Features and Perspectives of Emats Use for Metal Objects Testing

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Abstract. The methods of electro magnetic acoustic (EMA) excitation and reception of longitudinal and SH ultrasonic waves with radial and linear polarization with the use of constant or pulse magnetizing of signal inductor were researched. The settings and operation modes for pulse magnetic field were defined, the magnetizing system was chosen and specifications for the power supply unit for the electronic unit was developed.

The specification for parameters of the EMA Transducers (EMAT) was defined and the EMATs with apertures from 3 to 10 mm, small in sizes and weights and with high efficiency were developed. The results of the practical use of EMAT for acoustic thickness measurement and estimation of the anisotropy level for objects from aluminum alloys, titan, copper, brass, various carbonaceous and stainless steels are represented.

The possibilities of various EMATs application for assessment of one axial stressed condition at testing tightening strength of demountable connections and perspectives for testing of two axial stressed condition are shown

The method of point weld testing of aluminum alloys and various steel plates using EMA devices with pulse magnetic transducers was considered. Considering that the parameters specifying the character of the welding process are propagation time, amplitude and bending line of the echo signal, it is recommended to use devices with EMAT and correlation signal processing for point welding testing to measure thickness of welding point.

The characteristics of the device with automatic monitoring, when the thickness is out of the set limits with accuracy up to 0.01mm, allowing automatic control of the welding points are given

The examples of the successful use of EMAT in aerospace industries and in metallurgic industry are shown, the perspectives of use in automobile and machine building industries are detailed.

Introduction

Despite a lot of publications about the researches in the field of EMAT, the real success in production and application of this method and equipment could not have been achieved for a long time. One of the reasons for that was the absence of high-sensitive EMA transducers and equipment. But in the recent time the developments in the area of radio-electronics, constant magnets from alloys of rare-earth metals, perfected technologies of multilayer boards production allow the progress in development and application of EMA transducers, EMA equipment and systems for thickness measurement and flaw detection. This is also strongly connected with the new tasks for Non-Destructive Testing, appearing with the growth of such high-tech manufacturing branches as aerospace, automobile industries, metallurgy, railway transport and other.

The specialists of Research Institute of Introscopy of MSIA "SPECTRUM" (Moscow) made researches of Electro-magnetic Acoustic excitation and reception of shear and

Rayleigh waves, developed devices and multi-channel equipment for testing objects from different metals and alloys.

EMA excitation of ultrasonic oscillations

The methods (fig. 1) are based on combined action of eddy-current, created by coil – inductor, and magnetic-biasing field on the surface of electro-conductive material. As a result of this action the Lorenz forces are appearing, which provide excitation of ultrasound of corresponding type in material [7].

The volume density of Lorenz force:

$$\overline{F} = \overline{J} \times \overline{B}, \qquad (1),$$

where $\overline{B} = \mu\mu_0 \overline{H}$ is the induction of magnetic-biasing field in testing material, μ - relative magnetic conductivity, μ_0 - magnetic constant or vacuum magnetic conductivity, H - magnetic field strength, $\overline{J}$ - eddy-current.

To excite the body wave in perpendicular direction to the solid body the authors developed small sized power-independent EMA transducers with magnetic systems based on constant

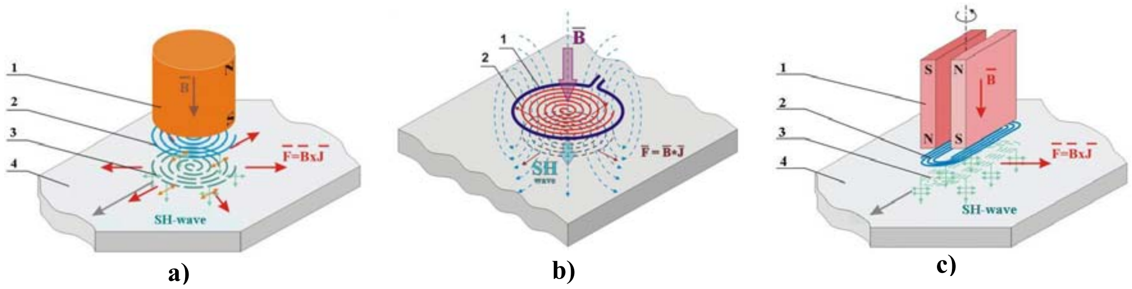


Fig. 1. Scheme of shear waves excitation with EMATs with radial polarization – with constant magnet- a) and pulse-magnetic biasing - b), and with linear polarization with constant magnet - c)

magnets from rare-earth metals (fig.1).

