

EMA TESTING OF “PROTON” ROCKET HULL THICKNESS

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Introduction

Thickness inspection of airframes and other parts of space launch vehicles is one of the main quality control demands to provide highest reliability of complex products, produced by the spacecraft industry. The measuring error of the mostly applicable ultrasonic thickness measurement method in this case depends on the range of specific features of the object, such as velocity variation of ultrasonic waves propagation in the material, state and geometry of object, quality of acoustic contact when using piezoelectric transducers, environmental temperature and other. Therefore the use of contact thickness gauges reduces the efficiency and quality of inspection. Due to the large volumes of inspecting areas and high requirements to the accuracy of wall thickness measurements on fairing and paneling, used for covering the “PROTON” launch vehicle’s body, it was necessary to develop a generally new method and new instrument, that would allow the enough speed of inspection and high accuracy of measurements. Basing on the technical specification prepared by Khrunichev State Research and Production Center to solve the above mentioned task JSC Spectrum-RII has developed Electro-Magnetic Acoustic thickness gauge A1270 (fig. 1). The EMA technology featuring the excitation and reception of shear horizontally-polarized ultrasonic waves with radial and linear polarization in frequency range of 2.5-5 MHz allows inspection of alloys produced using different technologies.



Fig. 1. View of EMA thickness gauge

Operation principle of the EMA thickness gauge

The main task was to develop a portable instrument with built-in power supply allowing measurements from one side of inspecting object. Therefore the magnetic system of EMA transducer was built on the constant magnets from rare-earth metals, in particular from alloy of Nd-Fe-B. As a result the EMA transducers made are of small sizes combined type for sending and reception of SH waves in operation frequency range of 2.5 – 5 MHz (fig. 2).

The main operation principle of EMA thickness gauge is sending and reception of ultrasonic waves to the object using the impact of alternative and direct magnetic fields on the object’s surface. A high frequency signal is applied to the EMAT coil (fig. 3) to induce eddy currents on the surface of the material. The surface currents interact with the magnetic field to generate a Lorentz force. The volume density of Lorentz force is $\vec{F} = \vec{J} \times \vec{B}$, where $\vec{B} = \mu\mu_0\vec{H}$ - induction of magnetic field in the inspected metal, μ - relative magnetic of the metal, μ_0 - vacuum permeability,



Fig. 2. EMATs



Fig. 3. EMA principle of excitation of shear horizontally-polarized waves with radial (a) and linear (b) polarization

\vec{H} - magnetic field strength, \vec{J} - eddy current. This disturbance is transferred to the lattice of the material, producing an elastic wave. In a reciprocal process, the interaction of the elastic wave in the presence of a magnetic field induces currents in the receiving. Depending on construction of the coil and orientation of polarization field the transducer can excite SH waves of

radial or linear polarization, which mainly depends on the form of the coil.

To get the SH wave with radial polarization the transducer with the spiral coil is used (fig. 3a). As a result of interaction between the eddy current J and magnetic field B the Lorentz forces appearing on the surface of the material are directed radial in regard to the lines of eddy current. At that the SH wave with radial polarization is excited directed perpendicular to the surface layer. The EMA transducer of this type can be effectively used for ultrasonic excitation both in ferromagnetic and non-ferromagnetic materials.

In case the EMA transducer has a columnar coil and magnetic system consisting of two magnets, which gives the magnetic flows B of opposite directions through the surface layers of metals with eddy currents J also of opposite directions (fig. 3b) the SH waves with linear polarization are excited in the metal. The Lorentz forces are at that in-phased in both areas of the surface. They are directed perpendicular to the lines of eddy current and parallel to the surface layer. Under the impact of Lorentz forces the SH wave appears in the surface layer and propagates in the metal perpendicular to the surface. The movements of the particles in the wave are parallel to the surface and perpendicular to the coil turns in its linear parts. At that conditions the SH wave is excited in-phase in the whole area under the impact of the Lorentz force.

