Peer-reviewed version available at Materials 2018, 11, 293; doi:10.3390/ma11020293

Progresses and Challenges of Ultrasonic Testing for Stress in Remanufacturing Laser Cladding Coating

Xiao-Ling Yan[1, 2, *] • Shi-Yun Dong[2] • Bin-Shi Xu[2] • Yong Cao[2]

1 *College of Material and Mechanical Engineering, Beijing Technology and Business University, Beijing 102488, China*

2 *National Key Laboratory for Remanufacturing, Academy of Army Armored Forces, Beijing 100072, China*

Received June xx, 201x; revised February xx, 201x; accepted March xx, 201x

Abstract: Stess in laser cladding coating is an important factor affecting the safe operation of remanufacturing components. Ultrasonic testing has become a hot direction in nondestructive evaluation of stress, because it has the advantages of safety, non-destructive and on-line detection. This paper provides a review of ultrasonic testing for stress in remanufacturing laser cladding coating. It summarizes the recent research outcomes on ultrasonic testing for stress, analyzes mechanism of ultrasonic testing for stress. Remanufacturing laser cladding coating shows typical anisotropic behaviors, the ultrasonic testing signal in laser cladding coating is influenced by many complex factors, such as microstructure, defect, temperature and surface roughness, etc. At present, ultrasonic testing for stress in laser cladding coating can only be done roughly. The paper discusses active mechanism of micro / macro factors to the reliability of stress measurement and the impact of stress measurement to the quality and safety of remanufacturing components. Base on the discussion, the paper proposes strategies for acquisition of nondestructive, rapid and accurate measurement of stress in remanufacturing laser cladding coating.

Keywords: remanufacture • laser cladding forming • stress • ultrasonic testing • complex factors coupling

1 Introduction

Supported by National Natural Science Foundation of China (Grant No. 50305035), Two Sciences Foundation Raising Project of Beijing Technology and Business University (Grant No. LKJJ2017-12)

✉ Xiao-Ling Yan
yanxl@th.btbu.edu.cn

[1] College of Material and Mechanical Engineering, Beijing Technology and Business University, Beijing 102488, China

[2] National Key Laboratory for Remanufacturing, Academy of Armored Forces Engineering, Beijing 100072, China

Remanufacturing engineering[1-2] takes advanced surface engineering as measures, takes high efficiency, energy saving, environment protecting as rule, takes the upgrade of the performance of worn products as goal, and it is the generic terms of repairmen techniques for worn products. Because it meets the necessity of society development, lots of basic science problems about remanufacturing engineering attract lots of attention, and how to evaluate the quality of remanufacturing products is the key for remanufacturing products, it can not only enhance confidence and protect life security of users, but also affect the application of remanufacturing engineering.

Laser cladding[3] has become one of the important means of green remanufacturing for old products, due to its technological advantages. In the process of laser cladding, high energy laser beam is used as the moving heat source, by rapid heating, melting and cooling, extreme non-equilibrium conditions which can't be achieved by conventional methods are provided for material processing, so that the forming parts have excellent comprehensive performance. Laser cladding has become an advanced technology in remanufacturing engineering[4]. Because of the uneven heating in the process of laser cladding and the difference of thermal expansion coefficient among different compositions in laser cladding coating, the stress distribution in laser cladding coating is complicated[5-6]. Stress[7-9] has become a key factor affecting the service performance and service life of remanufacturing mechanical parts. With the development of laser cladding remanufacturing technology, stress evaluation of remanufacturing coating becomes more and more important. The key issues in this field have shifted from the study of the apparent problems of quality and performance of remanufacturing products to the deep-seated problems of high quality and reliability assurance. At present, the stress

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 January 2018 doi:10.20944/preprints201801.0071.v1

Peer-reviewed version available at Materials 2018, 11, 293; doi:10.3390/ma11020293

testing methods[10] can be divided into two categories: destructive methods[11] (small hole method, stripping layer method, ring core method) and nondestructive methods[12-16](ray diffraction method, magnetic memory method, optical method and ultrasonic method), Although these methods can realize stress measurement, there are some problems which can't be ignored, for example, the destructive methods destroy the integrity of the component structure and can only realize the sampling testing, The X-ray diffraction method is harmful to the health of operator. The optical method has high requirements for the detection environment and can't be detected on-line. The magnetic memory method has limitations (only ferromagnetic materials can be detected). Ultrasonic method[17-18] has many advantages, such as wide detection range, safe, nondestructive and on-line detection. Therefore, it has become a hot research direction in stress nondestructive testing.

The author and his team explored the theories and methods of life prediction and quality assessment of remanufacturing parts, which supported by the national 973 project, "life prediction of remanufacturing parts and service safety verification of remanufacturing products"(No. 2011CB013405). After further thinking, we found that the primary problem to ensure the service reliability of laser cladding remanufacturing components is not to grasp the change law of lifetime during its service, but to evaluate and control the residual stress and initial defects of laser cladding coating. The evaluation of the residual stress and initial defects can provide guidance for the optimization of laser cladding process, so as to improve the service safety of such remanufacturing components. On this basis, the change law of lifetime of laser cladding remanufacturing components is discussed, which provides the basis for the realization of multi-life cycles of components.

At present, the theory and technology of nondestructive evaluation of defects in laser cladding coating are mature, but the nondestructive evaluation of stress in laser cladding coating is still in the "experience" and "rough" level, and the related theory and experimental research are not perfect yet. In view of the advantages of ultrasonic method in stress nondestructive testing, this paper introduces the theory and method of ultrasonic testing for stress in laser cladding coating, the interaction mechanism between anisotropic microstructure and ultrasonic testing signal.

2 Basic Theory of Ultrasonic Testing for Stress

The method for stress testing by ultrasonic wave is based on acoustoelasticity theory and nonlinear ultrasonic theory[19]. The application of acoustoelasticity theory is based on the establishment of a series of assumptions, such as: objects have the characteristics of continuity and uniformity, objects are hyperelastic, microvariations of ultrasonic wave are superimposed on the finite deformation of the objects, and the deformation process is isentropic, and so on. Nonlinear ultrasonic testing for stress is based on the nonlinear characteristics of ultrasonic waves propagating in a solid medium (under stress).

2.1 Acoustoelasticity Theory

In 1953, D.S.Hughes and J.L.Kelly proposed the early expressions of stress and ultrasonic velocity in isotropic solids based on the finite deformation theory, which laid the foundation of acoustoelasticity theory[20-21]. Since 1960s, The acoustoelasticity effect has been continuously improved by R A Toupin, B Bernstein, R N Thurston[22-24], et al.

