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# ACOUSTIC EMISSION IN FRACTURE MECHANICS OF WOOD

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Acoustic emission ($AE$) in wood can appear as a result of mechanical stresses caused by mechanical, external loading or wood-internal sorptive stresses. Since the $AE$ phenomena depending on both those reasons are of different nature, therefore the $AE$ generated under mechanical and sorptive loading will be described separately in this paper.

## 1. Mechanical loading

Conceptions of the effect of loading type (i.e. tension, compression, bending) on $AE$ are rather vague. It is a common opinion that the highest number of impulses is generated during tension along the grain, while the smalest one appears in wood compression and bending (cf DeBaise et al., 1966; Sato et al., 1983; Noguchi, 1985; Niemz and Hänsel, 1988a,b). The differences in diagrams of $AE$ versus deformation curves were observed. $AE$ increase is rather smooth under tension while signals are generated shortly before failure in explosive manner when registered in wood compression test (cf Sato et al., 1983). The recent research, have not fully confirmed the above observations, showing, in fact, some differences in "$AE$-deformation" curves for wood being under tension and compression (Fig.1) but the differences in $AE$ cumulative counts within the failure deformation area were rather irrelevant (Sato et al., 1985). Regarding that observation, the objection against credibility of an *AE* cumulative counts measurement in the failure area or at the failure point, is raising. To ensure high accuracy of *AE* cumulative counts registration during wood failure is difficult and even impossible in a lot of tests.

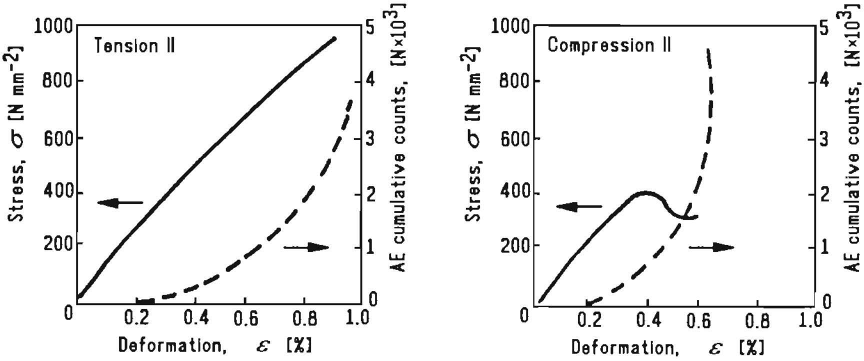

Fig. 1. Acoustic activity of spruce wood specimens (*Picea jezoensis*) in tension and compresion along-the-grain test (Sato et al., 1985)

There are usually three main stages of acoustic activity of wood which could be distinguished during material loading process. The first stage: low acoustic activity, in the beginning of loading. At the second stage acoustic activity grows gradually to attain exponential increase at the third stage until material breaks. As early as in the very first period random explosions of separated or concentrated *AE* impulses are observed. Those impulses are generated in the area of still elastic deformations as an effect of non-uniform stress field, resulting from a non-homogeneity of wood structure. At this stage modifications and reorientations in wood structure are observed, which are leading to wood inner adaptation for new conditions of loading.

The relationship between an annual increment structure of conifers and the *AE* in tension test were investigated by Ansell (cf Ansell, 1982a,b). In tests, separate for early and late wood of pine specimens, the rapid growth in *AE* impulse cumulative counts was observed at a very low elongation level i.e. approximately of 0.1%, while late wood was tested. For early wood specimens the *AE* was not registered at such a low elongation level. The author suggests that the different reactions could be a result of the state of stresses in both of annual ring zones, caused by former drying of a specimen. The late wood zone reveals a higher level of initial stress, therefore the microcracks are more likely to appear. In his later paper Ansell (1982b) using samples of Parana pine and Douglas fir wood, stated that: the higher is distinction between early and late wood in annual ring, the higher $AE$ cumulative counts should be expected during tension along-the-grain.

Sato et al. (1984) divided the $AE$ generated from wood samples in tensile along-the-grain test into two groups i.e. $AE$ slow signals $AE(S)$ and rapid signals $AE(R)$, respectively. The attempt was made to assign to both kinds of $AE$ impulses specified the failure mechanism. The authors suggest that $AE(S)$ signals originates probably from microdefects existing in wood long before mechanical loading. Those signals are in negative correlation with the stress level. Characteristics of rapid signals $AE(R)$ have shown their positive correlation with the stress level and have been mainly generated by shearing forces at the early-late wood boundary surface.

The $AE$ cumulative counts are rapidly decreasing while the angle between tensile force direction and wood fibers grows, what was revealed by Ansell (1982a). At fibre angle of 15 degree the $AE$ cumulative counts number equals only 10% of counts registered at fibre angle of 0 degree. For further fibre angle increase, lowering of $AE$ counts is insignificant. The decrease in $AE$ activity resulting from a slight growth in fibre angle is followed by a decrease in tensile strength of approximately 80%. This is probably the result of shearing mechanism domination in a failure process even at very slight fibres deflection from tensile forces path.

