Longitudinal critically refracted (L\textsubscript{CR}) ultrasonic wave for residual stress measurement

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Abstract. The article deals with the state-of-the-art in the field of Longitudinal critically refracted (L\textsubscript{CR}) ultrasonic wave, for non-destructive material evaluation. It checks its capability for residual stress identification, and reviews positives and negatives related to its use. Obtained information within the article, are used for the understanding of essence of method and for the evaluation of its use in the engineering practice. The article can be the source of information about the L\textsubscript{CR} wave measurement technology, which is the part of the complex ultrasonic testing method. For the frequency of using this technology for surface residual stress measurement, it is appropriate to have this information in one whole, which are gathered of the outputs of researches by various authors. The paper is divided in few sections and sub-sections. In the first section, information about L\textsubscript{CR} wave technique and factors correlated with this method, are provided. The next section writes about residual stresses and the importance of their identification. Next, the principal of residual stresses measurement and basic structure of measurement device, is described. A significant part of study, describes the state so far of theoretical and practical researches within the use of this method, in the technological practice of residual stress identification in surface layers of engineering components. In the conclusion, obtained knowledges are summarised and evaluated. Related positive and negative aspects are included, with a verifying the need of future researches.

1. Introduction

Residual stresses are point of interest for decades in the engineering practice. A lot of researches confirm the fact, that they have a significant impact on the component’s lifetime. So, it is necessary to monitor their states, in the best possible effectivity, by a technical and an economical point of view, with the relevant quality of results. Several destructive or non-destructive technologies provide solutions for this need, and all have their positives and negatives. In general, more suitable are non-destructive technologies, thanks to their non-invasive approach to the evaluated material. Ultrasonic testing, considering the application of other technologies, is method, generally used for a deeper volume evaluation of material. Nevertheless, solutions for the evaluation of materials surface layers discontinuities are available, in the form of Rayleigh or Longitudinal critically refracted (L\textsubscript{CR}) waves, by which the second are known for their significant stress sensitivity. However, all aspects which could affect the measurement process and stress states evaluation results in any way, need to be taken into account. So, this article summarizes historical and recent development of L\textsubscript{CR} waves, especially for residual stress identification. It is necessary to understand the essence of ultrasonic waving itself,
its behavior, advantages and disadvantages using available literature sources of information. These will be the source of information, for the residual stress influence in engineering components, and for the consideration of L\textsubscript{CR} probing capability. By the general knowledge of ultrasonic testing, one could say, that this technology has clear prerequisites for mentioned purpose. This argument needs to be checked, based on theoretical and practical researches in this field, done by well and less known authors. It is necessary to check the state-of-the-art of using this technology in practice, and evaluate derived conclusions within researches, considering unexpected impacts and limiting factors, which authors met during their experiments. Based on obtained information, conclusion will be made, including positives, negatives and unanswered questions, on which future researches need to be focused.

2. **Longitudinal critically refracted (L\textsubscript{CR}) ultrasonic wave**

The sound in its nature, is regarded as mechanic particle oscillation in a certain environment, at a certain frequency. Ultrasound corresponds to the oscillation, that runs at frequency higher than 20 kHz.[1] A set of together oscillating particles creates the wave, which can be diversified in four basic kinds. Namely longitudinal, transversal, Rayleigh and Lamb waves.[2][3] In the longitudinal wave, particles oscillate in the sense of the primary wave-motion. Compressive and expansive forces are present. So, it is also labeled as compressional wave, which reaches the biggest velocity of all four kinds. During the wave interaction with material, several accompanying phenomena occur, that have the influence on its behavior. Especially, during the wave passing through the two states of material, three phenomena occur: wave reflection, transmission and refraction. The mode conversion relates with the wave refraction. In principle, wave propagation angle variates on the materials interface, during the wave refraction. It relates with the wave velocity difference in various kinds of materials, which is caused by their different acoustic impedance Z.[4][5] Wave incident angle change and its velocity dependence is expressed by the Snell’s law:

\[
\frac{\sin \theta_1}{V_{L1}} = \frac{\sin \theta_2}{V_{L2}}
\]

By the wave incident angle increasing, also the wave propagation angle in the material volume changes. Until the first critical angle level (approx. 28° for a steel), the part of the longitudinal wave is transformed to the transversal and a part to the longitudinal critically refracted wave (L\textsubscript{CR}), also labelled as the longitudinal subsurface wave[6], lateral[7], skimming, or creep wave. But, the L\textsubscript{CR} is most common used. The sense of its propagation is parallel with the material surface.[8][9] Beside the incident angle (\(\alpha\)), the directivity of wave is also influenced by the frequency (f), probe diameter (D) and a product of frequency and probe diameter (f * D).[10] A general equation for the penetrating depth representation is not provided, but it can be regarded as the function of frequency.[11] In principle, the wave is present in the surface layer of material[58] and its major positives are high stress sensitivity and vice versa low material-texture sensitivity.