In summary, the existing expressions for acoustoelasticity equations of isotropic solids are as follows[20]:

equation (1): the direction of longitudinal wave propagation is parallel to the stress direction(v_{111} is the velocity of longitudinal wave):

$$\rho v_{111}^2 = \lambda + 2u + \frac{\sigma}{3K_0}[2l + \lambda + \frac{\lambda+\mu}{\mu}(4m + 4\lambda + 10\mu)] \quad (1)$$

equation (2): the direction of longitudinal wave propagation is perpendicular to the stress direction(v_{113} is the velocity of longitudinal wave):

$$\rho v_{113}^2 = \lambda + 2u + \frac{\sigma}{3K_0}[2l - \frac{2\lambda}{\mu}(m + \lambda + 2\mu)] \quad (2)$$

equation (3): the direction of transverse wave propagation and the direction of polarization is parallel and perpendicular to the stress direction respectively (v_{131} is the velocity of transverse wave):

$$\rho v_{131}^2 = \mu + \frac{\sigma}{3K_0}(m + \frac{\lambda n}{4\mu} + 4\lambda + 4\mu) \quad (3)$$

equation (4): the direction of transverse wave propagation and the direction of polarization is perpendicular to the stress direction (v_{132} is the velocity of transverse wave):

$$\rho v_{132}^2 = \mu + \frac{\sigma}{3K_0}(m - \frac{\lambda+\mu}{2\mu}n - 2\lambda) \quad (4)$$

equation (5): the direction of transverse wave propagation and the direction of polarization is perpendicular and parallel to the stress direction respectively (v_{133} is the velocity of transverse wave):

$$\rho v_{133}^2 = \mu + \frac{\sigma}{3K_0}(m + \frac{\lambda n}{4\mu} + \lambda + 2\mu) \quad (5)$$

equation (6): Longitudinal wave under static pressure (v_{111} is the velocity of Longitudinal wave):

$$\rho v_{111}^2 = \lambda + 2\mu - \frac{\sigma}{3K_0}(6l + 4m + 7\lambda + 10\mu) \quad (6)$$

equation (7): wave under static pressure (v_{131} is the velocity of transverse wave):

$$\rho v_{131}^2 = \lambda - \frac{\sigma}{3K_0}(3m - \frac{1}{2}n + 3\lambda + 6\mu) \quad (7)$$

where v_{ijk} first subscript i is the propagation direction of the ultrasonic wave, second subscript j is the polarization direction of the ultrasonic wave, third subscript k is the direction of uniaxial stress, ρ is the density of isotropic solid, σ is the stress in isotropic solid, K_0 is bulk modulus , λ、u is second-order elastic constants, m、n、l is third-order elastic constants.

Remanufacturing laser cladding coating is usually an anisotropic structure, in the preparation of the coating, the material will undergo elastic-plastic deformation, acoustoelasticity theory that consistent with the deformation perfectly needs to be developed further. Some universities and scientific research institutions in the United States, Japan and Britain have carried out a series of related studies and achieved some significant results since 1980s. in 1981,G C Johson[25-26] deduced the acoustic elastic formula under elastoplastic condition based on the elastic-plastic continuum model of Green. elastic strain, plastic strain, principal stretch ratio and strength hardening parameters are included in the formula, these complex parameters can be determined by elastoplastic experiment, so it is difficult for the formula to be popularized and applied in practice. In the same year, Okada[27]derived the acoustic elastic formula for weakly orthotropic materials under the assumption of nonlinear elastic constitutive relation of anisotropic materials. In 1985, Yih-HsingPao[28] deduced the acoustic elastic formula in the orthotropic medium with initial stress. The above research results are beneficial to the acoustoelasticity theory in anisotropic materials under elastic-plastic deformation, but most of these researches remain at the theoretical level and are far from practical application.

2.2 Nonlinear Acoustoelasticity Theory

As early as 1755, Euler proposed the concept of nonlinear acoustics, Lagrange, Strokes and Rayleigh Studied nonlinear acoustic theory[29]. In 1960s, researchers began to study nonlinear acoustic phenomena in solids. In 1963, the phenomenon of harmonic propagation in aluminum was observed by Hikata at metal laboratory of Brown University[30].

The laser cladding coating with residual stress has nonlinear characteristics of solids, when the ultrasonic wave propagates, the nonlinear characteristics of laser cladding coating can be characterized by nonlinear phenomena of ultrasonic propagation. When one-dimensional longitudinal wave propagates through a nonlinear medium, in the case of small strain, the equation of longitudinal wave's motion can be written as[31-32]

$$\frac{\rho^2}{E^2}\frac{\partial^2 u}{\partial t^2} = \frac{\partial^2 u}{\partial x^2} + \beta\frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial x^2} + \delta\left(\frac{\partial u}{\partial x}\right)^2\frac{\partial^2 u}{\partial x^2} \quad (8)$$

where ρ is the density of nonlinear medium, E is elastic modulus, u is the displacement in the x direction, β,δ are called two order and three order nonlinear coefficients respectively. They are related to the two, three and four order elastic constants of the materials respectively.

Since the equation (8) has no general analytic solution, the perturbation method is adopted by domestic and overseas scholars to obtain its approximate solution. The perturbation method is mainly to expand the required parameter in power series, here $u(x,t)$ is expanded by the power of x, finally, simplification and consolidation according to the same power of x, get the solution of the equation (8)[33-34].

$$u(x,t) = A_1\cos(kx-\omega t) - \frac{\beta}{8}k^2A_1^2x\cos 2(kx-\omega t) + \frac{\delta}{24}k^3A_1^3x[\cos 3(kx-\omega t) + 3\cos(kx-\omega t)] \quad (9)$$

where ω is circular frequency, k is wave number, A_1 is the amplitude of fundamental wave, $A_2 = \frac{\beta}{8}k^2A_1^2x$ is the amplitude of the second harmonic, $A_3 = \frac{\delta}{24}k^3A_1^3x$ is the amplitude of the third harmonic. Therefore, the expressions for the second-order and third-order nonlinear coefficients are as follows

$$\beta = \frac{8A_2}{k^2A_1^2x} \quad (10)$$

$$\delta = \frac{24A_3}{k^3A_1^3x} \quad (11)$$

It can be seen from the formula (10) and (11) that the amplitude of the two harmonic(A_2) and that the amplitude of the three harmonic(A_3) depend on the nonlinear parameter β,δ respectively. This two parameters indicate the characteristics of materials related to stress. Therefore, if the β,δ can be measured, the stress state of the material can be estimated. Since the symmetry of the three order elastic constants in laser cladding coating, the shear wave does not produce harmonic components in surface waves, so the description of the nonlinear coefficients for longitudinal wave is also applicable to surface wave.

3 Ultrasonic Testing for Stress in Laser Cladding Coating

Ultrasonic testing has become a hot direction in nondestructive evaluation of stress, because it has the advantages of safety, non-destructive and on-line detection. Remanufacturing laser cladding coating shows typical anisotropic behaviors, the ultrasonic testing signal in laser cladding coating is influenced by many complex factors. At present, the nondestructive evaluation of stress in laser cladding coating can only be done roughly.

3.1 Ultrasonic Testing Methods for Stress

The main methods for testing stress based on acoustoelasticity theory include: the use of the relationship between ultrasonic velocity and stress; ultrasonic attenuation degree and stress; incident angle of Rayleigh wave and stress; echo power spectrum and stress; the interaction of acoustic beams and stress, and the relationship between ultrasonic velocity and stress is the focus of current research[35]. The excitation waveforms used to measure stress in laser cladding coating include Rayleigh wave, critical refraction longitudinal wave or two wave combinations.