As represented on fig. 1a, to excite the shear wave with radial polarization the inductor in a form of flat spiral coil is placed under one of the poles of magnetic system. When interacting the induced eddy current $\overline{J}$ and magnetic field $\overline{B}$ create Lorenz forces in surface layer of material and as a result the surface becomes the source of ultrasonic wave. This scheme can be applied for excitation of shear waves both in ferromagnetic and non-ferromagnetic materials.

For EMA excitation of shear waves with radial polarization in pulse magnetic field the authors [8] made researches and proposed the method, represented on fig 1b. To create the necessary induction of magnetic field $\overline{B}$ the special magnetic biasing coil 1 covering the sending-receiving coil is used. The magnetic field in this case is created by the source of pulse current, providing pulse current in the coil of up to 300-400 A. The induction of magnetic field when working on ferromagnetic and non-ferromagnetic metals and alloys can achieve 1-2 Tesla (fig. 2).

Fig. 2. Relation between magnetic field induction n and time in the area close to EMAT surface.

The excitation of shear waves with linear polarization is made according to the scheme, represented on fig 1c. At that the inductor of elongated form and magnetic system from two magnets are used. The two magnets provide magnetic flows $\overline{B}$ of contrary directions through the areas of

solid layer with induced eddy currents $\overline{J}$ also of contrary direction. Under the action of Lorenz forces, which are in-phase in both areas of surface, the shear wave is appearing in surface layer, which propagate perpendicular to the surface.
The advantage of EMA excitation and reception of ultrasonic waves is the flexible choice of structural parameters of EMA transducers, which allows simultaneously send either shear waves with different polarization or longitudinal and shear waves. This is equally true for EMATs built on constant magnets and with pulse-magnetic biasing system.

EMA Transducers

Basing on requirements, given in papers [1-2], the authors developed structures of EMATs with different aperture from 3 to 10 mm, with high transduction efficiency, small sizes and weight from 20 g to 1 kg (fig. 3). The direct combined and with devided sender and receiver EMATs for sending and receiving shear ultrasonic waves with radial and linear polarization, angle EMAT for sending shear SH and Rayleigh waves are applicable for operation with EMA thickness gauges and flaw detectors.

Fig. 3. EMATs for thickness measurements of objects from metals and alloys

Application of EMA technologies for NDT of metal objects

Before the operational application of EMATs and devices for acoustic measurements, thorough researches of the utmost possibilities of these for thickness measurements and estimation of metal anisotropy characteristics for objects from aluminium, titan, copper, brass, different types of stainless steels and carbon steels. The possibilities of different types EMAT application were studied for testing mono-axial stress state when testing stress tightening for plug-type connections and for testing dual-axial stress state. The authors made researchers and developed the complex of equipment and EMATs for testing wheel-pairs of railway cars. The most effective application the EMATs found in aerospace industry and metallurgy. Among the perspective application areas is automobile industry and machine-building industry.

Thickness measurement of space crafts elements

One of the important element of quality control system, providing high level of quality and reliability of elements in space crafts at Khrunichev Research and Production Space Center in Moscow [1], is testing of panel walls thickness used for rocket airframe “PROTON.

Due to great volumes of testing and high demands on precision of thickness measurements, it was necessary to develop a principally new acoustic method and equipment, providing high efficiency and accuracy. For these purposes the specialists of Research Institute of Introscopy of MSIA "SPECTRUM" has developed the Electromagnetic Acoustic thickness gauge A1270 [2]. During the exploitation the operators distinguished the comfortable application of this thickness gauge for testing of large areas and of objects with complex forms and sizes from aluminium alloys. EMA transducers can be moved manually along the surface, but also they can be easily built-in an automated scanning system, which is very useful for testing large areas.

Fig. 4. Thickness measure-ment on big size objects

The EMAT with small aperture allows thickness measurement from the flat side of panel with milled cells and thickness measurement of residual thickness in cell.

The testing can be also made in any positioning of transducer and on the surface with any curvature (convex or concave) with minimal radius of 50 mm.

The additional possibilities, realized in thickness gauge A1270, such as quick adjustment of shear wave velocity up to 1 m/sec and built-in algorithm of correlation signal processing [3], increase the accuracy of thickness measurements of panels after their mechanical operation.

