Computerized measuring system for study of aluminum alloy defects

V Malikov¹, A Sagalakov¹, D Fadeev¹, A Katasonov¹, S Dmitriev¹ and A Ishkov²

¹Physical-technical faculties, Altai State University, Barnaul, 656049, Russia
²Department of technology of construction materials and repair of machines, Altay State Agricultural University, Barnaul, 656049, Russia

E-mail: osys11@gmail.com

Abstract. The hardware-software complex which allows carrying out defect detection in materials based on various aluminum alloys was developed using a transducer based on eddy current effects. The hardware-software complex included the developed software coded in C++. A digital displacement transducer operated by an Arduino microcontroller has been designed, which can automatically move the transducer over a test object. In order to test the system operability, a series of scans of plates made of duralumin and aluminum-magnesium alloys with knowingly existing internal defects in the form of cuts imitating the presence of cracks in the metal and located at depths from 1 to 5.5 mm was made. This paper provides information illustrating the correlations between the system response to a 700 Hz signal and the presence of internal material defects. The eddy-current transducer exciting winding signal frequency exerts significant influence on this process, and this has been also demonstrated in the study.

1. Introduction

Aluminum (Al) material is used in many industrial applications including aerospace components due to its low weight and high strength-to-weight ratio.

Modern engineering actively uses combinations of aluminum-based materials, as well as its magnesium-containing derivatives. In particular, such alloys are widely used in the aerospace industry due to the balanced combination of strength characteristics and saving in structures’ weight. Such alloys are also widely used in the motor vehicles production; leading motor manufacturers use aluminum alloys in their products. One of the well-known examples is Shinkansen high-speed trains produced by Japan Railways. Due to the excellent electrical conductivity, aluminum-based materials are widely used in electrical engineering, and their high ductility (for example, grade D16T alloy) and ease of processing have led to their expansion to the food and chemical industries (D16AM alloy is used at extremely low temperatures), and construction.

The use of various raw material processing methods determines the breadth of the stages at which defects can occur: these can be both errors during casting and post-processing.

A crack is one of the primary culprits for the failure of metallic structures and estimated that up to 90% of failures of in-service metallic structure are the result of fatigue cracks [1]. A fatigue crack is initiated from a damage precursor at unperceivable level (e.g. dislocation or micro crack in materials), when the material is subjected to repeated loading. The crack often continues to grow to a critical
point and leads to a sudden failure of the system without providing a sufficient lead time for prevention [2].

In recent years, the frequency of occurrence of the micro-cracks being the typical internal defects of the material has also increased against the backdrop of expanded use of aluminum-magnesium alloys in welded structures. As a result, the strength characteristics of the weld are compromised, and the resistance to corrosion processes deteriorates.

Therefore, the evaluation of surface and subsurface cracks and discontinuities in Al components is of high importance.

The devices based on eddy current effects use the non-destructive testing methods and can be applied to various conductive materials. Besides, such systems offer a range of opportunities for online product research.

To detect a crack at its early stage, several nondestructive testing (NDT) and structural health monitoring techniques have been developed. Radiographic technique which uses X or Gamma ray is a well-known and widely used NDT technique not only for fatigue crack detection but also for other industrial applications [3]. However, due to strict regulations by radioactive problem, the radiographic technique has a difficulty applying to large structure such as bridge. Eddy current technique is particularly well suited for detecting surface cracks in conductive materials, and can also be used for checking electrical conductivity and coating thickness measurements [4]. Acoustic emission (AE) technique detects elastic waves generated when a fatigue crack is initiated. AE technique has been used for detecting and localizing damage in composite, concrete and metallic materials [5]. However, the passive monitoring characteristic AE technique makes the sensors always be activated to ‘listen’ the elastic waves from crack and the wave from crack also can be missed due to ambient noise. Thermography technique is also applied for fatigue crack detection. A hybrid ultrasonic/infrared technique for fatigue crack detection was introduced using heat occurs at a crack due to friction between the crack surfaces when an ultrasonic wave propagates to the fatigue crack [6]. Laser lock-in thermography, which utilizes a continuous wave laser as a heat source for lock-in thermography technique is developed [7, 8].

So far, various Active Thermography (AT) techniques have been exploited to evaluate the defect depth in conductive metallic materials including Pulsed Thermography (PT) [9], Pulse-Phase Thermography (PPT) [10] and Lock-in Thermography (LT) [11]. These techniques can be applied on most of the heat sources, either being surface stimulation, e.g. flash lamp [12] and LED [13], or volumetric e.g. eddy current.

One of the most extensively applied is the Eddy Current Method (ECM). ECM uses a coil driven by an alternating current to generate Eddy Current (EC) inside the Sample Under Test (SUT). ECM has been demonstrated being able to detect surface cracks with higher reliability and reproducibility than vibrothermography and laser thermography [14]. In addition, the high performance of ECM, e.g. robustness to lift-off variations and applicability to defect orientation characterization and depth estimation, makes it suitable for fast quantitative evaluation [15]. The application of ECPT has been investigated for both detection and characterization of material degradation and failure such as fatigue cracks, corrosion and residual stress [16, 17].