A classical stress measurement system based on the relationship between Rayleigh wave velocity and stress is shown in Fig 1[36]. It mainly consists of Panametrics-NDT 5800PR ultrasonic pulse transmitting and receiving instrument, TDS5000B oscilloscope (highest sampling frequency is 2.5GHz) and Rayleigh wave transducers with frequency of 5MHz(an transmitting transducer and a receiving transducer).In the experiment, in order to ensure the coupling between the tranducer and the sample is stable, the contact between them is elastic, a simple device is used to fix the Rayleigh wave transducer to the detected area to collect data (the distance between the tranducers is 20mm). Because the Rayleigh wave velocity is inconvenient to measure, and the propagation time of Rayleigh wave can be measured directly, so the velocity is converted into the change rate of propagation time within a certain distance.

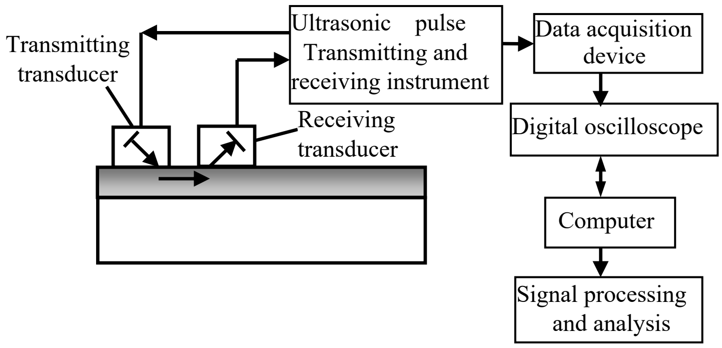

Fig. 1 A classical ultrasonic testing system for stress in laser cladding coating

The research on stress testing based on nonlinear ultrasonic theory is still few at home and abroad. In 2009, Chaki and others[37] analyzed the stress value of prestressed steel strand by using nonlinear ultrasonic guided wave technique, and discussed the sensitivity of different modes of guided wave to stress. In 2010, Liu[38] used nonlinear Rayleigh wave to test the residual stress in the aluminum alloy plate produced by shot peening. It was found that the stress values were in one-to-one correspondence with the nonlinear coefficients. The above researches on ultrasonic testing for stress in heterogeneous materials have strong novelty and reference significance, but what can't be ignored is that most of the researches remain at the level of experimental observation, and lack of deep theoretical analysis.

3.2 The Influence Mechanism of Micro Factors on Ultrasonic Testing for Stress

Remanufacturing laser cladding coating is usually an anisotropic structure, Fig. 2[36] shows the SEM micrograph of Fe314 laser cladding coating, It can be seen from Fig. 2 that its interior is obviously dendritic. Because the laser cladding sample was prepared by means of multilayer and multipass lap cladding , so there is obvious interface between two layers in the laser cladding coating. the growth direction of dendrite in single layer is basically identical, which is perpendicular to the interface between two layers approximately. The continuity of dendrite growth in the adjacent laser cladding layer is interrupted by interface between two layers, and the growth direction is slightly different. The adjacent cladding layers are bonded together by metallurgical bonding, which ensures the continuity of dendrite growth in the inner layer and the strength of interlayer bonding. Fig.3[39] shows the SEM micrograph of $Fe_{55}Cr_{20}Ni_{10}B_2Si_2$ laser cladding coating, inclusions and microcracks at their boundaries can

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 January 2018 doi:10.20944/preprints201801.0071.v1
Peer-reviewed version available at Materials 2018, 11, 293; doi:10.3390/ma11020293

be seen from Fig.3.

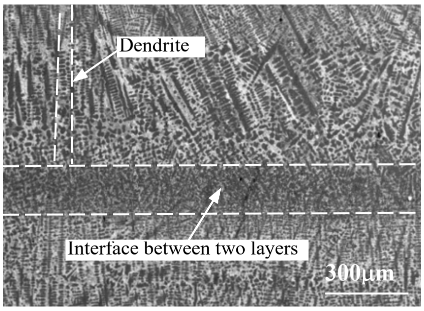

Fig. 2 SEM micrograph of Fe314 laser cladding coating

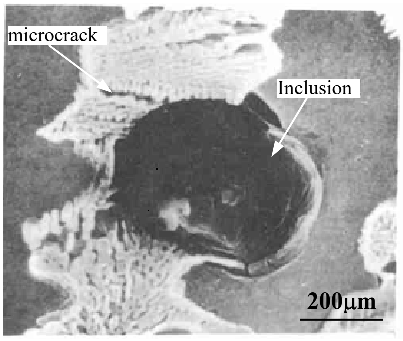

Fig.3 SEM micrograph of $Fe_{55}Cr_{20}Ni_{10}B_2Si_2$ laser cladding coating

How micro factors such as textures, inclusions and defects in the laser cladding coating affect the stress testing results based on ultrasonic wave. Experimental studies have been carried out by related universities and research institutions. In 1983, King[40] used the oblique incidence horizontal polarization shear wave (SH wave) to achieve the measurement of plane stress state under weak orthogonality conditions. This method separated texture effect and stress effect effectively. It is assumed that the principal stress coincides with the material symmetry axis, and the acoustoelasticity equation in the plane stress state is:

$$\frac{SH_{23}-SH_{13}}{SH_0}=\frac{c_{55}-c_{44}}{c_{44}}\cos^2\theta+\alpha(\theta)(T_{22}-T_{11}) \qquad (12)$$

Where SH_{ij} is the velocity of SH wave propagating in the surface ij, SH_0 is the average velocity of two kinds of SH wave, c_{44}, c_{55} are the elastic constants of the material, $\alpha(\theta)$ is the elastic constant at different angles, T_{22}, T_{11} are the principal stresses.

In 1984, Thompson[41] adopted plane SH wave propagating in vertical direction to separate texture effect and stress effect, the expression presented is:

$$\rho(v_{ij}^2-v_{ji}^2)=\sigma_{ii}-\sigma_{jj} \qquad (13)$$

Where v_{ij}, v_{ji} is the velocity of SH wave propagating in the surface ij, σ_{ii}, σ_{jj} are the principal stresses.

In 1984, Allen and Sayeres[42] used the method of combining focused P-wave and S-wave birefringence to separate tissue effects, the method was validated by measuring the residual stress at the crack tip. In 1992, Rokhlin[43] proposed GAO technology, using two kinds of transverse wave and one kind of longitudinal wave, the relation between the polarization angle of transverse wave and stress was established. In 2002, the residual stress in butt welded plate was measured by using the critical refraction longitudinal wave in the French Mechanical Industry Technology Center[44], the effect of microstructure in the heat affected zone and weld zone on the test results was considered, the results were in good agreement with the small bore method. In 2015, the author's research group[36] used Rayleigh wave to test the stress in laser cladding coating, and analyzed the effect of the anisotropic microstructure on the testing results combining with the theory of elastic-plastic deformation. the expression presented is:

$$\begin{cases}\dfrac{v_1-v_1^0}{v_1^0}=k_1\sigma_1+k_2\sigma_2+\alpha_1\\[2mm]\dfrac{v_2-v_2^0}{v_2^0}=k_2\sigma_1+k_1\sigma_2+\alpha_2\end{cases} \qquad (14)$$

Where v_i, v_i^0 is the velocity of Rayleigh wave propagating in laser cladding coating under the condition of in stress and no stress respectively, k_1, k_2 is the acoustic elastic coefficient of laser cladding coating in two directions perpendicular to each other respectively, α_1, α_2 is tissue effect factor in two directions perpendicular to each other respectively.