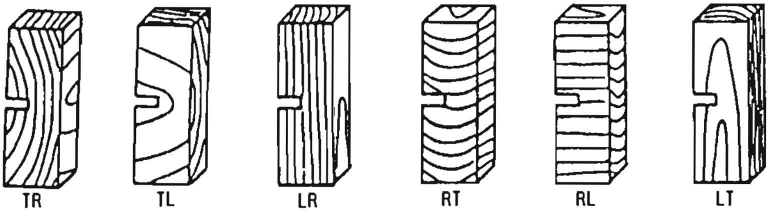

Fig. 2. Elementary direction of tension forces action (the first index) and cracks propagation (the second index) (cf Sato et al., 1986)

The first paper on $AE$ in wood, in relation to fracture mechanics categories was published by Sato et al., (1986). In that work the crack propagation during tensile tests on *Cryptomeria japonica* (hinoki) wood was investigated. The specimens were prepared as single-edge-notched in all orthotropic surfaces of a wood structure. The experiments were carried out for six basic systems i.e.: $TR$, $RT$, $TL$, $RL$, $LR$ and $LT$ (Fig.2). The first letter of index refers to tensile forces direction i.e. the direction perpendicular to crack propagation plane, the second letter to names the crack propagation direction. His research showed, that the relationship between the crack opening displacement $COD$

and the load value is of linear nature until reaching either a material failure point or a proportional limit for $LR$- and $LT$-specimens. The stress intensity factor and fracture toughness were calculated according to theoretic formulas of fracture mechanics. As evident from the model curve of stress intensity factor versus the $COD$, $AE$ starts at the moment when plastic deformation around the crack tip appears (Fig.3).

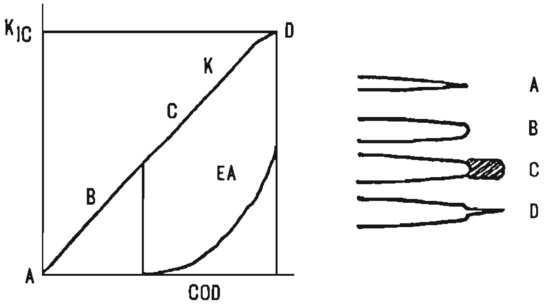

Fig. 3. Ilustration of fracture mechanism and $AE$ in wood (Sato et al., 1986); $K_{IC}$ – stres intensity factor (critical value for mode I), $COD$ – crack opening displacement, $A$ – non-loading, $B$ – elastic deformation, $C$ – local plastic deformation, $D$ – crack propagation

As it could be expected, for $LR$ and $LT$ systems, the fracture toughness values are 10 times higher than for other specimen orientations when cracks develop along the fibres. The authors of the paper being considered focused on a most discriminated cracking plane i.e. the $TR$ system, because of that case special importance to desorptive cracking of wood. There were observed as well a difference in cracks resistance and $AE$ generation in pith-side-notched samples (Fig.2 $TR$ system) and bark-side-notched ones i.e. in opposite direction. That distinction is likely to appear in reaction to a notch location in annual rings in which the specific density gradient is observed. As it emerges from a recent research, crack resistance of wood is closely connected to wood density (cf Gibson and Ashby, 1988). It is worth to recall the fundamental assumption about wood fracture micromechanics in an opening mode of fracture (mode I – cleavage) made by the authors mentioned above. According to the crack development path there are two basic types of crack propagation, i.e. cracking as a result of cell walls breaking and cell walls peeling, respectively, (Fig.4).

In wood of low specific gravity ($\rho < 0.3$ g/cm$^3$) and thin-walled early wood cells of other species, the cracks develop mainly by cell walls breaking (Fig.5a). For the $RT$ crack orientation breaking is almost the only manner of propa-

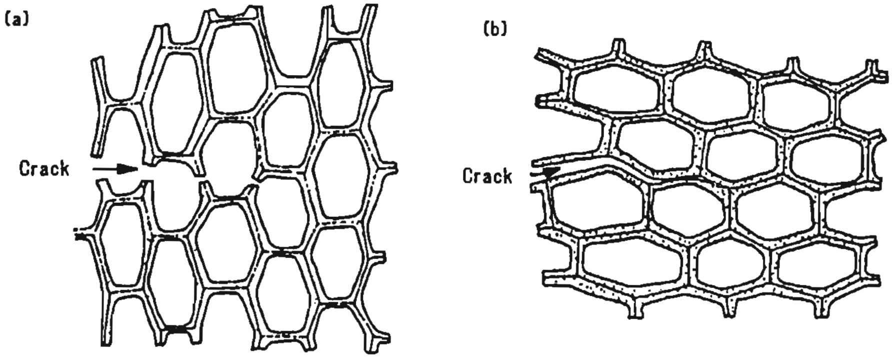

Fig. 4. Cracks propagation in coniferous wood (cf Gibson and Ashby, 1988); (a) – cell wall breaking, (b) – cell wall peeling

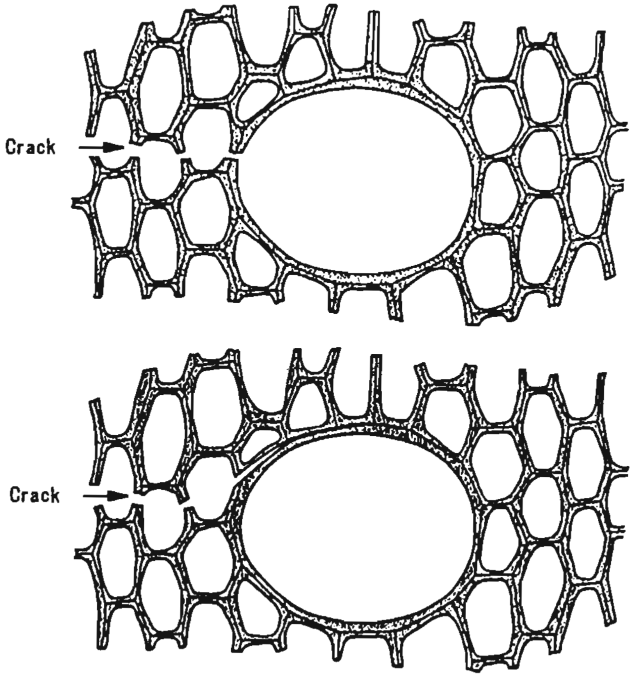

Fig. 5. Crack propagation in broadleaf wood (cf Gibson and Ashby, 1988)

gation. For wood species of higher specific gravity ($\rho > 0.3$ g/cm$^3$), cracking is a result of both cell walls breaking and joined cells peeling (delamination) (Fig.4b). If crack development is of the $TR$ orientation, the delamination process dominates over cell walls breaking. For the $TR$ orientation cracks reach wood rays and develop along them. In that case the main mechanism is the cell walls peeling even for higher specific gravity of wood. Vessels bundle or even a single vessel in hardwood species can arrest the crack development. When developing, the crack opens the vessel or turns aside around the vessel and then stops (Fig.5). Energy required for the cell walls breaking is almost 5 times higher than for the cell walls peeling (cf Gibson and Ashby, 1988). As it is evident from the above, crack resistance depends on wood structure, geometry and mostly on bonds between wood rays cells and fibres or tracheids. Those bonds are the weakest centres initiating low-energy failures of a peeling type.

