, speed of shift 20 mm/s, induction current frequency $4\cdot10^4$ 1/s, heating time 5 s, and simulated time of heating and cooling 10 s.

The simulation results obtained in front surface (heated) during the detection of defects are shown for Model 1 in Table 3. The following parameters are presented: ΔT – maximum temperature difference between two selected points (above and without the defect) on the surface of the sample, τ_m –

time from start of heating, which is the maximum value of ΔT, and C – maximum temperature contrast.

Table 3. The simulation results – Model 1

Material	Defect	ΔT [ºC]	τ_m [s]	C [%]
Steel	Defect1	12.83	3.35	100
Aluminum	Defect1	1.91	2.8	37
Steel	Defect2	0.88	4.05	37
Aluminum	Defect2	0.79	2.8	15
Steel	Defect3	0.12	4.45	5
Aluminum	Defect3	0.19	2.8	4

Table 4. The simulation results – Model 2

Material	Defect	ΔT [ºC]	τ_m [s]	C [%]
Steel	Defect4	0.07	4.95	4
Aluminum	Defect4	0.27	2.85	5
Steel	Defect5	0.17	4.8	8
Aluminum	Defect5	0.61	2.85	12
Steel	Defect6	0.48	4.3	22
Aluminum	Defect6	1.63	2.85	32

Table 5. The simulation results – Model 2 for different speeds of shift

Material	Defect	Speed of shift [m/s]	ΔT [ºC]	τ_m [s]	C [%]
Steel	Defect4	0.01	0.16	7.15	3
Steel	Defect4	0.02	0.07	4.95	4
Steel	Defect4	0.03	0.05	3.9	4
Aluminum	Defect4	0.01	0.32	5.6	3
Aluminum	Defect4	0.02	0.27	2.85	5
Aluminum	Defect4	0.03	0.24	1.95	6
Steel	Defect5	0.01	0.37	7.5	8
Steel	Defect5	0.02	0.17	4.8	8
Steel	Defect5	0.03	0.12	3.7	8
Aluminum	Defect5	0.01	0.68	5.6	6
Aluminum	Defect5	0.02	0.61	2.85	12
Aluminum	Defect5	0.03	0.53	1.95	14
Steel	Defect6	0.01	1.02	7.65	21
Steel	Defect6	0.02	0.48	4.3	22
Steel	Defect6	0.03	0.33	3.4	23
Aluminum	Defect6	0.01	1.76	5.6	17
Aluminum	Defect6	0.02	1.63	2.85	32
Aluminum	Defect6	0.03	1.45	1.95	41

Before starting the computer simulation it was assumed that defects could be detected reliably if the temperature signal at the surface of the sample over the defect met the following conditions:

- The maximum excess temperature on the surface of the sample, which occurs at end of heating, must be below that of the melting damage of the sample (100°C);
- The temperature signal over the defect must exceed the temperature resolution used by the thermal camera (0.05°C);
- The running contrast of temperature must exceed the noise level (2%).

Comparing the results obtained, which are shown in Tables 3–5, it was found that:

- The temperature at the surface of the sample during the simulation was less than 40°C;
- For over all defects, $\Delta T \geq 0.05$ºC;
- Over all defects, $C > 2\%$.

As can be seen from the results shown in Table 5, reducing the speed of shift of the heating line can improve the detection conditions of defects.

Conclusions

The simulations indicate that eddy current thermography can be an effective method for detecting subsurface defects (micro-cracks, delaminations) and corrosion areas in steel plates and aluminum sheets used in marine structures. The use of a movable heat source at a constant speed of shifting minimizes the impact of non-uniform heating of all surfaces of the sample, which usually occurs when using heating lamps and often results in difficulties in detecting deeper defects.

Further work is warrented to verify the results of computer simulations by experimental testing.

References

1. Bogucki, R. (2007) *Wpływ obróbki cieplnej na własności mechaniczne niskowęglowych stali stopowych z dodatkiem miedzi*. Praca doktorska. Politechnika Krakowska.
2. Dragan, K. & Świderski, W. (2010) Multimode NDE approach for structure health assessment of composite elements in aerospace applications. *Acta Physica Polonica A*. 117, 5.
3. Ibarra-Castanedo, C., Grinzato, E., Marinetti, S., Bison, P., Avdelidis, N., Grenier, M., Piau, J-M., Bendada, A. & Maldague, X. (2008) *Quantitative assessment of aerospace materials by active thermography technique*. 9th International Conference on Quantitative InfraRed Thermography, Kraków.
4. Jurczak, W. & Dudzik, K. (2012) Odporność korozyjno-naprężeniowa i zmęczeniowo-korozyjna okrętowych stopów aluminium i ich spawalność. *Zeszyty Naukowe Akademii Marynarki Wojennej*. 2 (189), Gdynia.
5. Jurczak, W. (2010) Problemy i perspektywy stopów aluminiowych w zastosowaniach na konstrukcje morskie. *Zeszyty Naukowe Akademii Marynarki Wojennej*. 4 (183), Gdynia.
6. Kiran Kumar, Ch.B., Krishnamurthy, C.V., Maxfield, B.W. & Balasubramaniam, K. (2008) Tone Burst Eddy-Current Thermography (TBET). *Review of Quantitative Nondestructive Evaluation*. 27. D.O. Thompson and D.E. Chimenti, American Institute of Physics.
7. Lewińska-Romicka, A. (1997) *Defektoskopia wiroprądowa*. Warszawa: Biuro Gamma.
8. Maldague, X.P.V. (2001) *Theory and Practice of Infrared Technology for NonDestructive Testing*. New York: John Wiley-Interscience.
9. Świderski, W. (2003) Lock-in Thermography to rapid evaluation of destruction area in composite materials used in military applications. *SPIE*. 5132.
10. ThermoEdCur (2014) Operation Manuel, Tomsk.