Fig. 4 shows when the stress is zero, the Rayleigh wave signal propagates in a fixed acoustic path in different testing positions of Fe314 laser cladding coating. Fig. 5 shows the results of stress testing before and after removal of the tissue effect. It can be seen that the method proposed by the author's research group can improve the reliability of the testing results effectively. The above researches have greatly promoted the development of ultrasonic nondestructive testing for stress in anisotropic materials, and have strong reference significance, however, there is some blindness in exploring the method of separating tissue effects, without combining the ultrasonic propagation theory with material microstructure, the influence mechanism of tissue effects on ultrasonic testing for stress in anisotropic materials isn't analyzed in depth, and a convincing explanation isn't given for the separation of tissue effects.

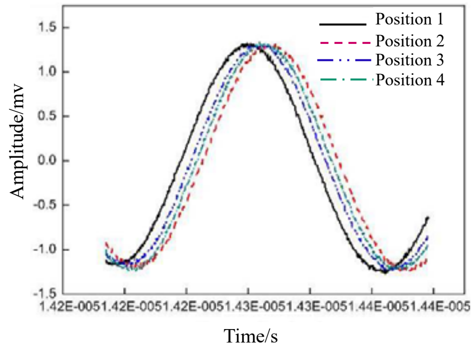

Fig.4 Rayleigh wave signals of laser cladding Fe314 alloy coating responding to the zero stress

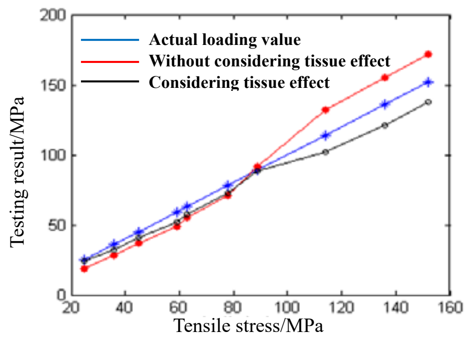

Fig.5 Stress testing results of Fe314 laser cladding coating

3.3 The Influence Mechanism of Macro Factors on Ultrasonic Testing for Stress

How macro factors such as Temperature, probe coupling mode, coupling layer thickness, surface roughness affect the stress testing results based on ultrasonic wave. Currently, the most influential methods in this respet include: 1) explore the influence of macro factors on stress testing results through tentative experiments, and propose methods for correcting errors [45-47]. 2) improve the accuracy of testing characteristic parameters. (such as ultrasonic signal propagation speed, amplitude, etc.) in ultrasonic testing for stress experiments[48-49]. Explore the methods for correcting errors through tentative experiments, once the testing object and experimental condition change, many experiments are needed to find the method to correct the error. Modern signal processing technology can improve the reliability and accuracy of stress testing result to a certain extent.[50-51] Fig.6 (a) and (b) are Rayleigh wave signal propagating in a fixed acoustic path in Fe314 laser cladding coating under 34MPa and 230MPa tensile stress respectively[52]. It can be seen from Fig. 6 that the acquired Rayleigh wave signals contain a lot of noise. Evaluate the stress of laser cladding coating based on Rayleigh wave, the extraction of acoustic time delay is the key technology. Fig.7(a) shows the acoustic time delay analysis result based on correlation method. Fig.7(b) is the acoustic time delay analysis result based on complex cepstrum method proposed by the author's research group. As can be seen from Fig.7, the signal-to-noise ratio of correlation analysis result is low, the time delay peak is very close to the surrounding interference signal, so it is not easy to locate accurately. The signal-to-noise ratio of complex cepstrum analysis result is relatively high, the time delay peak is very sharp, and it is convenient for accurate positioning (the time difference between two signals is only 20 sampling points (8ns)).

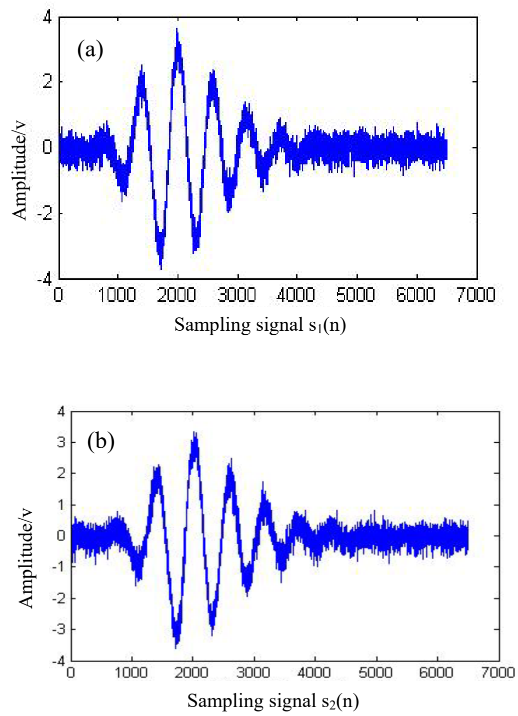

Fig.6 Time-domain map of sampling signal (a) under 34MPa tensile stress (b) under 230 MPa tensile stress

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 January 2018 doi:10.20944/preprints201801.0071.v1

Peer-reviewed version available at Materials 2018, 11, 293; doi:10.3390/ma11020293

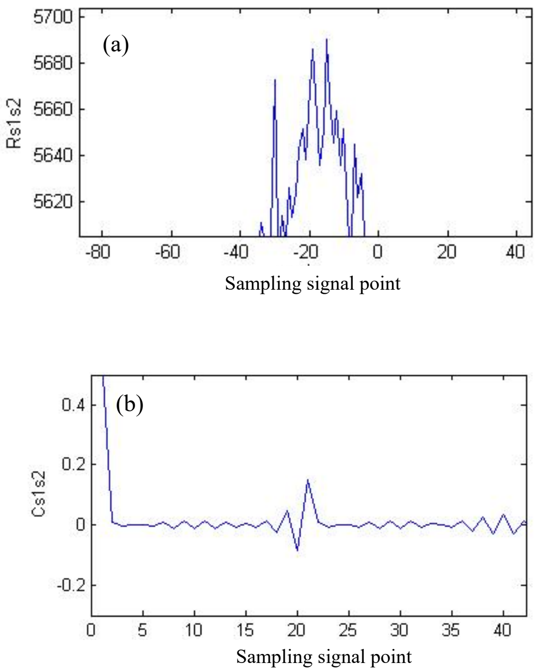

Fig.7 Contrast of acoustic time delay analysis result (a) correlation analysis result (b) complex cepstrum analysis result

To sum up, there are still many basic scientific problems unsolved in the field of ultrasonic nondestructive testing for stress in laser cladding coating. Summarized as follows: 1) the interaction mechanism of anisotropic laser cladding coating and ultrasonic is not clear; 2)The effect of laser cladding coating and the substrate "combination" , "sound transmission" on stress testing result remaining to be studied; 3) The essential principle for separation of tissue effects in anisotropic materials is not given; 4) The stress testing for anisotropic materials based on nonlinear ultrasonic lack in profound theoretical analysis. The preliminary research of author's research group showed some basic scientific problems in the field of ultrasonic stress testing can be solved by using relevant technologies.