Contribution of the $AE$ phenomenon in research into wood fracture mechanics is in its very beginning. Further investigations concerning various wood species of different density and research for verification of selective $AE$ analyse of high-energy cell walls breaking processes and low-energy cells delamination processes are necessary.

One of the $AE$ research into mechanical properties of wood area main purposes of is a material failure prediction. In failure prognosing the relation between stress at the $AE$ initiation moment and the maximum stress could be helpful (cf Ranachowski et al., 1989). Introductory research into this subject seems to confirm the linear relation between load at the moment of $AE$ initiation and stress at the failure point (cf Ohya et al., 1989; Raczkowski and Cegiela, 1992). Some investigations show that the $AE$ method could be used for wood hardness estimation.

Application of the $AE$ method to research into wood rheological properties has been carried out in specific, separated areas, so far. However, already in the earliest works concerning the $AE$, wood rheology aspects were considered. Debaise et al. (1966) observed acoustic activity in creep processes of wood samples which were bending under load of 80% of the maximum stress. The experiments revealed that acoustic activity increases together with failure development. An analogy in creep curves and acoustic activity plots was confirmed by further research (cf Morgner et al., 1980; Niemz et al., 1983). It seems that especially in research into wood properties variation under long-term loads, the $AE$ method shows its great usefulness for defects accumulation monitoring in creep processes (cf Raczkowski, 1969). In wood creep research it is essential to determine the relationship between stress level, even below the long-lasting strength and $AE$ parameters at each stage of a creep process.

In cycles of repeated tension along the grain, under stress rising from 0 to approximately 70% of the ultimate stress level, *AE* cumulative counts decrease with the increasing number of cycles (cf Sato et al., 1983). The decrease in *AE* activity after 2nd cycle reached 80%, and after 9th cycle 95% of acoustic activity compared to the 1st cycle. The authors suggest that the so called Kaiser effect might occur (cf Kaiser, 1953). However, some *AE* activity appears in following cycles, which implies some doubts as for the stress memory phenomenon appearance (cf Beall, 1989). The problem of Kaiser effect adequacy in wood – being a viscoelastic material – has not been solved yet, and still requires more advanced investigation e.g. into the effect of rest period duration between subsequent cycles on the Kaiser phenomenon.

In fatigue research conducted in terms of wood tensile along-the-grain tests with 20 Hz frequency, it was shown that the *AE* increases with the number of cycles and is equal approximately to 100 impulses in one cycle just before failure (cf Sato et al., 1983). Together with the number of loading cycles, as it was stated by Kovalčuk and Gurin (1991), on bended pine-wood samples, a gradual accumulation of defects increased. After cyclic interactions there start to create, not only small defects, but the medium-size or even greater defects as well. The failure of such samples appears unexpectedly, with small defects creation observed at the same time.

Discontinuities and structure disturbances existing already in wood before loading, have an effect on acoustic activity. Such a natural wood structural disturbance in macroscopic scale is knot. More intensive acoustic activity of wood containing knots showed Adams (1969). As a reason of increasing acoustic activity of knotted wood, desorptive cracks were revealed. Desorptive cracks appear in knots or around the knots area during timber drying process, and still before mechanical loading. Similar observations, concerning higher acoustic activity of wood samples containing knots were made by Sato et al. (1985) (Fig.6). The estimation of knots effect on wood strength was shown with the aid of *AE* method.

The investigations were carried out into natural defects of wood structure i.e. internal crushes resulting from living tissue reactions on heavy winds (typhoons). The *AE* recorded during bending tests of so defected samples was examined (cf Sato et al., 1985). Samples containing local crushes generate a higher number of *AE* impulses than clear wood. This enables one to detect the local crushes in wood structure with aid of *AE* method. It should be noticed here that the Young modulus values of sound wood samples and locally crushed samples, respectively, do not show any significant differences. That is why that defect cannot be detected using traditional methods of wood stiffness measuring.

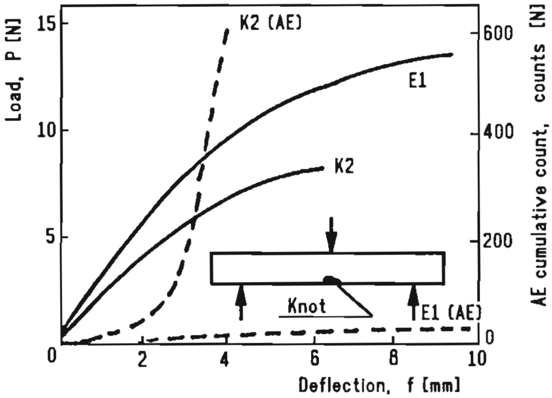

Fig. 6. Knots effect on bending test and $AE$ diagrams in spruce wood (*Picea jezoensis*); $E1$ – clear wood specimen, $K2$ – knotted wood specimen (cf Sato et al., 1985)