Influence of the anisotropic characteristics of the alloy of SH wave propagation

The mostly wide-spread construction material - the rolled metals from aluminum alloys are anisotropic materials, which means mechanical characteristics of the material in different directions are different. This is due to the specific production technology of rolled sheets, including thermo-mechanical processing, resulting with deformation of metal crystals during rolling and recrystallization after thermal impact. As the physical-mechanical properties of the rolled metal are not the same in different directions, anisotropy also appears in the values of ultrasonic wave propagation speed in direction of metal thickness for different directions of displacement vector in the wave in regard to rolling direction.

When measuring wall thickness or investigating the physical-mechanical properties of rolled metal transmitting the ultrasound perpendicular to its surface, there are two types of SH waves appearing with different velocities. In case of anisotropy all the displacement vectors of shear waves divide on components according to two main elasticity directions: across and along the direction of rolling. As the displacement modules in these directions are different, the SH-wave vFig.4. Multiple echo-signals of SH wave, propagating in orthotropic-isotropic (a) and anisotropic (b) plates velocities are also different.

The typical waveforms for multiple echo-signals of SH-waves, propagating in the orthotropic-isotropic and anisotropic plates at EMA excitation are given on the fig. 4. The waveforms for SH-wave with radial polarization propagating in isotropic plates and SH-waves with linear polarization with displacement vector direction along and across the rolling direction in anisotropic plates (fig. 4a) are specified with monotonous reducing of signal amplitude with the time at insignificant changes in signal forms from pulse to the next pulse. The repetition period of echo-pulses depends on the thickness of the material and wave velocity. The waveforms for multiple echo-signals of SH waves with radial polarization in anisotropic plates and SH-waves with linear polarization with displacement at 45° angle to the rolling direction (fig. 4b) shows that depending on the material anisotropy level already the second –the third pulses of echo-signals are doubled in their form. This doubling can be explained the

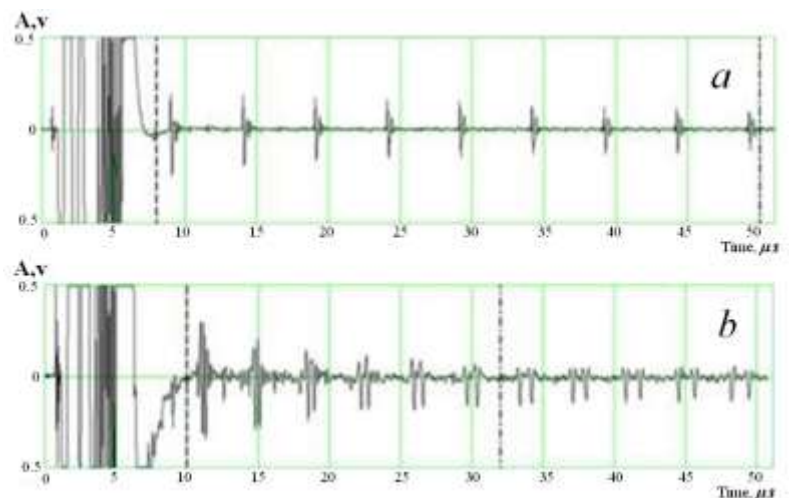


Fig.4. Multiple echo-signals of SH wave, propagating in orthotropic-isotropic (a) and anisotropic (b) plates

following way: the originally excited SH-waves with different displacement angle (transducer with radial polarization) or with 45° angled displacement to the rolling direction (transducer with linear polarization) during their propagation gradually transform into two components with oscillation directions along and across the rolling. The propagation velocities of these two components are different.

This causes doubling of echo-pulses and their dividing on two signals at quite long way of signal propagation in the material. The higher the anisotropy level of the material, the bigger the time shift in pulses from two components of SH-waves at the same way of their propagation in the material (at the constant thickness). When the propagation way is quite long (up to dozens of pulse repetition in the layer), the time shift between the pulses with different polarization can be equal to the double time propagation of the wave in thickness or even exceed this time. As a result at a big interval of signal analysis this is shown as beating (fig.5).