4 Strategies for Solving Related Problems

To solve the technical bottleneck problems in ultrasonic testing for stress in laser cladding coating, researches should grasp the principal contradiction and decompose the complex problems. The factors that affect the reliability of ultrasonic testing for stress in laser cladding coating are classified into two categories: micro and macro. The influences of micro factors and macro factors can be stripped. Firstly, by changing the laser cladding process, specimens with different microstructure and stress state are prepared. In the process of testing, the stability of macro factors such as environment, instrument and personnel is maintained, and the influence mechanism of micro factors on testing signal is studied; Secondly, in view of the same laser cladding sample (to ensure the consistency of micro factors), the change law of stress testing result is studied when the macro factor changes; Then, the coupling effect of macro and micro factors is considered. The micro and macro factors related to stress testing are extracted by data mining, and the coupling effect of multiple factors in ultrasonic stress tesing are proved by orthogonal and uniform experiments; Finally, the multiple factors coupling analysis results are used as input samples of Support Vector Machine(SVM), Prediction model of optimum testing method based on multidimensional analysis and multi-source information is established to realize nondestructive, fast and reliable testing for the stress in remanufacturing laser cladding coating.

4.1 Get Full-Effective Information of Acoustic Field

Compared with the experimental research, numerical simulation is more flexible and convenient in model making, parameter selection and variation, and data processing of simulation results. It can highlight some details which are not easily observed in the experiment. The numerical simulation technology of ultrasonic testing with the objective of acoustic field analysis and flaw echo prediction has developed rapidly in recent years, Its applications include: 1) scattering and echo prediction of different types of flaws[53-55]; 2) ultrasonic propagation and acoustic field analysis in isotropic and anisotropic materials[56-58]; 3) ultrasonic imaging simulation[59-60]. It has not been found that other scholars have carried out the research of ultrasonic nondestructive testing for stress in anisotropic materials by means of numerical simulation.

The author's research group using ANSYS/LS-DYNA Finite Element Method(FEM)[61], got the acoustic elastic curve of Rayleigh wave in aluminum alloy (as shown in Fig.8) through the implicit and explicit solution. The red point is the data collected during static load test, and the experimental results are in good agreement with the numerical simulation results. Fig. 9 is the Rayleigh wave signal in aluminum alloy under different stress. Therefore, it is more convenient to obtain the intrinsic relationship between the velocity of ultrasonic signal and stress in material by using FEM. In addition, the influence of anisotropic laser cladding coating on the propagation behaviors of ultrasonic beam was analyzed by the author's research group. The propagation behaviors of ultrasonic beam in the laser cladding Fe314 alloy coating were

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 January 2018 doi:10.20944/preprints201801.0071.v1

Peer-reviewed version available at Materials 2018, 11, 293; doi:10.3390/ma11020293

investigated with the help of Rayleigh integral combined with pencil method. Fig10 – Fig.14 are part of the numerical simulation results[62]. Fig.10 shows the grain orientation angle in laser cladding coating and the coordinate system direction. Fig.11 shows when longitudinal wave vertical incidence, the grain orientation angle is 30^0, the numerical simulation results of ultrasonic field distribution in the xoz section of Fe314 laser cladding remanufacturing specimen (the white line in Fig.11 is the joint surface of laser cladding coating and the substrate). The results show that the grain orientation can affects the propagation behavior of acoustic beam in the anisotropic laser cladding coating, when the grain orientation angle is 30^0, the propagation direction of vertical incidence longitudinal beam will steer. Fig.12 shows the vertical incident wave propagation principle in Fe314 laser cladding coating, it can be seen from Fig.12 , the grain orientation angle is 30^0, , the slowness surface of longitudinal wave in the laser cladding coating is not an ideal circle, so the direction of group velocity (the normal vector direction of slowness surface) is inconsistent with that of phase velocity (the direction of refraction longitudinal wave beam) , the longitudinal wave beam will steer. As shown in Fig.13, under the same conditions, the oblique incidence transverse beam not only steer but also splits into two shear beams with different propagation velocities. Fig.14 is the echo of flaw in Fe314 laser cladding remanufacturing specimen (numerical simulation and test results are in good agreement). Thus, theoretical analysis, numerical simulation and experimental detection can be verified mutually, numerical simulation technology can be more intuitive to analyze the propagation behaviors of ultrasonic in anisotropic materials, and realize “transparency” and “detail” for the acquisition of ultrasonic field information in the process of ultrasonic testing for stress.

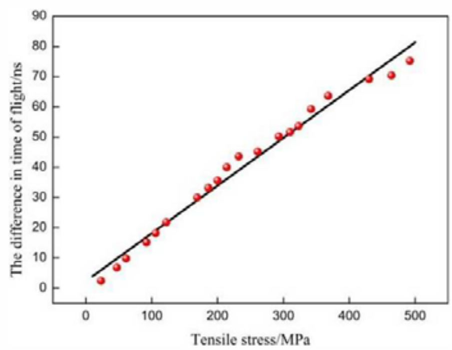

Fig.8 Relationship between propagation time difference of Rayleigh wave and tensile stress

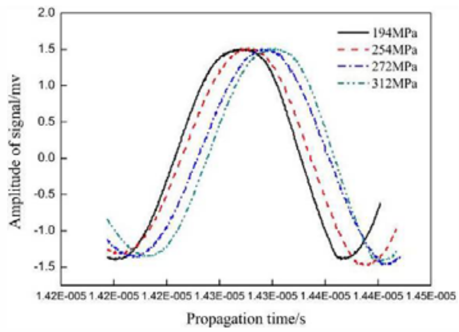

Fig.9 Rayleigh wave signals in aluminum alloy under different stress

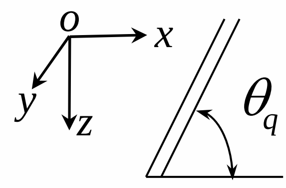

Fig.10 Grain orientation angle θ_q and orientation of coordinate system

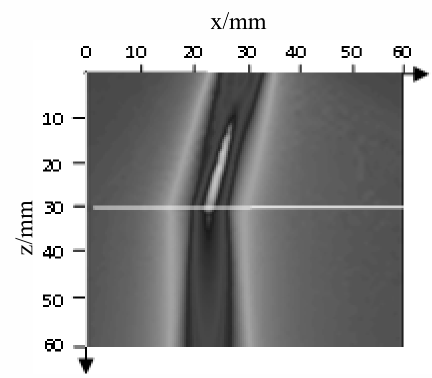

Fig.11 Radiated ultrasonic field of longitudinal wave probe in Fe314 laser cladding remanufacturing specimen