As early as in the firsts papers on the moisture content $MC$ effect on acoustic activity it was found that $AE$ cumulative counts rate (i.e. $AE$ density) recorded in cleavage test of oven-dry wood was three times as high as for wet samples (cf DeBaise et al., 1966). While testing the oven-dry samples in along-the-grain tension test the $AE$ was recorded at lower elongation level and showed a higher cumulative counts number than for air-dry samples (cf Ansell, 1982b). It was shown by Niemz and Hänsel (1988a,b) that together with wood moisture content lowering, $AE$ generation starts at lower stress levels. At the same, fixed stress level, $AE$ cumulative counts are the higher the lower moisture content in tested wood is. The essential role in that case seems to be played by raising plasticization due to increase of the moisture content in wood. It should be noticed, however, that the growth of $AE$ activity in wood of a low moisture content could be a secondary effect resulting from wood structure deterioration during drying process. Therefore further experiments (cf Okumura et al., 1987; Beall, 1989) are still necessary, especially to show the relationship between methods of slow reaching various initial moisture contents in vacuum atmosphere and $AE$ activity of wood. Preheating of wood results in generation of the $AE$ at lower stress levels. Pine wood samples formerly heated up to 120°C in various periods, generate the $AE$ already at stress level about $10 \div 20\%$ of failure load (cf Niemz and Hänsel, 1988a).

Important and interesting results were obtained in research into detection of very early stages of fungi decay of wood. Noguchi et al. (1986) experiments – $AE$ measurments in wood bending tests – proved the possibility of decay detection for the wood mass loss even below 1% which is unlikely to be detected by any conventional analytical method. This field of research was developed by Beall and Wilcox (1987) in compression tests perpendicular to grain in radial direction of fungi decayed wood samples (mass loss ranging from 1 to 28%). The ratio of $AE$ signals number and stress proved to be extremely sensitive indicator of the cell walls biotic destruction range (Fig.7).

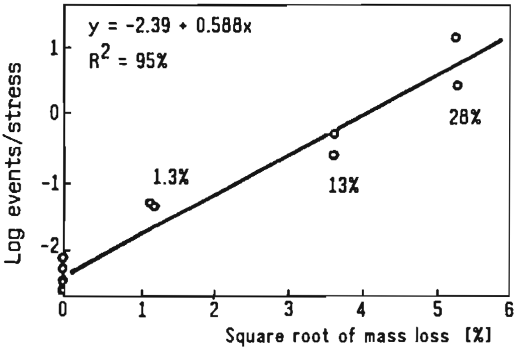

Fig. 7. Logarithm (of base 10) of events per unit stress to 0.75 percent elastic compression versus square root of mass loss (cf Beall and Wilcox, 1987)

The dispersion of tested samples deterioration grades was approximately tenfold in that case. Very good correlation between fungi decay and acoustic activity was recorded by Wagenführ and Niemz (1989) in bending test. The $AE$ was used by Niemz et al. (1990) for assessment of tissue destruction level in wood exposed to industrial pollution. Nevertheless there still exists an unsolved problem how to apply the $AE$ method to testing objects in their natural environment when bodies being examined are structural beams, pillars or other objects built into existing building structure (cf Noguchi et al., 1985a).

Processes appearing in wood based materials under external loading are of much more complex nature than those in solid wood. Since defects create and develop not only in the wood tissue or in cells themselves but in an adhesive joint and a "glue-wood" boundary area as well. For instance the acoustic activity in particleboards being loaded is observed as early as at $10 \div 20\%$ of the maximum stress while in solid wood the process appear at a stress level at least $50 \div 60\%$ of the maximum stress (cf Morgner et al., 1980; Beall, 1985; Niemz and Hänsel, 1988a). Very high correlation between a load value at selected $AE$ cumulative counts level and the particleboard lamination strength ($R^2 = 96\%$) was revealed by Beall (1986). To locate the failure process area (wood, adhesive joint) is not possible with *AE* analysis at the present stage of art. From experiments on adhesive joints strength in plywood it emerges however the possibility of distinguishing the destruction in wood or in an adhesive joint on the base of " *AE*-deformation" curve shape. The curves are of linear nature for a glue joint failure process and non-linear for destruction in wood itself (cf Beall, 1989). In investigation at structural parameters of particleboards (particles geometry, glue content, density) it was proved (cf Niemz and Hänsel, 1987, 1988a,b; Hänsel and Niemz, 1989) that the parameters increase implies the rise in acoustic activity. Particles length enlarging effects in the *AE* generation at a lower stress level. That could be the result of so called technological defects i.e. desorptive microcracks originating from primary particles drying. In research into *AE* activity of wood particle-cement boards it was observed that samples failure had not been preceded by defects cumulation, therefore the destruction process is more rapid than the one taking place in particleboards (cf Kovalčuk et al., 1988). Experiments carried out with plywood proved the possibility of using the *AE* method for indication of non-glued or improperly glued places (cf Yoshimura et al., 1987).

## 2. Sorptive loading

It is known that wood is hygroscopic material. Moisture content gradient and anisotropy of sorptive deformations accompanying the moisture content changes are the reason for induction of woods own sorptive stresses. The stresses originate on all levels of wood internal structure, and can reach very high values which evident demonstration is wood cracking during a drying process. The mechanism of hygroscopic cracks creation has not finally been recognized yet. Research into the *AE* generated by wood moisture content changes, started in 1980s and is still continued in the USA, Japan and other countries; it brings important information about a fracture mechanism. Signals being recorded come directly from defects and non-continuities existing in wood, initiating the cracking process.

