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RESEARCH REGARDING ULTRASONIC EXAMINATION OF COMPLEX PARTS

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Lucrarea prezintă un proces de evaluare nedistructivă stabilit în scopul de a observa fisuri sau delaminări ce pot avea loc în interiorul unor piese din titaniu, în special în interiorul unor piese de formă complexă. Datele obţinute în urma evaluării ultrasonice pot oferi o mai bună înţelegere a mecanismelor de rupere în acest material. Un sistem de control în imersie este prezentat împreună cu datele experimentale.

The paper presents a non-destructive evaluation process established in order to observe cracks and delaminations that occur below the surface in titanium parts and in particular in complex shaped parts. The ultrasonic data can be used to give a better understanding of the failure mechanisms in this material. An immersion ultrasonic inspection system is presented along with data from experiments.

Keywords: immersion, ultrasonic testing, nondestructive testing, immersion tank.

1. Introduction

Titanium is a chemical element with the symbol Ti and atomic number 22. It has a low density and is a strong, lustrous, corrosion-resistant (including sea water and chlorine) transition metal with a silver color.

Titanium can be alloyed with iron, aluminum, vanadium, molybdenum, among other elements, to produce strong lightweight alloys for aerospace (jet engines, missiles, and spacecraft), military, industrial process (chemicals and petro-chemicals, desalination plants, pulp, and paper), automotive, agri-food, medical prostheses, orthopedic implants, dental and endodontic instruments and files, dental implants, sporting goods, jewelry, mobile phones, and other applications.

The processing of titanium metal occurs in 4 major steps: reduction of titanium ore into "sponge", a porous form; melting of sponge, or sponge plus a master alloy to form an ingot; primary fabrication, where an ingot is converted into general mill products such as billet, bar, plate, sheet, strip, and tube; and secondary fabrication of finished shapes from mill products [1].

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Research into the processing method and into the microstructure of the material has shown that inherent chemical and physical inhomogeneous regions appear between individual grains mainly due to the method of fabrication. These regions invariably lead to weak spots causing a variation of the material properties and eventually failure of the material due to fatigue.

Delaminations or cracks are the primary indicators of material fatigue and also the primary defects thought after in the evaluation process [4].

The available methods of inspection for these defects require some form of destructive process in order to expose the cracks or delaminations, rendering the sample useless for any other form of testing. Whatever testing technique is used, it must be able to detect the smallest possible defect and must do so reliably, regardless of the material and the shape of the sample. Although X-rays might be an obvious choice, they are not effective in many cases, particularly when the defect has the same density as the surrounding material. Ultrasonic waves can detect variations in the elasticity of the material, as well as in the density.

That is why the article suggests the use of acoustic evaluation and more precise the use of immersion acoustic examination.

2. The possibility of defects detection using NDT methods

The process of nondestructive testing reveals the existence of flaws, discontinuities, leaks, contamination, thermal anomalies, or imperfections in materials, components or assemblies without impairing the integrity or function of the inspected component. Nondestructive evaluation is also utilized for real-time monitoring during manufacturing, measurement of physical properties such as hardness and internal stress, inspection of assemblies for tolerances, alignment, and periodic in-service monitoring of flaw/damage growth in order to determine the maintenance requirements and to assure the reliability and continued safe operation of the part.

Advances in the use of lasers and imaging technology (including video, holography and thermography) have made non contact NDT more viable in many situations.

There are seven NDT basic methods: (Visual Testing (VT) - Ultraviolet, Infrared, and Visible Light. Penetrant Testing (PT), Electromagnetic Testing (ET), Magnetic Particle Testing (MT), Acoustic Emissions Testing (AET), Ultrasonic Testing (UT), Radiographic Testing (RT) - X-Rays, Gamma Rays, Beta Particles, Protons, Neutrons).

Ultrasonic Testing (UT) is among the oldest and most widely used Non Destructive Testing (NDT) methods [5]. This method has been used typically for locating internal defects, such as cracks, voids, spongy areas, and other structural discontinuities, which may or may not be exposed to the surface. Defects can be particularly difficult to detect when the composition of the material varies or when the sample has a complex geometry, thus the use of several transducers is often needed to provide ultrasonic signals from a range of positions.

In order to overcome this problem, the usual approach is to immerse the sample and transducers in water, which ensures that the signal from the transducers only contains a longitudinal component.