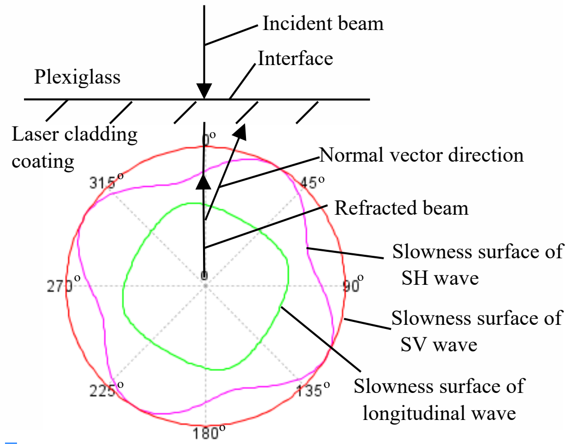

Fig.12 Schematic diagram of vertical incidence longitudinal wave propagation in Fe314 laser cladding coating

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 January 2018 doi:10.20944/preprints201801.0071.v1

Peer-reviewed version available at Materials 2018, 11, 293; doi:10.3390/ma11020293

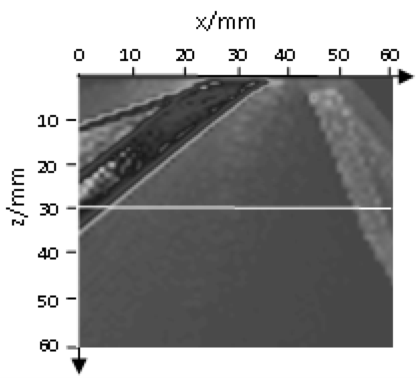

Fig.13 Radiated ultrasonic field of transverse wave probe in Fe314 laser cladding remanufacturing specimen

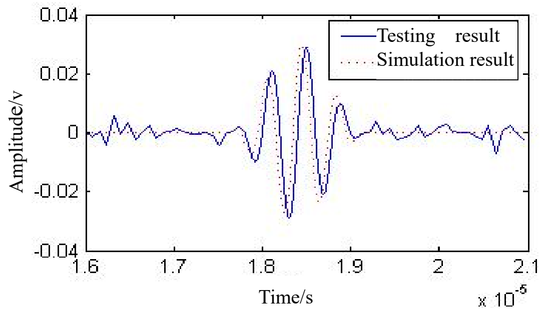

Fig.14 Simulation and testing results of flaw echo signal in Fe314 laser cladding remanufacturing specimen

4.2 Technology Roadmap

To realize nondestructive, fast and reliable testing for the stress in remanufacturing laser cladding coating, draw up the technology roadmap shown in figure 15.

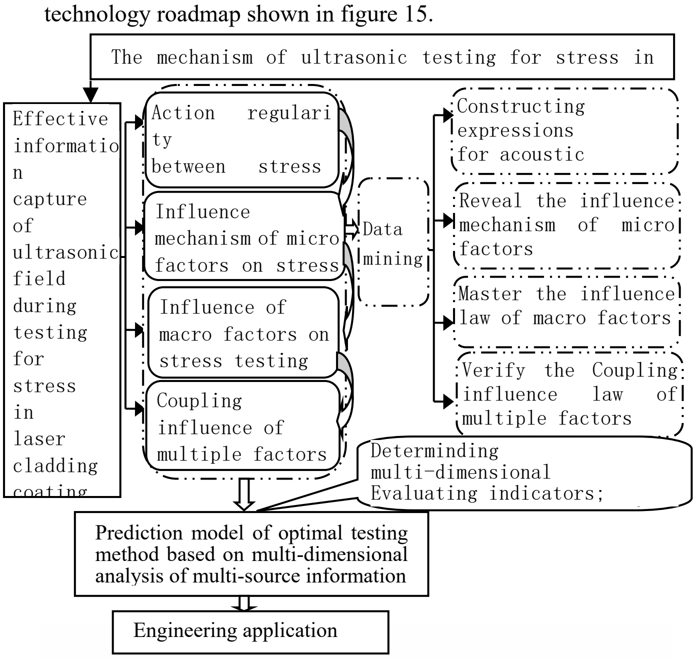

Fig.15 Technology roadmap

5 Conclusions

Laser cladding, due to its technological advantages, has become one of the important means of green remanufacturing for old products. But practice shows that stress in laser cladding coating is one of the key factors that affecting the service performance and life cycle of remanufacturing parts. In order to realize nondestructive, fast and reliable testing for the stress in remanufacturing laser cladding coating, the ultrasonic non-destructive testing technology was adopted. This paper discusses active mechanism of micro / macro factors to the reliability of stress measurement and the impact of stress measurement to the quality and safety of remanufacturing components. Strategies for acquisition of nondestructive, rapid and accurate measurement of stress in remanufacturing laser cladding coating are proposed in this paper. Based on the review, the paper summarizes conclusions:

(1) Master the influence law and mechanism of stress in laser cladding coating on ultrasonic testing signal, which is the basis and key to evaluate the stress in laser cladding coating. The transient dynamics and viscoelastic absorbing boundary techniques[63-64] can be introduced into the finite element analysis technique for ultrasonic testing for stress in laser cladding coating , the full-effective information of ultrasonic field in testing for stress in laser cladding coating can be collected through the finite element postprocessing. The relationship between stress and characteristic parameters of ultrasonic signal can be refined by using data mining technology, so as to grasp the influence rules and mechanism of stress in laser cladding coating on the ultrasonic signal.

(2) Clarify the mechanism of texture, inclusion, defect and other micro factors affecting the result of ultrasonic testing for stress in laser cladding coating, and weaken or separate its influence effectively, which is the key to improve the reliability of ultrasonic testing for stress. The theoretical model of ultrasonic propagation is established by using semi-analytical method. The full-effective information of ultrasonic field in testing for stress in laser cladding coating can be obtained through numerical simulation. The stress testing methods of "insulation" and "sensitive" to tissue effect are selected by cluster analysis and threshold setting, the corresponding methods are extended to experimental observation stage further, combined with elastic-plastic deformation and nonlinear dynamics theory, the essential principle of separating or weakening the tissue effect can be clarified.

(3) To build a prediction model of optimum testing

Peer-reviewed version available at *Materials* **2018**, *11*, 293; doi:10.3390/ma11020293

method based on multidimensional analysis and multi-source information is the key to realize nondestructive, fast and reliable evaluation of stress in laser cladding coating under multi-factor coupling action. Based on the results of multi-factor coupling experiment, the kernel principal component analysis (PCA)[65] is used to extract the multi-dimensional indexes (stress sensitivity, separation organization effect, detection signal recognition, probe layout convenience) that affect the testing effect. The digital representation method of each dimension index is defined, and its indication function to the feasibility of detection method is inversed. Support vector machine method is used to establish the prediction model of optimum testing method.