The *AE* recorded during a wood drying process is of explosive nature, what indicates the presence of local stress cumulations and their releasing (cf Noguchi et al., 1980; Skaar et al., 1980). It was revealed as well, that hardwoods generate a much higher *AE* level than softwoods being dried under similar process conditions (cf Noguchi et al., 1985b; Niemz et al., 1990). Moreover, experiments show that *AE* intensity and a cumulative counts number

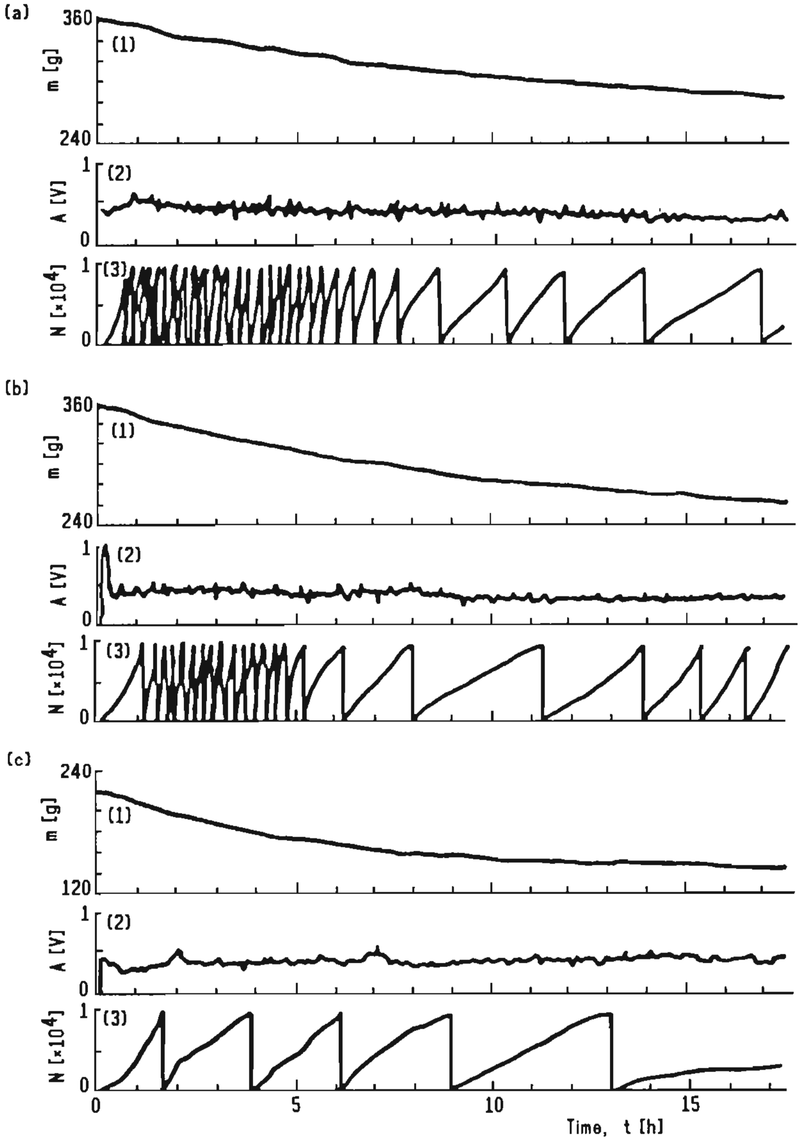

Fig. 8. Changes in specimen weight $m$, mean $AE$ amplitude per 100 events $A$, and of $AE$ cumulative event count $N$, respectively, during drying; (a) – mizunara (*Quercus crispula*), (b) – keyaki (*Zelkova serrata)*, (c) – sugi (*Cryptomeria japonica*) (cf Noguchi et al., 1985b)

is highly dependent on internal non-homogeneity of a wood structure. Wood of high non-homogeneity (e.g. oak) produces during a drying process more *AE* signals compared to wood of a more homogeneous structure (e.g. birch). Spectral analysis of signals generated during a wood drying process shows that *AE* impulses are formed in stress waves of various shapes, and their duration time ranges from approximately $50 \div 200$ ms. Component frequencies of those waves are included in range $50 \div 700$ kHz (cf Noguchi et al., 1985b; Sadanari and Kitayama, 1989; Nakao, 1990). Mean amplitude distribution, estimated per 100 *AE* events is almost constant over the whole drying process and does not show any correlation with dimensions and shape of the specimen being examined (Fig.8).

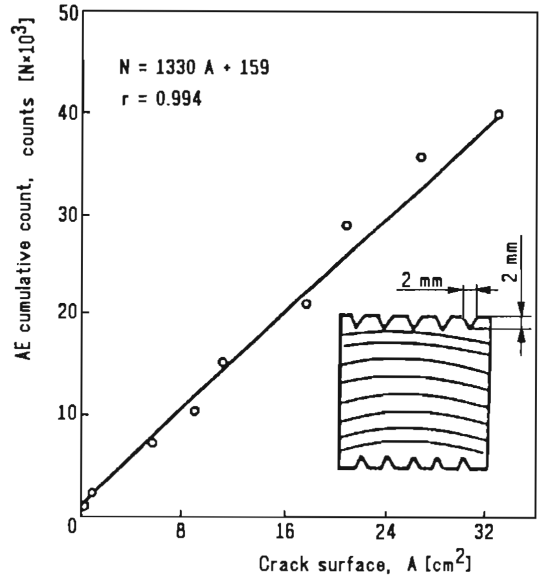

Fig. 9. Relationship between *AE* cumulative count and surface of cracks developed during drying process of beech wood samples of dimensions $30R \times 30T \times 10L$ mm (cf Raczkowski et al., 1990)

Only the first acoustic signals indicating the cracking process, so that being the result of structural defects development within the cell wall i.e.: flows creation, delamination of cells, are exhibiting a fairly high amplitude. Observation, of the almost constant value of average energy of *AE* signals emitted during the drying process, is of great importance as it enables one the conclusion that *AE* cumulative counts should be proportional to the surface of developing drying cracks. To create a crack of a certain surface requires of breaking a certain number of bonds which is proportional to that surface. Some investigations attempting to verify that assumption were made by Raczkowski et al. (1990). It was proved, in experimental recording of *AE* cumulative counts from the prismatic beech wood sample being dried (dimensions $30T \times 30R \times 10L$ mm) and measurements of crack surfaces created then, that the relationship between *AE* counts number and cracks surface was precisely linear (Fig.9).