Thus, the task of defect control in aluminum and aluminum-magnesium alloys becomes extremely urgent. Therefore, the purpose of this study is to develop, design and test an eddy-current software-hardware complex enabling to search for deep-lying defects in aluminum-magnesium and duralumin alloys.

2. Material choices and design
The need for local material analysis tools (particularly, for aluminium alloy plates and their junction points) became a basis for the development of a compact scanning system. A feature of this software-hardware complex distinguishing it from analogues is the capability of the eddy-current transducer, a key element of the system, to conduct localized measurements with a scanning depth of up to 5 mm
over an area in the range of 100 µm. At that, the material parameter subjected to direct measurement is its electrical conductivity, or more precisely, its depth and surface distribution throughout the object.

The method of object studying based on eddy currents rests on the technique of comparing such parameters as the current intensities in the scanned material and their distribution across the volume of the test substance, electromagnetic properties of the material, and the mutual position of the measuring device and the test surface. The parameters necessary for the correct operation of the hardware-software complex are summarized thus making it possible to characterize the test material, measuring circuit and electromagnetic field frequency in the form of a combined parameter $\beta_0$. The parameter $\beta_0$ has is non-dimensional one, and the following formula is used to determine it:

$$\beta_0 = D_{eq} \cdot \sqrt{\mu_0 \cdot \omega \cdot \sigma},$$

where $D_{eq} = D_1 + 1.5h$, $D_1$ is the average excitation winding diameter; $h$ is the linear value of the distance between the excitation winding and the scanned surface, $\omega$ is the electromagnetic field frequency, $\mu_0$ is the magnetic constant, and $\sigma$ is the electrical conductivity.

It should be noted that the task of a model construction capable of operating with several variables and reconstructing the stress hodographs for small values of the combined parameter is quite complex and requires high accuracy of calculations. Nevertheless, within the scope of this work we managed to construct hodographs [18] making it possible to visually demonstrate the correlations between the medium parameters, receiving sensor characteristics, and eddy-current transducer winding voltage values.

For conducting measurements of the ECT voltage diagram on aluminum alloys, a system based on ECT (19) and a digital displacement transducer operated by an Arduino microcontroller was used. 3D image of the eddy-current transducer is shown in figure 1. The winding used for signal reception (1), the exciting winding (2) and the winding compensating the influence of the exciting winding (3) are located in platform 5. This platform allows accommodating the magnetic core 4. The windings are impregnated with a compound (6) in order to protect them from destruction when a ferrite shield 7 is applied. The sensor is also placed in a corundum washer 8 protecting the core 4 from contact with the test object.

![3D image of the eddy-current transducer.](image.png)
compound (6) at 200 °C after winding. Such a procedure made it possible to exclude destruction of the windings during the application of the ferrite screen (7), which was used for the electromagnetic field localization on the test object. The outer side of the ECT was embedded in a special corundum washer (8) to avoid contact of the core with the test object.

The parameters of the designed ECT make it possible to concentrate the magnetic field in a certain area approximately 2500 μm² in size, and achieve the field penetration field to a considerable depth of the test object through working at a reasonably low frequency.

The measuring system is based on a generator of a sine-wave signal transmitted to the exciting winding of the ECT where it creates an electromagnetic field that penetrates the test object and excites eddy currents in it. They, in turn, introduce EMF into the measuring winding, thus transmitting information about the test object’s state. Then, the signal is amplified in a special amplifier and filtered from noise.

After signal filtering, it is transmitted to an amplitude detector, and then to a computer using an analog-to-digital converter. At the same time, the generated signal frequency and the cutoff frequency of the filtering system is changed. As a result, a useful signal is extracted that contains information about the test object. Software control changes the operating frequency of the measuring system. The useful signal is transmitted to a personal computer through the sound card input.

The software part is coded in C++ and is Windows platform-oriented. The application interacts with the mixers built into the operating system, which makes it possible to precisely control the values of voltage applied to the exciting circuit, as well as to process the signal incoming from the measuring winding with high sensitivity.

The implementation of the hardware-software complex through the use of the computer audio subsystem gives scanning considerable flexibility in controlling the frequency of the electromagnetic field in the exciting circuit within the range from 100 Hz to 2 kHz.

3. Experimental results

In order to verify the operation of the hardware-software complex, a series of scans of samples consisting of duralumin, as well as an aluminum-magnesium alloy was made. In the first case, the 5.5 mm thick study object knowingly had three internal structural imperfections (defects) sized 1 mm. The depths of defects were 1.5, 3.5, and 4.5 mm (plate №1). The transducer exciting circuit voltage was 2 V. Herewith, scanning was performed from the defectless side in order to specify the level of the device sensitivity to the internal structure imperfections. The results are shown in figure 2.