The use of EMA transducers significantly simplify the testing process and increase the efficiency, besides the thickness gauge has processor and graphic display which give additional testing information, possibility of saving and showing the parameter of minimal thickness reading and data storage.

Basing on received during testing operation data the range of ultrasonic velocities in different types of aluminium alloys and range of velocities in one product was detected. The online thickness measurement of panels wall thickness allows influence and make corrections in technology and production of important parts. The metrological base for wall thickness measurement is checked on standard calibration blocks and samples of Khrunichev Research and Production Space Center.

The solutions on saving the power consumption of the unit realized in EMA thickness gauge A1270 such as possibility of charging from net, using of constant magnets inside the EMA transducers, automatically switch-off when the item is not in use during the set time, provide guaranteed operation during the working day.

The manufacturer is constantly developing and improving the methodical and software base for the unit.

Ultrasonic testing of spot welding using EMATs

The methodology of spot welding with ultrasound is based on sounding the spot weld with piezoelectric transducers of contact type or local-immersion type on frequencies 10-20MHz, with visual estimation [1, 2] or automated analyze [3] of multiple signals realizations. The informative parameters in this case are: the character of sequence, amplitude and attenuation of echo-signals, intervals between the echo-signals.

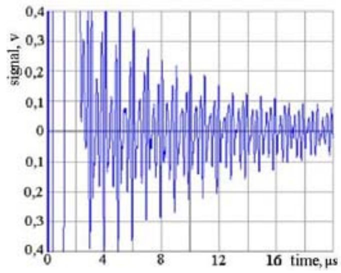
The disadvantage of the existing methods, based of using piezoelectric transducers, is the dependence of information signals from the state of acoustic contact, unstabil size of contact area for transducer with local-immersion bath.

The authors researched the influence of cast kernel grain size, nonparallel input surface, its roughness and kernel size on the quality of spot welding. Basing on that was concluded that it is difficult to estimate the quality of spot welding by the attenuation of echo-signals.
The authors also made researches of EMA transduction in pulse magnetic field [6], determined the parameters and modes of pulse-magnetic field, chose the type of magnetization system, determined the requirements and parameters for power supply of electronic unit.

To create the necessary induction of magnetic field $\overline{B}$ there is a special magnetic coil 1, covering the sending-receiving coil 2 is used (fig 2). The magnetic field in this case is created by the source of pulse current, providing 300-400A pulse current in coil. To reduce the power consumption, the thickness measuring range is limited by 0,5 –50 mm, which is corresponding to 40us duration of signal reception operation area.
The induction of magnetic field when working on ferromagnetic and non-ferromagnetic metals and alloys achieves the level of about 1 Tesla (fig. 3). The energy necessary for one magnetic biasing cycle is2-5 Joules.
The EMAT for spot weld testing is characterized by high efficient transduction, small aperture 3-10mm, small sized and weight.
The trials made on samples from steel plates 0,8 mm thick with spot welding proved the possibility of detecting defects in welds basing either on multiple signals amplitude analyze or on the changing in echo-signals propagation time or welds thickness (fig. 5-9).

Parameters of echo-signals:
- time of propagation 0,98 – 0,995us,
- velocity of echo-signals attenuation 0,01v/mm

Size of welding spot – 2 mm

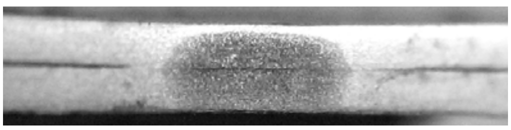


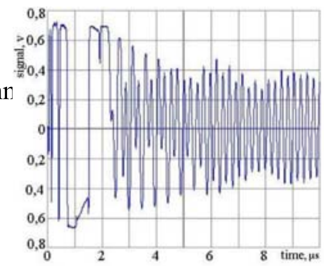
a) **b)**

Fig 5. Cling at incorrect welding of steel plates 0,8 mm thick:
a) photo of plate, b) echo-signals realization

At incorrect welding technology (insufficient metal heating and pressure effort) there are the cling type defects (fig. 5) appearing, featured with the small zone of thermal impact and absence of weld point crater.

Parameters of echo-signals:
- time of propagation 0,49 – 0,50 us,
- velocity of echo-signals attenuation 0,01v/mm





a) **b)**

Fig.6. Spill at incorrect welding of steel plates 0,8 mm thick:
a) photo of plate, b) echo-signals realization

At that the propagation time of shear wave with horizontal polarization was 0,98-0,995us, which corresponds to the summarized thickness of welded plates, because the cling doesn’t influence the ultrasound propagation. The distinctive feature of cling is a low attenuation level of ultrasound due to absence of metal melting during welding, absence of kernel of welding spot and of changes in metal structure, which is confirmed also by the photograph of section.