Piezoelectric transducers convert an electric pulse into a short ultrasonic pulse, which is transmitted into the liquid. At the liquid/solid interface, some of the ultrasonic energy is transmitted into the solid, while the rest is reflected. Any defect in the sample will reflect part of the ultrasonic pulse back towards the transducer, which converts it back to an electrical pulse.

In the area separating the two environments, an acoustic wave undergoes a reflection - a part of the incident sound energy is restored to the first medium, and refraction - the rest of the sound energy is transmitted into the second medium (Fig. 1). In the case of waves with normal incidence, a reflected wave and a transmitted wave are produced in this way. In the case of sinusoidal waves, where there is no loss of acoustic energy at the separation surface, the equation of the three waves is [2]:

$$p_i = P_i \sin(\omega t - k_1 x);\ p_r = P_r \sin(\omega t + k_1 x);\ p_{tr} = P_{tr} \sin(\omega t - k_2 x); \quad (1)$$

in which k_1 and k_2 are wave numbers for first and second medium, P_i, P_r, and P_{tr} - complex quantities corresponding to acoustic pressure amplitude.

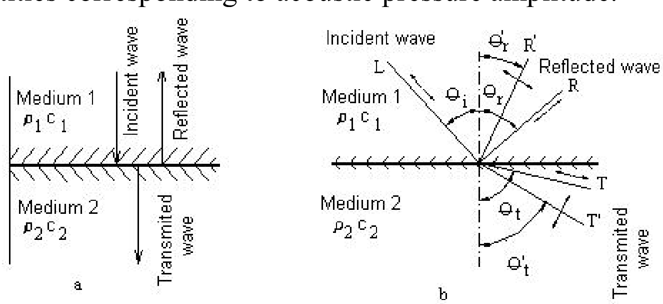


Fig. 1. Reflection and refraction of acoustic waves
a – normal incidence; b - under oblique incidence.
$\rho_i c_i$ – acoustic impedance; θi; θr; θt – angles of incidence, namely the reflection and transmission; L; R; T –incidence and reflection longitudinal waves; R'; T' – transversal waves of reflection and transmission

From the law of continuity of pressure and oscillation speed of particles from the two environments it results [2]:

$$p_i - p_r = p_{tr}, v_i - v_r = v_{tr}. \quad (2)$$

If the impedances of the two environments are $\rho_1 c_1$ and $\rho_2 c_2$, the acoustic reflection factor is [2]:

$$R_a = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \tag{3}$$

and the acoustic transmission factor is [2]:

$$T_a = \frac{2\rho_2 c_2}{\rho_2 c_2 + \rho_1 c_1}. \tag{4}$$

Using ultrasonic energy in nondestructive testing poses the problem of ultrasonic waves propagation in three environments or more. Generalization the problem may be to consider acoustic waves in their propagation cross three mediums extended to infinite with $\rho_1 c_1$, $\rho_2 c_2$ and $\rho_3 c_3$ impedances and the middle layer having a thickness *d* (Fig. 2.). Due to the reflection plane of separation between environment 1 and environment 2 in environment 1 there will be an incident wave p_{i1} and a reflected one P_{r1}[2]:

$$p_{i1} = P_{i1} \exp[jk_1(c_1 t - x)] \quad p_{r1} = P_{r1} \exp[jk_1(c_1 t + x)]. \tag{5}$$

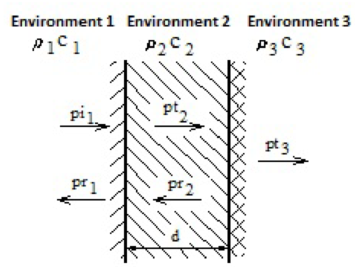


Fig. 2. Acoustic wave propagation under normal incidence through multiple environments

In the second environment there will be a second wave transmitted from the first medium p_{t2} and a reflected one p_{r2} [2]:

$$p_{t2} = P_{t2} \exp[jk_2(c_2 t - x)] \quad p_{r2} = P_{r2} \exp[jk_2(c_2 t + x)]. \tag{6}$$