References

[1] E Z Li, P J Shi, B S Xu, et al. Analysis of Policies and Regulations of China Remanufacturing. *Journal of Mechanical Engineering,* 2015,51(19):117-123(in Chinese).

[2] United States International Trade Commission. *Remanufactured goods：An overview of the USA and global industries，markets，and trade*. Washington：USITC Publication, 2012.

[3] H Feng, J F Li, J Sun. Study on remanufacturing repair of damaged crank shaft journal surface by laser cladding. *Chinese Journal of Lasers*, 2014,41(8):80-85(in Chinese).

[4] S X Yan, S Y Dong , B S Xu, et al. Effect of molten pool convection on pores and elements distribution in the process of laser cladding. *Infrared and Laser Engineering*, 2014, 43(9): 2832-2839.

[5] J X Fang, S Y Dong, Y J Wang, et al. The effects of solid-state phase transformation upon stress evolution in laser metal powder deposition . *Materials and Design,* 2015,87(12): 807–814.

[6] P Kattire, S Paul, R Singh, et al. Experimental characterization of laser cladding of CPM 9V on H13 tool steel for die repair applications. *Journal of Manufacturing Processes*, 2015, 20(3): 492-499.

[7] Y M Rong,Y Huang, J J Xu, et al. Numerical simulation and experiment analysis of angular distortion and residual stress in hybrid laser-magnetic welding. *Journal of Materials Processing Technology,* 2017,245(7):270-277.

[8] S X Yan, S Y Dong , B S Xu, et al. Mechanics of removing residual stress of Fe314 cladding layers with laser shock processing. *Chinese Journal of Lasers*, 2013,40(10):97-102 (in Chinese).

[9] J Lin , N Ma, Y Lei, et al. Measurement of residual stress in arc welded lap joints by cosα X-ray diffraction method. *Journal of Materials Processing Technology,* 2017, 243(5):387-394.

[10] Q M Wang, Y Sun. Research development on the test methods of residual stress. *Journal of Mechanical & Electrical Engineering*, 2011, 28(1):11-15.

[11] M Steinzig ,D Upshaw , J Rasty. Influence of drilling parameters on the accuracy of hole-drilling residual stress measurements. *Experimental Mechanics* , 2014 , 54 (9) :1537-1543.

[12] B Liu, S Y Dong , B S Xu, et al. Coating thickness affects surface stress measurement of brush electro-plating nickel coating using Rayleigh wave approach. *Ultrasonics,* 2012,52(7):861-865.

[13] M Junge, J Qu, L J Jacobs. Relationship between Rayleigh wave polarization and state of stress. *Ultrasonics*, 2006,44(3): 233-237.

[14] H B Li, P C Zhang, G Li. Stress measurement for nonstoichiometric ceria films based on Raman spectroscopy. *Journal of Alloys and Compounds,* 2016, 682(10): 132-137.

[15] K Lalik, I Dominik, P Ćwiąkała. Integrated stress measurement system in tower crane mast. *Measurement*,2017,102(5):47-56.

[16] L H Dong , B S Xu, S Zhu, et al. Magnetic nondestructive testing of fatigue damage of ferromagnetic material. *Nondestructive Testing,* 2006, 28(5): 245–248.

[17] K Tanuma, C S Man, Y Chen. Dispersion of Rayleigh waves in weakly anisotropic media with vertically-inhomogeneous initial stress. *International Journal of Engineering Science*, 2015, 92(7): 63-66.

[18] R Pamnani, G K Sharma, S Mahadevan. Residual stress studies on arc welding joints of naval steel (DMR-249A). *Journal of Manufacturing Processes*,2015,20(10):104-108.

[19] Rose J. L. *Ultrasonic in solid*. C F He，B Wu，X Y Wang, translation .Beijing:Science Press,2004.

[20] D S Hughes.Ultrasonic velocity in an elastic solid.*Journal of Applied Physics*, 1950, 21(3): 294- 301.

[21] D S Hughes, J L Kellyt. Second-order elastic deformation of solids[J]. *Physical Review,* 1953, 92(5): 1145-1149.

[22] R A Toupin, B Bernstein.Sound waves in deformed perfectly elastic materials acoustoelastic effect.*The Journal of The Acoustical Society of America*, 1961, 33(2): 216- 225.

[23] R N Thurston, K Brugger.Third-order elastic constants and the velocity of small amplitude elastic waves in homogeneously stressed media.*Physical Review*, 1964, 133(6A): 1604- 1610.

[24] R N Thurston. *Wave propagation in fluids and normal solids in Physical Acoustics*. New York: W.P.Mason Academic Press,1964.

[25] G C Johson. Acoustoelastic theory for elastic-plastic materials. The Journal of the Acoustical Society of America, 1981, 70(2):591-595.

[26] G C Johson.The effect of plastic deformation on the acoustoe-lastic response of metals[J].*Journal of Applied Mechanics*, 1983(50): 689-691.

[27] Kenichi, Okada.Acoustoelastic determination of stress in slightly orthotropic materials.Experimental *Mechanics*, 1981(11):461- 466.

[28] Y Pao, U Gamer. Acoustoelastic waves in orthotropic media. *The Journal of the Acoustical Society of America*, 1985, 77(3): 806-812.

[29] B Leif. Forty years of nonlinear ultrasound. *Ultrasonics*, 2002, 40(1-8):11-17.

[30] A Hikata , B Chick, C Elbaum . Effect of dislocations on finite amplitude ultrasonic waves in aluminum. *Applied Physics Letters*, 1963, 3:195-197.

[31] H L Zhang . *Theoretical acoustics*. Beijing ：Higher Education Press, 2002.

[32] A Kkoen, D A Van, A Sutin, et al. Micro-damage diagnostics using nonlinear elastic wave spectroscopy (NEWS) . *NDT&E International,* 2001, 34(4)：239-248.

[33] H J Yan,C G Xu,Q Lin, et al. Metal surface fatigue detection using nonlinear ultrasonic. *Applied Mechanics and Materials*, 2014, 156：156-162.

[34] M Amura, M Meo, F Amerini. Baseline-free estimation of residual fatigue life using a third order acoustic nonlinear parameter. *Journal of the Acoustical Society of America*, 2011, 130(4):1829-1837.

[35] S S Cleudiane, H C Aliandro, P Paulo, et al. Application of Design of Experiments to Evaluation the Propagation Speed of Lcr Waves//*5th Pan American Conference for NDT*, Cancun, Mexico, October 2-6，2011:1-10.