The cracks surface measurement was taken with a Brinell magnifying glass with 0.1 mm accuracy. Crack paths were forced by notches made on tangential surfaces of the wood specimen before experiment course. The constant value of *AE* signals energy during wood drying process is also the result of a cracks propagation nature i.e.: mainly along one, particular symmetry plane of wood, that is a radial plane. In direction normal to a radial plane direction the highest values of tension stress are induced as the wood shrinkage is the most restrained in that direction (cf Noguchi, 1987). Moreover, in a radial plane the shearing stresses are induced as a result of differences in shrinkage of wood rays cells and axial structures of a surrounding tissue. Those additional shearing stresses contribute the wood fracture process taking place in radial plane.

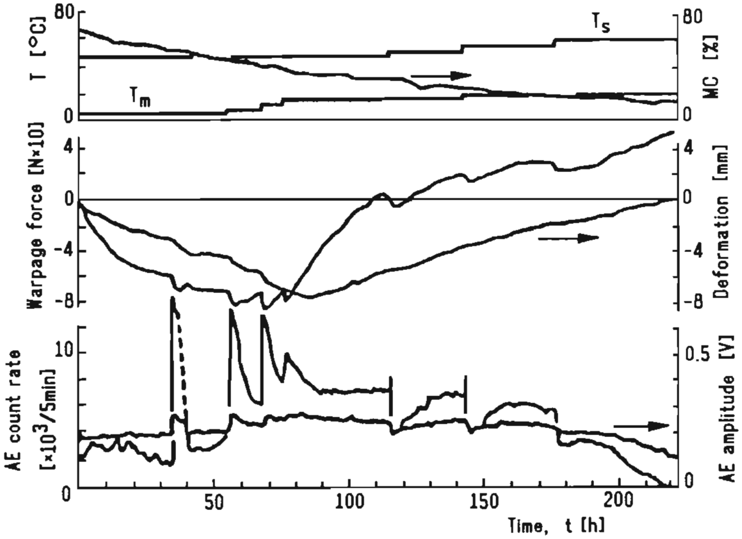

Fig. 10. Plots of wood moisture content, warpage force, deformation, *AE* cumulative count rate and *AE* amplidude, respectively, in oak wood drying process; $t_m$ – wet bulb temperature, $t_s$ – dry bulb temperature; (cf Okumura, 1986b)

*AE* sources at initial stages of a wood drying process, are located near under the timber surface. That takes place when wood outer layers are subjected to tension stress i.e. at the moment when the shrinkage process starts. In a course of time the *AE* sources are being moved into deeper, inner wood layers after the moisture content equal to the fibre saturation point *FSP*[1] is there reached (cf Okumura, 1986a and 1987; Wassipaul, 1986; Rice and Skaar, 1990). *AE* intensity depends on the wood own shrinkage stresses, which are concentrated around microcracks tips level. When the crack tip develops into an area which is stress resistant enough, crack propagation is stopped. Its further propagation is possible only when an acting stress is increased to a level which ensure extension over a new limit for that crack initiation. The above mechanism of crack propagation is well described by plots of *AE* counts rate and warp reaction force during a wood drying process at unstable parameters of drying medium (Fig.10).

Later works (cf Raczkowski et al., 1990) leading to determination of the relationship between difference of shrinkages within the wood block being dried and the *AE*, verified the assumption that the *AE* intensity level reflects the state of stress in wood being dried. The *AE* counts rate reached its maximum at the point of critical moisture content in wood i.e. at the moment when a shrinkage stress reached the highest level.

When the wood specimen being dried, is of a shape of thin board, where the drying process is defined by water evaporation from wide surfaces, then the *AE* intensity maximum is observed in the beginning of the process (cf Niemz et al., 1990 and 1991). While drying the thin specimen the outer layers reach the equilibrium moisture content *EMC* under conditions being, and start to shrink. The outer layers, however, are bonded with inner wood tissue layers of a still higher moisture content, what restrains shrinking process of outer layers. That process results in stress cumulation in areas of the largest non-homogenity of a tissue structure. Thus, the *AE* sources are being initiated, despite of relatively low values of shrinkage stresses measured under conditions of restrained deformations for the whole sample. Numerous structural defects, dispersed over the large inner area of wood, generate *AE* impulses of a high amplitude. This fact reflects in the values of *AE* signals being recorded. After some time of drying structural defects link together creating microcracks. During a drying process the moisture content decrease rate is lowering, which is specific for moisture movement towards outer layers of wood, and reflects in decrease in *AE* intensity (cf Melzow et al., 1986). Movement of the *AE* sources towards the areas which had already achieved the FSP and shielding the moving crack by plastic strains zone (cf Wassipaul,

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[1] *FSP* – a fibre saturation point, the wood moisture content corresponding with the maximum content of bonded water in wood fibres (approximately 30% of wood dry weight)

1986) caused that the great part of elastic strain energy was dissipated. To continue the crack propagation an increase in shrinkage stresses is necessary. So, the $AE$ intensity depends on kinetics of dry wood front movement deep into piece being dried.

An important aspect of research into wood drying cracking can be a hypothesis of so called moisture analogy of the Kaiser effect. In observations of the wood moisture change cycles, the highest number of $AE$ impulses was recorded in the first cycle of drying. In the second cycle of wood drying (after its moistening in humid air up to the FSP) the $AE$ is not observed or is recorded at a very low level (cf Okumura, 1987). However during next drying (after soaking in water) tested wood generates the $AE$ at a high level (Fig.11).