![Figure 2. Scanning results of plate №1 with one ECP.](image)
During scanning at a frequency of 700 Hz, it was possible to successfully identify all internal defects with a thickness of 1 mm by a signal amplitude attenuation (figure 2). The change in the signal amplitude at each of the three defects was 0.7 V, 0.25 V, and 0.12 V respectively. As a result of scanning, positive conclusions about the applicability of this complex for the detection of internal defects of up to 1 mm in size and 4 mm in depth may be made.

In order to determine more precisely the boundaries of the field created by this software and hardware complex, a sample with 0.2 mm thick internal structural defects located at a depth of up to 5.5 mm (plate №2) was scanned at the next stage. The exciting circuit voltage equal to that used at the previous stage made it possible to successfully identify the first defect occurring at a depth of 1 mm. The output signal amplitude attenuation was 0.11 V (figure 3).

![Figure 3. Scanning results of plate №2 with one ECP.](image)

However, it is necessary to note that the increase in the exciting circuit signal amplitude resulted in significant distortion of the results due to exceeding of the permissible level of the measuring circuit output signal.

The indicated circumstance necessitated the modernization of the hardware-software complex by adding a second eddy-current transducer. These measures made it possible to significantly increase the localization of the electromagnetic field by increasing the exciting circuit voltage from 2 V to 3.7 V. Thereat, the separation of the transducers’ functions was implemented: the stationary first transducer was used for recording the signal from the defect-free part of the test object; the second transducer was focused on direct defect finding. The software algorithm of the designed hardware-software complex recorded both signals and subtracted the data of the second transducer from the values of the first one. Thus, the response differences of the two transducers were taken as the final data of the measuring system output signal.

In the second case, the sample of the same thickness already had six defects in the form of cuts with a thickness of a quarter of a millimeter at the depths varying from 1 to 5.5 mm. The applied method allowed successful identification of five defects (figure 4).
Figure 4. Scanning results of plate № 2 with two ECP.

The decrease in the signal amplitude at each of the defects was 2.6 V, 1.1 V, 0.45 V, 0.18 V and 0.09 V, respectively. When passing over the sixth defect, it was not possible to register changes in the signal response.

4. Conclusions

Summarizing the research results, the following conclusions may be made. The prospects of application of systems based on the principles of eddy currents for internal defects scanning in materials are quite promising. Where classical eddy-current transducers were used, the control systems could track only surface material defects. Compact new-generation hardware-software systems using a combination of standard circuits and computer algorithms are capable to effectively localize the electromagnetic field over a limited surface area and achieve significant field penetration deep into the sample. In the future, it is planned to implement the second eddy-current transducer-based software-hardware complex, which will improve the magnetic field localization to 1000 μm², thus enabling to find and identify defects with linear dimensions of 0.25 mm and less. As a result, the opportunity to study the internal material defects at a considerable depth can appear subject to proper selection of the exciting circuit signal frequency.

References

[1] Campbell F C 2008 Elements of Metallurgy and Engineering Alloys (Materials Park, OH-ASM International)
[2] Zhou C, Hong M, Su Z, Wang Q and Cheng L 2013 Smart Mater. Struct. 22 015018
[3] Williams J J, Yazzie K E, Padilla E, Chawla N, Xiao X and De Carlo F 2013 Understanding Int. J. Fatigue 57 79
[4] Zilberstein V, Schlicker D, Walrath K, Weiss V and Goldfine N 2001 Int. J. Fatigue 23 477
[5] Roberts T M and Talebzadeh M 2003 J Conser. Steel. Res. 59 695
[6] Favro L D, Han X, Ouyang Z, Sun G and Thomas R L 2000 Rev. Sci. Instrum. 71 2418
[7] An Y-K, Kim J M and Sohn H 2014 NDT E Int. 65 54
[8] Hyung J L and Yongtak K 2016 Smart Materials and Structures 25 9
[9] Castanedo C I 2005 Quantitative subsurface defect evaluation by pulsed phase thermography: depth retrieval with the phase (Quebec-Faculté des sciences et de genie Université Laval)
[10] Ishikawa M and Utsunomiya S 2013 Infrared Physics & technology 57 42
[11] Wallbrink C and Jones R 2007 Journal of applied physics 101 104907
[12] Omar M A and Zhou Y 2008 Infrared Physics & Technology 51 300
[13] Rajic N 2002 Composite structures 58 521
[14] Almond D P 2011 Insight: Non-Destructive Testing and Condition Monitoring 53 614
[15] Cheng L, Gao B and Berthiau G 2014 IEEE Sensors Journal 14 (5) 1655
[16] Cheng L 2011 IEEE Sensors Journal 11 (12) 3261
[17] Shejuan X 2020 Sensors and Actuators A: Physical 309 112030
[18] Malikov V N and Dmitriev S F 2017 Welding International 31(8) 608
[19] Dmitriev S F, Katasonov A O and Sagalakov A M 2015 IOP Conf. Ser.: Mater. Sci. Eng. 71 012065