[36] Y S Dong, X L Yan, B S Xu. Influence of microstructure and residual stress on surface stress measurement of laser cladding layer

Peer-reviewed version available at Materials 2018, 11, 293; doi:10.3390/ma11020293

by Rayleigh wave. *Journal of mechanical engineering*, 2015,51(24):50-56(in Chinese).
[37]S Chaki,G Bourse.Guided ultrasonic waves for non-destructive monitoring of the stress levels in prestressed steel strands. *Ultrasonics*, 2009,11(6)：230-235.
[38]M Liu, Y K Jim. Experimental study of nonlinear Rayleigh wave propagation in shot-peened aluminum plates-feasibility of measuring residual stress. *NDT&E International*, 2010, 43(1)：1107-1114.
[39]Q B Liu, S J Li. Microstructures of laser clad coating repairing cast defect in aeroengine blade. Heat Treatment of Mentals, 2007, 32(5): 21-24(in Chinese).
[40]R B King, C M Fortunko. Acoustoelastic evaluation of arbitrary plane residual stress states in nonhomogeneous anisotropic plates. *Ultrasonics,* 1983,21(6): 256- 258.
[41]R B Thompson, J F Smith, S S Lee. Microstructure-independent acoustoelastic measurement of stress.*Applied Physics letter*,1984, 44(3): 296- 298.
[42]D R Allen, C M Sayeres. The measurement of residual stress in textured steel using an ultrasonic velocity combinations technique.*Ultrasonics*, 1984,22(4): 179-188.
[43]S I Rokhlin, W Wang. Double through-transmission bulk wave method for ultrasonic phase velocity measurement and determination of elastic constants of composite materials.*Journal of the Acoustical Society of America*, 1992, 91(6):3303- 3312.
[44]H Walaszek, J Hoblos, G Bourse, et al. Effect of microstructure on ultrasonic measurement of residual stress in welded joints. Material Science Forum , 2002(404-407): 875- 880.
[45]B Liu，S Y Dong，B S Xu, et al.Study on stress measurement of thin plating coating with Rayleigh wave.*Transactions of Materials and Heat Treatment*, 2012, 33(3):111-114(in Chinese).
[46]H Du, J A Turner. Dependence of diffuse ultrasonic backscatter on residual stress in 1080 steel[J]. *Ultrasonics*, 2016,67(4):65-67.
[47]X C Liu, B Wu, F Qin, et al. Observation of ultrasonic guided wave propagation behaviours in pre-stressed multi-wire structures. *Ultrasonics*, 2017,73(1): 196-205.
[48]S K Pedram, A Haig, P S Lowe, et al. Split-spectrum signal signal processing for reduction of the effect of dispersive wave modes in long-range ultrasonic testing. *Physics Procedia*, 2015,70:388-392.
[49]H G Li, Z G Zhou. Air-coupled ultrasonic signal processing method for detection Stomata defects in materials. *NDT & E International*, 2017,92(12):167-176.
[50]S K Pedram, A Haig, P S Lowe, et al. Split-spectrum signal processing for reduction of the effect of dispersive wave modes in long-range ultrasonic testing. Physics Procedia, 2015,70(8) :388-392.
[51]S Fateri, N V Boulgouris , A Wilkinson, et al. Frequency-sweep examination for wave mode identification in multimodal ultrasonic guided wave signal. *IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control*, 2014 , 61 (9) :1515-1524.
[52]X L Yan, S Y Dong, B S Xu,et al. Cepstrum analysis method in surface acoustic wave signals time delay estimation. *Vibration and Shock*, 2013, 32(12): 159-162(in Chinese).
[53]N Xu, Z G Zhou. Numerical simulation and experiment for inspection of corner-shaped components using ultrasonic phased array[J]. *NDT & E International*, 2014,63(4): 28-34.
[54]X Y Zhao, T Gang. Nonparaxial multi-Gaussian beam models and measurement models for phased array transducers. *Ultrasonics*, 2009, 49(1): 126-130.
[55]J Siegler, L Leifsson, R Grandin, et al. Surrogate modeling of ultrasonic nondestructive. *Procedia Computer Science*, 2016, 80(5):1114-1124.
[56]P Comot, P Bocher, P Belanger. Ultrasonic guided wave inspection of Inconel 625 brazed lap joints: Simulation and experimentation, *NDT & E International*, 2017,91(10): 71-78.
[57]L Shi, C S Wu, G K Padhy, et al. Numerical simulation of ultrasonic field and its acoustoplastic influence on friction stir welding, *Material & Design*, 2016,104(8):102-115.
[58]AV Pamel，P Huthwaite，CR Brett, et al. Numerical simulations of ultrasonic array imaging of highly scattering materials, *NDT & E International*, 2016,81(7): 9-19.
[59]K Nakahata, H Sugahara, M Barth, et al. Three dimensional image-based simulation of ultrasonic wave propagation in polycrystalline metal using phase-field modeling,*Ultrasonics*, 2016,67(4):18-29.
[61] M C Wang. *Finite element method*. Beijing: Tsinghua University Press, 2003. (in Chinese)
[62] X L Yan, S Y Dong, N Xue. Numerical simulation of ultrasonic propagation and defect testing in laser cladding remanufacturing parts, *Chinese Science Bulletin*,2016, 61(18): 45-51. (in Chinese)
[63] X L Yan, S Y Dong, B S Xu. The numerical simulation for ultrasonic wave based on stress boundary, China Mechanical Engineering, 2014,25(19):2578-2582.(in Chinese).
[64] X L Du, M Zhao, J T Wang. A stress artificial boundary in fea for near-field wave problem, *Chinese Journal of Theoretical and Applied Mechanics*, 2006, 38(1): 49~55. (in Chinese)
[65] M Kallas，G Mourot，K Anani,et al. Fault detection and estimation using kernel principal component analysis, *20th World Congress of the International Federation of Automatic Control*, Toulouse, France, July, 2017:1025-1030.

Biographical notes

Xiao-Ling Yan, born in 1974, is currently a associate professor at *College of Material and Mechanical Engineering, Beijing Technology and Business University, China*. She received her PhD degree from *Beijing Institute of Technology, China*, in 2015. Her research interests include laser cladding remanufacturing and ultrasonic nondestructive testing.
Tel: 13717678385; E-mail: yanxl@th.btbu.edu.cn

Shi-Yun Dong, born in 1973, is currently a professor at *National Key Laboratory for Remanufacturing, Academy of Army Armored Forces, China*. He received his PhD degree from *Harbin Institute of Technology , China*, in 2000. His research interests include laser cladding remanufacturing and ultrasonic nondestructive testing.
Tel: 13911655167; E-mail: syd422@vip.sohu.com

Bin-Shi Xu, born in 1931, is currently an Academician of Chinese Academy of Engineering, *Key Laboratory for Remanufacturing, Academy of Army Armored Forces, China*. He received his bachelor degree from *Harbin Institute of Technology, China*, in 1954. His research interests include theory and technology of Remanufacturing Engineering.
Tel: 01066719248; E-mail: wwlwyd2002@sina.com.cn

Yong Cao, born in 1974, is currently a postdoctoral researcher at *National Key Laboratory for Remanufacturing, Academy of Army Armored Forces, China*. He received his PhD degree from *Academy of Army Armored Forces, China*, in 2010. His research interests include laser cladding remanufacturing and ultrasonic

nondestructive testing.
Tel: 18010084610; E-mail: wwlwyd2002@163.com