Correlation processing of signals

Another important difference of the EMA thickness gauge A1270 is the correlation processing applied to the signals, which almost excludes the influence of changes in signal form and amplitude on the resulting measurement error.

Autocorrelation function (ACF) of received echo-signals is given on fig. 5b. The behavior of ACF of signals of the waves with radial polarization or waves with linear polarization and displacement angle of 45° to rolling direction in anisotropic samples (fig. 5b) is characterized with significantly different form of ACF in the type repeats in the form of ACF. Especially clearly this can be noticed at the long interval of signal observation.

The time interval from zero point of coordinates to the first ACF maximum is equal to the double time of ultrasonic pulse propagation in the material. This value is used for recalculation of velocity of ultrasound wave propagation and at thickness measurements accordingly.

There are two variants of thickness measurements algorithms used in EMA thickness gauge to increase the accuracy and reliability of measurements on the rolling with corrosion and erosion damages and high level of anisotropy.

The first algorithm is the following: in the beginning the ultrasonic pulse is excited in the special zeroing sample and basing on it the hardware time is set up in the device the way that the difference between the hardware time and the delay time of the first pulse in zeroing sample is equal to the argument of ACF for the received echo-pulses in the zeroing sample. After that when measuring the thickness of the object its thickness is recalculated using the argument of ACF and the delay time for the first echo-signal without the hardware time. The measurement result is chosen by the criteria of maximum value of ACF and relation between t_{echo} delay of the first echo-pulse and t_{dz} time dead zone. Another (the second applied) algorithm of thickness measurement: if the maximum value of ACF argument is $A > 0.4$, the result of thickness measurement is chosen by the argument of ACF meaning; in case the maximum of ACF argument is $A < 0.4$ и $t_{\text{echo}} > t_{\text{dz}}$, the result of thickness measurement is chosen by the delay time of the first echo-signal; and the last case if $A < 0.4$ and $t_{\text{echo}} < t_{\text{dz}}$, the measurement is unsuccessful (not possible).

For analysis the interval from the whole waveform of received echo-pulses is chosen where the amplitude of informative signals is higher than the noise level.

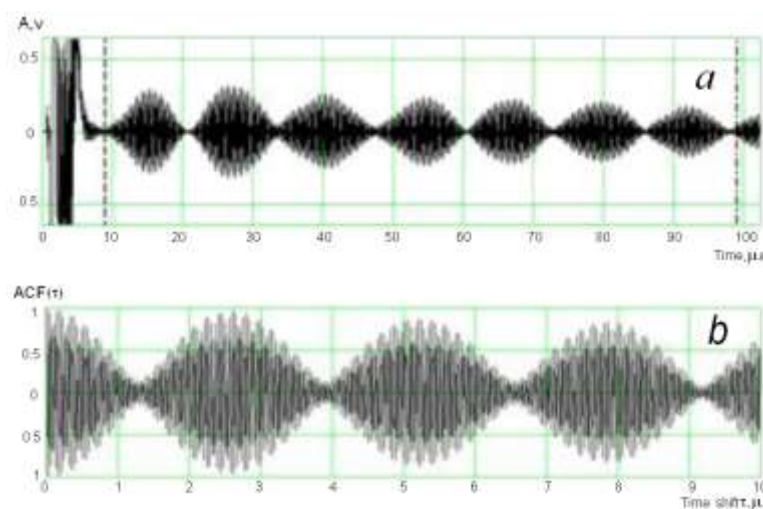


Fig.5. Multiple echo-signals of SH-waves, propagating in orthotropic-area of local maximums, the beating anisotropic plate – a) and their autocorrelation function – b)

The distinctive features of EMA thickness gauge

The SH-waves sent and received by EMATs have two-times smaller velocity of wave propagation in comparison to P-waves, therefore the thickness measurements on significantly thinner objects from aluminum alloys rolling with high accuracy is possible. The EMA method of wave excitation and reception doesn't require any couplant to provide reliable and stable acoustic contact between the transducer and the metal, so no special preparation of the surface for inspection is necessary.