Another defect caused by the incorrect welding technology is a spill (fig. 6). In this case despite the distinctive thermal impact zone there is no kernel and weld point crater and there is no connection between the metal layers.

The echo-signal realization, corresponding to this welding point, shows that the ultrasonic time propagation in this area is 0,49 – 0,50 us. This means that the pulse is multiple reflected in the upper layer. At that the attenuation of echo-signal is the same as in previous case due to minimal changes in metal structure.

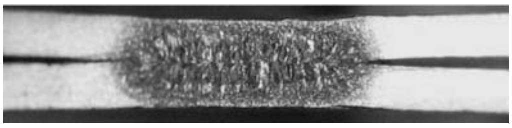
In case of correct spot welding technology (fig. 7) there is a distinctive kernel of welding spot appearing, on the photo of section there are also crater, thermal impact zone and specific metal structure in the place of welding is well seen.

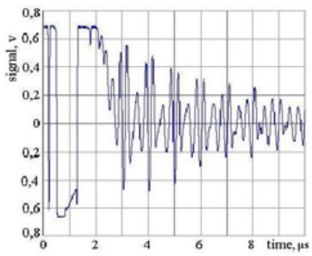
The propagation time of shear wave with horizontal polarization is 0,965-0,975 us.

After testing four spot welds with correct welding the form of signal realizations and ultrasound time propagation were fully equal for every case. The character of ultrasound attenuation has changed due to the increase of signals attenuation in large-grained area of weld, which conforms the conclusions of other researchers [1-3].

Parameters of echo-signals:
- time of propagation 0,965 – 0,975 us,
- velocity of echo-signals attenuation 0,03 v/mm

Size of welding spot – 5 mm





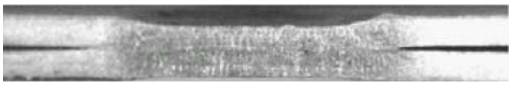
a) **b)**

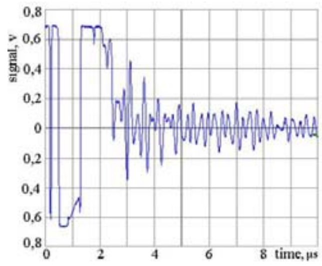
Fig.7. Quality welding of steel plates 0,8 mm thick:
a) photo of plate, b) echo-signals realization

Another specific defect of incorrect welding technology is burn. The distinctive features of this defect are increased sizes of spot's kernel and crater with rough surface (fig. 8), accompanying by thinning of kernel. Due to that the shear wave propagation time in this place is 0,78 us, and the echo-signals attenuation is high.

Parameters of echo-signals:
- time of propagation 0,63 – 0,76 us,
- velocity of echo-signals attenuation 0,03 v/mm

Size of welding spot – 7 mm





a) **b)**

Fig. 8. Burn at welding of steel plates 0,8 mm thick:
a) photo of plate, b) echo-signals realization

Depending on quality of welding technology there are significant changes in sizes of thermal impact area and in kernel of welding spot. At incorrect welding technology there is no kernel at welding spot and the size of thermal impact area for steel plates 0,8 mm thick is 2 mm for cling defect type and 2,5 mm for spill defect type. For non-defected welding the kernel size is 5 mm and in case of burning – 7 mm.

The results of these researches were taken into the account when developing the portable device for ultrasonic testing of spot welds. This device is developed on the base of EMA thickness gauge A1270 with the following modifications: self-contained power supply, unit for pulse-magnetic biasing and small-sized EMAT.

Fig.9. Process of weld testing with pulse-magnetic biasing EMAT

The operational algorithm contains the automatic monitoring when the thickness is beyond the set limits, which allows rejection of welds in automated (on-line) mode with the accuracy up to 0,01 mm.

At the same time the operator or the welder himself can additionally estimate the quality of weld spot by the character of echo-signals and by their autocorrelation function. Fig.9 shows the testing process. As the ultrasound is excited directly in surface layer of welding spot, the orientation of EMA transducer, the force of its pressing to the surface and other factors don’t influence the efficiency of sounding process.