In the third environment there will be only one wave, the one transmitted across the separation plane between the second and the third environment p_{t3} [2]:

$$p_{t3} = P_{t2} \exp[jk_3(c_3 t - (x - d))]. \tag{7}$$

Setting conditions at the separation limit between the first and the second environment (x=0) results in the following expressions for the continuity of acoustic pressure and particle speed [2]:

$$p_{i1} + p_{r1} = p_{t2} + p_{r2} \; ; \; \rho_2 c_2 (p_{i1} - p_{r1}) = \rho_1 c_1 (p_{t2} + p_{r2}). \tag{8}$$

At the separation limit between the second and the third environment (*x*=*d*) the same conditions lead to [2]:

$$P_{t2}\exp(-jk_2d)+P_{r2}\exp(jk_2d)=p_{t3}\;;\;\rho_3c_3\left[\rho_{t2}\exp(-jk_2d)-P_{r2}\exp(jk_2d)\right]=\rho_2c_2p_{t2} \tag{9}$$

Using the expressions (5) to (9) we can determine the expression of the acoustic transmission coefficient k_{tr} with the following expression [2]:

$$k_{tr}=\frac{4\dfrac{\rho_1c_1}{\rho_3c_3}\left(1+tg^2kd\right)}{\left(1+\dfrac{\rho_1c_1}{\rho_3c_3}\right)^2+\left(\dfrac{\rho_1c_1}{\rho_2c_2}+\dfrac{\rho_2c_2}{\rho_3c_3}\right)^2tg^2k_2d} \tag{10}$$

The expression (10) shows the sound transmission coefficient dependence k_{tr} of the relative size of characteristic impedances of the environment in which the acoustic waves are travelling. [2]

In the majority of industrial applications, manual-contact UT testing is performed, resulting in measurement of a limited number of points on a structure or part. In recent years, Automated Ultrasonic Testing (AUT) has been applied whenever detailed inspection of critical structures or components, e.g. in nuclear power plant, was required. In addition AUT has also been applied to other fields such as the Process or Production Industry.

Typical industrial applications are corrosion mapping of storage tanks, pressure vessels and pipes as well as on line testing for lamination and inclusions detection in plates and pipes during manufacturing.

2.1 Experimental Stand

There are several AUT systems on the market that can perform either fully automated scanning or manually assisted.

The hardware has variations in the design but in general such a system consists of one or more ultrasonic transducers, a 1/2/3 axis motion system (Fig. 3a) or encoders to trace a moving probe (even in 3D in some cases), a pulse generation and A/D receiver sub-system, a motion control sub-system, an immersion tank (Fig. 3b) and either dedicated digital circuits that collect and process information (A-Scans, Gate values etc) during the scanning or normal computers that control the entire system with appropriate software.

The AUT system can data log thickness, amplitude and A-Scans from several gates.

Multi-channel systems can do this for more than one probe and there are purpose built systems with ten or more sensors that scan for example parts on a production line.

In this case the system used was an NDT Automation, Immersion Systems (Ultra PAC) system with the 12-bit AD-IPR-1210 PCI Pulse/Receiver/AD board. The probe used was a 5MHz-focused transducer.

a b

Fig. 3 Ultra PAC a – AUT motion system ; b. AUT system - Immersion tank.

2.2 The Ultrasonic Imaging and Analysis software

The software (UTwinTM) that is used to control the system, has the task to allow the user to setup the UT system (gain, delay, gates etc), control the motion or the probe, encode its position, collect the information from the A/D system, display the data on a screen during the test as A/B/C-Scan plots (real-time) (Figure 4) and store all data so that it can be used later and kept for a permanent record if required. The data acquisition software has also some capabilities for analysis of the results such as statistics and images.

The software (UTwin^{TM}) used provides the user with a complete set of tools for manipulating / post-processing, viewing and exporting ultrasonic scanning data. These tools allow for easy viewing, statistics, composite C-Scan images, 3D C-Scan images and image/data export to other application [3].