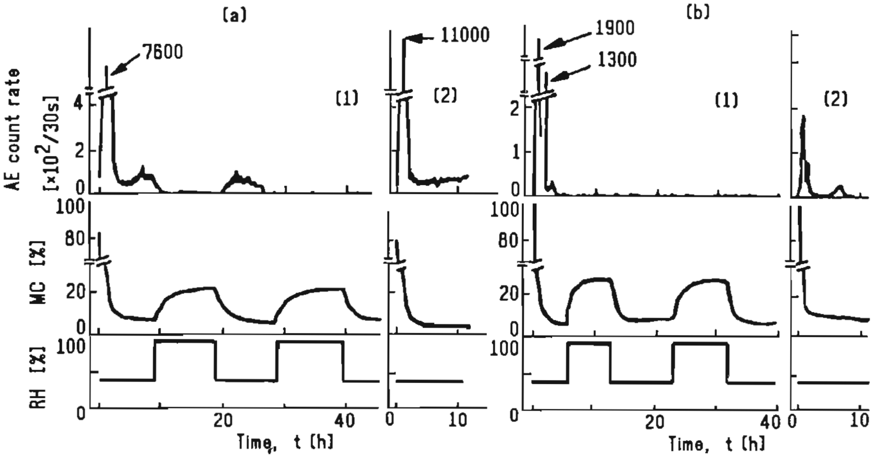

Fig. 11. $AE$ generated from wood in drying process after cycles of moistening in wet air (1) and re-moistening in water (2); (a) oak (*Quercus* sp.), (b) sugi (*Cryptomeria japonica*) (cf Okumura, 1987)

Data presented in Fig.11 show the possibility of the Kaiser effect appearing in further cycles of wood drying. Trying to give a complete answer whether the Kaiser effect appears in cycles of moisture changes, the experiment was conducted by the authors of this paper. Samples of beech green wood of dimensions $20T \times 20R \times 25L$ mm were dried in a laboratory drying chamber at a temperature of 80°C down to 1% of the $MC$. Then after cooling down to a room temperature, the samples were soaked in distilled water up to the initial moisture level (approximately 80%). After reaching the assumed $MC$, the samples were subjected to the following drying-moistening cycles. Ten complete cycles of moisture changes were carried out. During those processes the $AE$ was recorded, with the parameters: piezoelectric transducer of resonance frequency 100 kHz, total amplification of measuring track $80dB$, noise discrimination level $0.2V$. The results of experiment are presented in Fig.12.

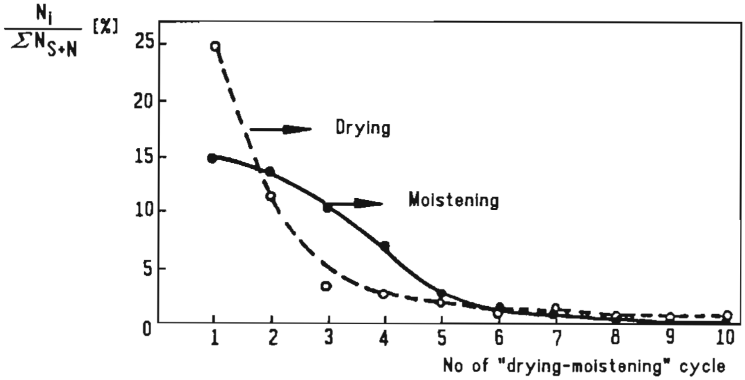

Fig. 12. Effect of number of wood $MC$ change cycles on $AE$ cumulative counts recorded during drying or moistening (by soaking) in water beech wood samples. $AE$ cumulative counts in a single cycle $N_i$ is presented as a ratio to $AE$ cumulative counts per 10 cycles $N_d + N_m$ of drying and moistening of wood

Data shown in this Figure reveal that in following cycles of wood drying and moistening $AE$ cumulative counts decrease. For a drying half-cycle the decrease in $AE$ counts is more rapid than for a moistening half-cycle. $AE$ signals recorded in the second and following moisture change cycles could testify to further propagation of moisture cracks and activation of newly created structural defects.

From the survey of research of into desorptive cracking of wood it emerges that the $AE$ accompanying that process could be used for wood cracking prediction. That implies the possibility of preventing the cracking during wood kiln-drying, in terms of the signals coming from wood itself (cf Noguchi, 1987).

Cracks audible with a "naked ear" which are emitted from rapidly soaked dry wood indicate that the $AE$ is generated during the wood moistening process, as well. Research into the $AE$ generated in the process of wood moistening is much less advanced than for the $AE$ from drying processes. The reason is probably a lawer practical value of adsorptive cracks comparing desorptive cracks created in the process of drying which is the fundamental process of wood treatment. The first paper regarding that problem was published only in 1985 and concerned the $AE$ generated in chipboards seasoning treatment under variable air humidity conditions (cf Beall, 1985a and 1986). It was found that the $AE$ was generated in the first moistening cycle and reached a much higher level than the *AE* released in following drying cycles. *AE* intensity during the moistening process is strongly correlated with kinetics of wood swelling. In following cycles of air humidity changes the *AE* appeared only at the initial stage of the drying operation. Further moistening processes did not induce any *AE* signals.

In papers on the *AE* generated during wood soaking in water it was found that the reason of the *AE* phenomenon is a crack formation process in a still non-penetrated by water, inner zone of wood. The crack existence in a dry zone was revealed with the aid of *X*-ray photography method (cf Moliński et al., 1991a). That fracture is a result of interaction between wet outer and dry inner zones of wood. The outer zone during its moistening has not got a possibility of free swelling as it is restrained by a dry inner zone which counteract free adsorptive swelling of a wood tissue in outer layers. The result of that process is induction of compression stresses acting across the grain in outer zone and tension stresses in inner zone. Those two kinds of stresses are balanced up until reaching the wood ultimate stress level for tension perpendicular to the grain in the inner zone. Before reaching this point *AE* impulses are not recorded in spite of whole specimen volume growing. To induce local deformations exceeding the ultimate values it is necessary that the defined volume of outer zone is penetrated by water. Those processes imply crack creation and propagation in a dry wood tissue.