Small sizes and weight of EMAT are comfortable for manual testing and at the same time they can be easily built in mechanical multi-positioning system for testing welding spots. For manual operation to save the power consumption the pulsing is made with the frequency of 1Hz or by manual start pulsing.

High resolution is provided by using the shear waves with horizontal polarization and operation frequency of 3-5MHz.

The main characteristics of EMA device for testing spot welds

Measurement range	0.5 ÷ 50 mm (on steel)
Main error	± 0.05 mm
Minimal curvature radius	20 mm
Surface roughness, R_z	up to 160 um
EMAT* sizes	ø18 x 37 mm
EMAT* weight	50 g
Testing object’s temperature range	-50 ÷ +100°C
Sizes of electronic unit	245 x 120 x 40 mm
Weight of electronic unit	650 g
Operating temperature range	-20 ÷ +50°C
Continuous operation time	8 hours
The exactness of thickness rejecting monitoring setup	0,01 mm

The advantage of the proposed method and developed equipment is the low dependence of readings from the state of surface, high portability of equipment, dry contact (no couplants is necessary), large range of operating temperatures, possibility of automation estimation of welding quality, possibility of signal saving and transmission to the external PC for printing and archiving.

Basing on the results it is possible to make the on-line estimation of welding technological process.

Wall thickness measurement of aluminium drill pipes

For well-boring in fields located in the area of continental shelf, conservancy territories and in hard-to-reach areas the more applicable becomes directional drilling and horizontal drilling with big cant of well bottom. At that during rotation the drill pipe is exposed to reversed stress, which achieves high levels when drifting angled and horizontal boreholes.

Fig. .10. Aluminum drill pipes

Calculations showed that at equal geometrical parameters for aluminium drill pipes bending stress is three times less, then for the steel drill pipes, that's why at drifting the curved parts of boreholes it is preferable to use the aluminium drill pipes with smaller modules of elasticity.
For controlling the geometrical parameters of aluminium drill pipes during their production under the order of Kamensk-Uralsky Metallurgical Works (manufacturer of drill pipes) the specialists of Research Institute of Instroscopy of MSIA "SPECTRUM" made researches and supplied to the Customer the EMA thickness gauge A1270 [10].
After a year of exploitation the characteristics and high efficiency of thickness gauge A1270 were confirmed. During the project "Aquatika" the specialists of the Metallurgical Works tested over 300 aluminium drill pipes 147 mm in diameter and 13 mm wall thickness. The subjects of testing were: wall thickness in thickened ends of pipes, pipe's body. The number of tests on one pipe varied from 24 to 30, so the general number of tests was over 10 thousands.
The application of EMA thickness gauge significantly increased the efficiency of testing and simplified the testing procedure.

Flaw detection on wheel-pairs of railway cars

Under the order of JSC "Russian Railways" was developed the new multi-channel flaw detector A2001 BASIS for operation as a part of automated complex for axle and wheel-pairs diagnostics.
The particular feature of this flaw detector is that it is working both with piezoelectric and EMA transducers. This allows increasing possibility of flaw detection and reducing the demands to the state of testing surfaces.
Developed EMA transducers are applicable for detection of cross surface defects of the wheel rolling surface (1) and of the middle part of axle with Rayleigh waves (3) and for testing of web and underhub part of axle (4) and of the main rim (2) with shear waves with an angle of 40˚.
The testing scheme is represented in Fig. 12. The EMA transducer for excitation and reception of Rayleigh waves is working on the frequency of 400 kHz, the EMA transducer for angle excitation of ultrasound is working on the frequency of 1MHz.

The flaw detector A2001 BASIS (fig. 13) can be used as a part of different automated systems for Non-Destructive Testing and thickness measurement of other products and objects from metals and alloys.

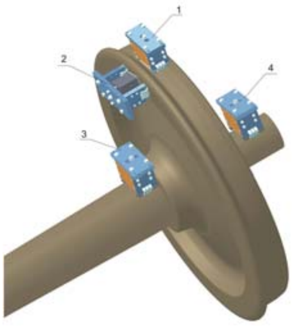


Fig. 12. Testing of wheel-pair

Fig. 13. Multi-channel flaw detector A2001 BASIS

Conclusions

The world experience of development and application of EMA transducers and equipment for Non-Destructive Testing and Technical Diagnostics and the results received by the specialists of Research Institute of Introscopy of MSIA "SPECTRUM" show a great potential application of EMA technologies in different industries for solving different tasks of testing.

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