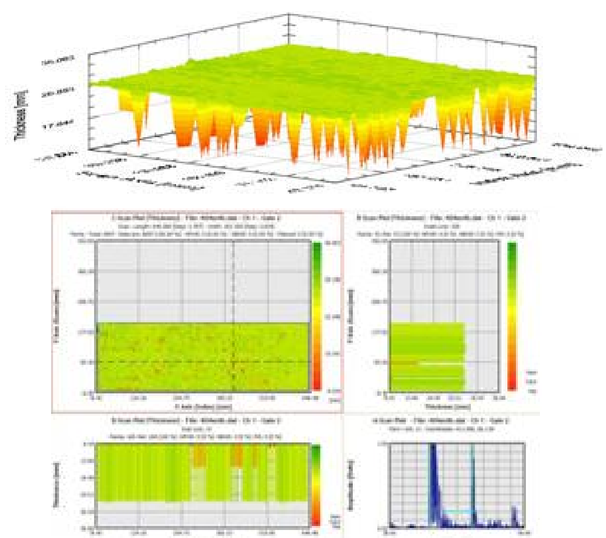


Fig. 4: A-B- C-3D-Scan images.

3. Application case

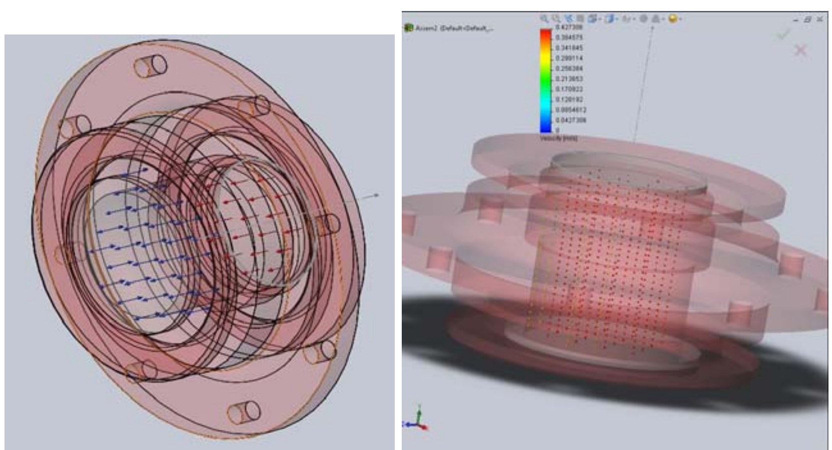
A titanium alloy part (flange) (Fig. 5) was tested (part of the cooling system from a commercial plane) using the above mentioned immersion system and the ultrasonic data gave a good correlation with the optical data in terms of location of possible defects.

The flange is part of a cooling system and its role is to connect elements in order to transport fluid (cooling agent) from one end to another

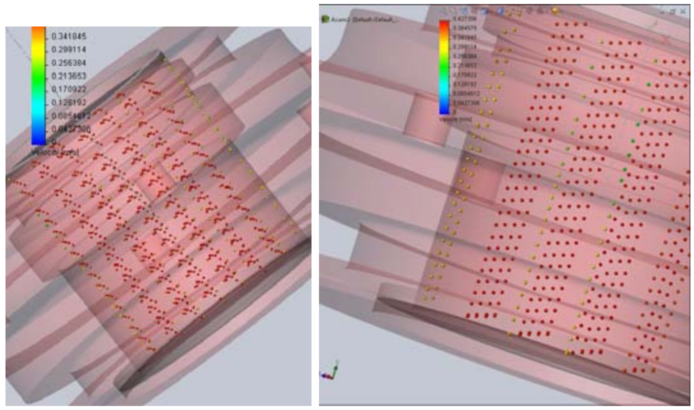
A simulation was made in order to better portray the purpose of the analyzed part (Fig. 6).

The analysis was performed using SolidWorks FloXpress from SolidWorks package. SolidWorks FloXpress is a first pass qualitative flow analysis tool which gives insight into water or air flow inside a SolidWorks model.

Fig. 5. Titanium alloy flange



a b



c d

Fig 6. Flow simulation in titanium alloy part,
a – fluid direction, b, c, d – flow representation with different speeds inside the model

Calibration was performed on a standard block with a number of thickness steps, flat bottom and side-drilled holes (as shown in Figure 7).

A standard time of flight method for acoustic measurement was employed to obtain the sound velocity of 6100m/s

The A-Scan (Fig. 8) width was set as wider as possible in order to have the maximum possible resolution.

Special problems arose from the scanning point of view due to its complicated shape.

The problems that such a test posses to an automated UT system are to achieve good signal in varying surface and material condition, the treatment of non-relevant indications (NRI), composition of various C-Scans to produce a vertical scan in its entirety, the C-Scan presentation in a meaningful, color-coded universal color scale taking into account the different nominal thicknesses.