*Figure 1* L\textsubscript{CR} wave creation using the three-probe measurement device[33]
3. Residual stresses and their measurement

Residual stresses are stresses, that are induced into the material during the manufacturing processes. Mechanical and thermal loads are their main sources.[12] Their main characteristic is that they stay in the material after the load influence is canceled. Residual stresses can be divided into compressive and tensile stresses. In principle, compressive residual stresses have positive impact and they are induced into the material intentionally.[13] On the other side, tensile residual stresses have negative impact, because they support a defects initiation, for example crack arising and its growth.[14] With few other elements, residual stresses define a set, which is called the surface integrity.[15] They are present in the whole volume of material, but their influence is important mainly in a surface layer. This phenomenon confirms the argument, that fatigue load, which causes more than 90% components failure, is initiated mostly in the surface layers of materials.[16] Beside other methods[17], the \( L_{CR} \) could be successful in the residual stress identification within these areas. A good review of non-destructive methods for residual stress identification is provided by Totten[56] or Hauk[18], including ultrasonic testing, on which E. Schneider participated. R.B. Thompson, R. Schramm, or H. Fukuoka are other significant authors in this field. S.Y. Sokolov, was the first, who used the ultrasound for flaws detection in metals (1929). For the stress evaluation, the key is the theoretical description of acoustoelastic effect by Hughes and Kelly (1953)[19], based on the Murnaghan’s theory.[20] The effect describes a correlation between the wave velocity and the elastic strain. Acoustoelastic effect application was performed by Egle and Bray (1976)[21]. The biggest variances were reached by the longitudinal wave, with polarization identical with stress direction. The next equation (2) describes the acoustoelastic effect, where \( \Delta V \) is the velocity variation between the stressed and the stress-free (V\( _0 \)) state, \( K \) is the stress coefficient, involving acoustoelastic constants and \( \Delta \sigma \) is the stress variation, respectively:

\[
\frac{\Delta V}{V_0} = K \cdot \Delta \sigma
\] (2)

3.1. Measurement principle using the \( L_{CR} \) wave

The measurement using the \( L_{CR} \) is based on the pitch-catch method.[22] It means, that measuring system includes one transmitting and minimal one receiving probe. For securing the right incident angle into the sample, probes are installed in the wedge made by PMMA (poly-methyl-methacrylate) or PS (polystyrene) materials. Two or more receiving probes[23] are often used during the \( L_{CR} \) wave application, so the environment temperature influence is eliminated (Figure 1). Piezoelectric transducers[24] are used. Their working principle is based on piezoelectric effect, described by Curie brothers in 1880. The coupling medium (grease, oil, water) is needed between the probe and evaluated surface, in contrast with ACUS[25], laser[26], or EMAT[27] designs. Decision between the using of contact probe with coupling medium or using the immersion probe in water, has not important influence on residual stress measurement.[36] Nevertheless the necessity of coupling medium presence, the piezoelectric probes application is common. The load source (e.g., hydraulic piston), which pushes the probe on the evaluated sample surface, is mounted on the top of a device assembly. Thanks to that, the operator impact and various differences in coupling medium thickness are eliminated. The principle of measurement corresponds to the time-of-flight (TOF) method, when the wave time-of-flight is measured between the fixed probes distance.[59] Next, stresses are derived as the function of time, based on the acoustoelastic effect. The next equation (3) describes it, where \( \Delta t \) is the time variation:

\[
\Delta \sigma = K \cdot \Delta t
\] (3)

The stress coefficient \( K \) calculation example was given by Xu[28], with known measuring distance, velocity and elastic constants. However, more appropriate is its obtaining by the experimental method. At the end, obtained measurement results are compared with calibration zero-stress samples, or with zero-stress area on the evaluated sample.
3.2. State-of-the-art

The steel, as the frequently used material in the engineering practice, was a subject of several researches, related to the L\textsubscript{CR} wave measurement method, in its early stage. A significant part of these researches was done by D.E. Bray. For example, he used it on the railroad steel, where the acoustoelastic effect was applied with Egle’s participation, or rolled steel plates, where welding residual stresses were probed. The results show, that the method is capable for distinguishing samples with stresses and without stresses.[29] A stress value can be expressed by a difference between these samples. Stresses induced into the steel by welding, were objective of several researches[30][57], that were also performed by Javadi and coworkers.[31][32] Often, results were compared with simulations and destructive technologies, by which the relevance of technology was checked. Obtained measurement outputs can be interpreted on a good level, using the combination of L\textsubscript{CR} and FE (finite element) methods, labeled as FEL\textsubscript{CR} method.[33] A material microstructure influence, need to be taken into account, during welds investigation.[31] Experiments made by Liu[60] or Qozam and collective[34] showed, that various microstructures differently affect the wave time-of-flight. Considering, that melted zone (MZ), heat-affected zone (HAZ) and parental material (PM) includes various microstructures, the time-of-flight varies through these zones. The time-of-flight is also affected by the grain size. As the research showed[35], it extends, as the austenitic grain grows. In the case of stress evaluation in dissimilar materials weldments, acoustoelastic constants are quite different on the both sides of weld main axis, mainly in heat affected zones.[36] During the majority of previously mentioned researches, the measurements were performed in such a way, when the probing device detected stresses parallel to the weld axis. By the measuring stresses separately in the MZ, HAZ and PM, the microstructure variations impact was suppressed.