By the constructional performance and exploitation characteristics the thickness gauge is a portable handheld instrument for manual inspection in workshops and can work in open air conditions with higher dust level, air humidity and moderate precipitations. The instrument is protected by IP65.

The EMA thickness gauge has a built-in processor and display for more informative measurements, gives the possibility of saving the minimum thickness reading, allows calibration on the velocity in the material by the sample with known thickness with the accuracy up to 1 m/sec. The built-in rechargeable battery and charging unit supplied in the basic kit, together with some power saving facilities in the instrument (like nonvolatile constant magnets in the construction of EMA transducers, auto off after a set pause interval between the measurements and other) provides effective operation during the whole working day.

The instrument has a protective cover for the electronic unit, which also using special belts supplied in the kit can provide a hands-free operation or fixing of the instrument on the operator's belt.

The graphical display also allows representation of signals as A-scans for flaw detection of parts and products searching for delaminations, non-metallic inclusions, erosion and corrosion damages of the metal.

The use of EMA transducers with excitation of shear wave with linear polarization and measurement of velocity of ultrasonic wave propagation polarized along and across the rolling direction allows to use the thickness for evaluation of anisotropic characteristics of the alloy.

The advantage of the EMA method of the thickness gauge is in its comfortable operation in any positioning on any kind of surface curvature (convex or concaved) with min. radius of 50 mm, as the thickness measurement procedure doesn't depend on the quality of acoustic contact.

Specification of A1270 EMA thickness gauge:

Thickness measurement range*	0,5 -100 mm
Reading resolution*: 0,5 -25 mm	0,01 mm
25-100 mm	0,1 mm
Display type:	LCD, 80 x 60 mm (320 x 240 pxl)
Operation temperature range:	-20°C -f +45°C
Power supply	4 x AA Alkaline elements
Continuous operation time	8 hours
Continuous operation time with backlight	6 hours
Ultrasonic velocity range	2500 - 6500 m/sec
Size of electronic unit:	235 x 98 x 33 mm
Weight with batteries and w/o transducers	800 g

* The parameters can be different depending on inspection objects

Some application examples for EMA thickness gauge A1270

The application of EMA thickness gauge A1270 at the Spacecraft factory of Khrunichev Space Research and Production Center significantly simplified the quality control procedure in the area of thickness measurements and increased the productivity and efficiency of inspection (fig. 6). The possibility of correcting the ultrasound velocity in the material after calibration on the velocity by the known thickness and the autocorrelation function applied for thickness measurements provide the highest possible accuracy of wall thickness measurements on the paneling after its mechanical treatment.



Fig.6. Wall thickness measurements of panel of launch vehicle "PROTON"

The experience received after a long exploitation of the instrument A1270 in the industry allowed setting the ultrasonic velocity range for the alloys used in the production, depending on the aluminum type, delivery party and for the specific production parts.

The quick and easy thickness measurement of panel wall thickness during its production increases the quality of the whole production process of critical construction parts. Methodical support of inspection process for panels wall thickness measurements is approved by using the certified standard samples. The trial confirmed the instrument gives reliable and stable accurate results both of certified standard samples and real objects.

The instrument can be connected to the PC for further data analysis and keeping researches aimed to improve the metal treatment and production technology, as well as for data storage for information about the technological process and technical condition of complex structures.

Conclusions

1. EMA thickness gauge can be used for thickness measurements on flat, cylindrical and spherical parts and units from aluminum alloys with registration of measurements results at production or exploitation site for aerospace machinery.

2. The thickness gauge can be used for evaluation of corrosion damage of the objects by the form and behavior of multiple echo-pulses, evaluation of anisotropy of rolled sheets and for measurements of ultrasonic velocity propagation in the material by the known thickness of objects.

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