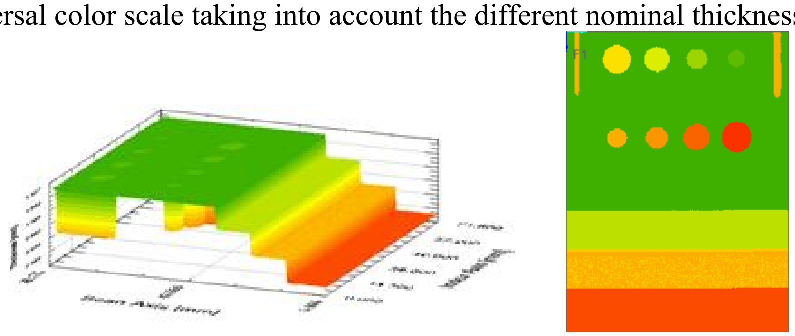


Fig. 7: C-Scan and 3D of standard calibration block.

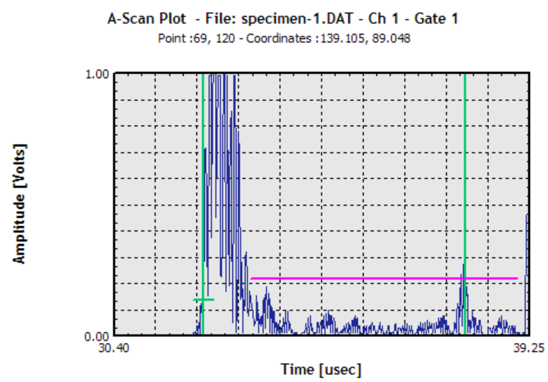


Fig. 8: Typical waveform and gate settings.

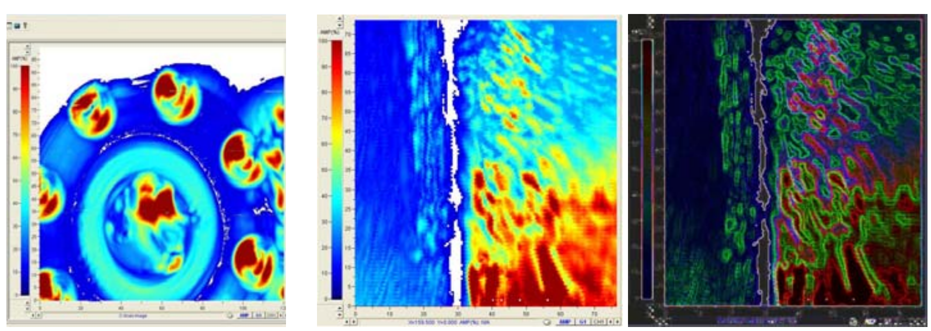
In Fig. 9, it can be seen that the ultrasonic image gives a close image of the actual problem regions within the retrieved sample.

The images obtained with the 5MHz transducer did not pick up all details of the sub-surface defects, but this was expected, as the transducer did not possess a high enough resolution.

Regions of different density came across as red patches in the image. These regions may be particularly dangerous in a structure because they are harder and more brittle than the surrounding material.

Such defects cause cracks to form in the material and can ultimately cause the component to fail. As seen in the image (Figure 9) these regions were observed to be widely distributed throughout the structure of the examined sample.

Improved images can be achieved with an even higher lateral resolution transducer but it requires a purpose-built design in order to detect defects with a 100-300 μm resolution.



a b

Fig. 9. Test results and C-scan images generated by the system, a – analyzed part, b – enhancement of problem region.

4. Conclusions

Results from this project show that it is possible to use the ultrasonic non-destructive evaluation technique in order to examine sub-surface features in titanium alloys type materials.

More accurate measurements will require however a purpose built transducer in order to achieve a better resolution.

From both the laboratory and the industrial point of view the requirements for testing, data quality, and data presentation and communication of results require, in many cases, the use of dedicated post-processing software.

Although there are a number of methods that can be used to investigate complex shaped parts, ultrasonic testing gives the best results from the viewpoint of accuracy and the percentage of detectives.

Even if the method has its disadvantages, remains the first choice when it comes to this type of material testing.

R E F E R E N C E S

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