![Figure 2 Typical welding residual stress character][34]

Also, the L\textsubscript{CR} application on a thin steel bar loaded by tensile strain, was checked by Bray[37]. The method was compared with the shear wave (SH) technology.[38] The good potential of method was also showed during the stress measurement in the steel bar loaded by bending. In addition, comparing the 2,25 MHz and 5 MHz frequency was found, that higher frequency wave is more stress sensitive, but on the other side it is able to penetrate in a lower depth, than the lower frequency wave.[39] Within the experiment made by Belahcene[30], 6,6 MHz frequency wave penetrated in the 1 mm depth of material and the greatest depth (2,5 mm) was reached at 2,25 MHz frequency. Within the
similar experiments[32][33], maximal reached depth was 5 mm at 1 MHz. In the aluminum sample maximal depth was 6.5 mm[51], and in the nickel-based alloy it was 7 mm[52], at the 1 MHz frequency. All previously mentioned depth detections were made using the method, when grooves are made in the sample and their influence on wave is examined. During a depth detection in the way like these, results could be affected by three factors: 1. stresses induced into grooves by the machining 2. groove dimension deviations, 3. influence by the coupling medium thickness variations, caused by measurement device relocating. These factors were taken into account in a theoretical model analyzing the L\textsubscript{CR} wave penetration depth.[40] Obtained results pointed on some differences in comparison with that experimental, but they were not notable. Moreover, the material, which was the wedge made of, piezoelectric probe diameter and excitation voltage influences were analyzed. The study confirmed known fact, that the penetration depth is mainly frequency dependent.

At the early state, the L\textsubscript{CR} method was checked also in specific parts, by the Bray. For example, in a turbine disk[42] and compressor rotor.[43] One of his newer L\textsubscript{CR} researches is load evaluation in steels for high-temperature uses [41]. For better stress evaluation in circumferential parts, the special apparatus was proposed. Solutions like this were used by Javadi within the welding stresses (axial and hoop) identification in pipes and pressure vessels.[36][44][52] Designs were adapted to the inner and outer wall, in the axial and radial direction.

Beside the steel samples, technology was used for stress identification in ductile iron[46] and aluminum welds[47], by Bray. Other researches related to the application in similar or different components and materials, by various authors, are summarized in Table 1.

During the stress identification using ultrasonics, is necessary to take the environment temperature into account. Generally, three predicted aspects can be influenced: 1. L\textsubscript{CR} wave propagation velocity, 2. Acoustic path dimension, 3. Evaluated component’s dimensions. Considering the fixed distance of probes, the third aspect is negligible. Based on Song’s research[45], as the temperature increases, the time-of-flight increases, too. Another study showed[55], that the temperature impact is important in polymers in the same way.

Table 1 Various L\textsubscript{CR} wave technique applications

| First author | Field of application |
|--------------|----------------------|
| J. Wank      | Steel turbine disk   [48] |
| A.A. Santos  | Rim of railroad forged disk [49] |
| Q. Pan       | Gear surface [50] |
| S. Sadeghi   | Friction stir welds on aluminium plates [51] |
| Y. Javadi    | Nickel-based alloy pressure vessel welds [52] |
| X. Liu       | Titanium welds after UIT [53] |
| B. Liu       | Laser cladding coating [54] |
| D. Jia       | Polymer samples [55] |

4. Conclusion
The article evaluates the state-of-the-art of the residual stress identification, using the ultrasonic method, on the basis of longitudinal critically refracted wave (L\textsubscript{CR}). The wave was theoretically examined in its nature, and based on the available sources, its relevance for the residual stress identification was checked. Based on available information sources by various authors, it can be stated that method has presumptions for the residual stress evaluation. The vast majority of researches, dedicated the attention to stress states in weld joints of steel thin-walled parts, like plates, or tubes. A factor, which relates with applications on such components, is penetration depth. The best possible way for its identification, is its detection before the measurement process. Nevertheless, this wave kind has significant potential, thanks to its high stress sensitivity. Based on many information sources, microstructure is the element, which considerably disturbs residual stress identification. The
neglect of its influence already in the calibration phase, along with the temperature effect, can lead to poor measurement results. If the influence of these factors is decreased, the good effectivity can be reached. It is confirmed by experiments, during which the results were compared with other non-destructive, destructive, or simulation methods. It must be mentioned, that evaluated stresses are average stresses through the penetration depth of wave, so the technology cannot identify stresses in a certain depth. Few researches were done in aluminum and titanium parts. However, they are not many and especially, the unconventional materials, like composites or polymers, deserve the attention. Improvements in the field of factors-influence and in the measurement devices, are also still required. Anyway, answer to the question, if the LCR wave method is suitable for residual stress identification, can be positive. Despite the influence of mentioned factors, beneficial are properties like: non-destructiveness, structural and price availability, or measurement speed, in the comparison with other methods. The necessity of practical tests of analyzed technology, will be the key element of the future research routing. Correlated principles and problems mentioned in the article, need to be taken into account for subsequent creation of measurement methodology for residual stress identification in surface layers of chosen engineering components.

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