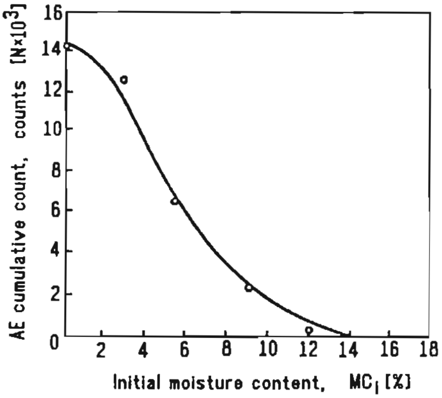

Fig. 13. Relationship between initial moisture content in pine wood samples and *AE* cumulative count recorded in soaking in water process; samples dimensions $30R \times 30T \times 10L$ mm (cf Moliński et al., 1991b)

Crack propagation is directed mainly in a radial plane of wood being soaked and a crack path is slightly broken at annual increment boundary. That is obvious if we consider very weak bonds between axial elements and wood rays cells. The wood fracture level, resulting from wood soaking, depends on the initial moisture content, the moistening stresses level, a dry wood resistance to tension across the grain direction, as well as on the previous moisture history of wood being tested. The highest *AE* counts level is recorded in oven-dried wood and while increasing its initial moisture content *AE* cumulative counts are gradually decreasing (Fig.13) (cf Moliński et al., 1991b).

For the initial *MC* over 13% the *AE* phenomenon is not registered at all. That fact could be an effect of moisture stress values which depend on a moisture gradient over the tested specimen thickness or length (cf Morgner et al., 1980). Therefore the higher is the wood initial *MC* the lower are moisture stresses. Lower is the wood stiffness what implies its higher susceptibility to deformations, therefore the more uniform distribution of stresses induced by moisture changes is more likely. The plots of adsorptive stresses versus *AE* cumulative counts both in normalized to their maxima scale, confirm the above observations (cf Moliński et al., 1991a). The most important fact is that levels of moisture deformations and stresses corresponding to the *AE* process initiation are different depending on the initial *MC* (Fig.14).

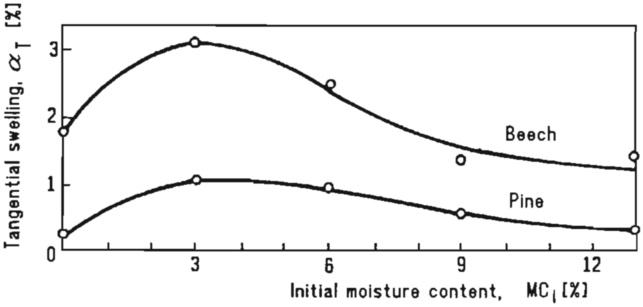

Fig. 14. Tangential swelling measured at the moment of *AE* initiation in wood soaking process (cf Suchorski and Moliński, 1990)

It emerges from Fig.14 that the very first *AE* signals are recorded at a lower moisture stress level for oven-dried wood and at a higher level for the *MC* corresponding with water bonded with hydrogen bridges. That could be explained by the effect of so called adsorptive strengthening of wood observed in tension, shearing and bending tests within the range between 0 to 8% of the *MC* in wood.

Regarding the quantitative description of the *AE* phenomenon with wood soaking, for model simplification it was assumed (cf Poliszko et al., 1991/92) that in a cross-section *RT* of swelling wood, a crossing system of defect paths exists. The crossing points determine a basic dimension of microcracks width. According to that model the total number of elementary microcracks in the cross-section of tested sample is expressed by the following formula

$$N = 2\frac{a_R a_T}{l_R l_T} \tag{2.1}$$

where: $a_R$, $a_T$ and $l_R$, $l_T$ are average sample and microcrack radial and tangential dimensions, respectively.

It take into consideration the decrease in acoustic waves amplitude, on the way between the source and piezoelectric transducer, what is the result of energy dissipation $AE$ signals number in soaked square-cross-sectioned specimens could be defined by formula

$$N = 2k\frac{a^2}{l_R l_T}\exp\Big(-\frac{\sigma a}{2}\Big) \tag{2.2}$$

where
$k$ – measuring track sensitivity coefficient
$\sigma$ – acoustic energy losses in tested medium.

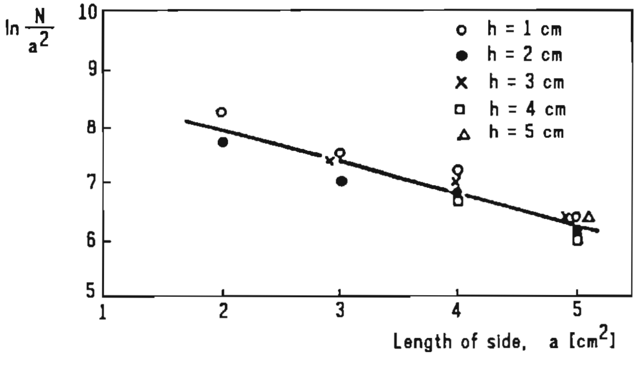

Fig. 15. Diagram of dependence of the $AE$ total event counts per unit area of $RT$-plane cross-section of beech wood samples on the length of sample edges (cf Poliszko et al., 1991/92)

Plot of the relationship between $\ln(N/a^2)$ versus the sample edge length $a$ observed in Fig.15, reveals good conformity of experimental and theoretical, data given above. Limiting the value of $\ln(N/a^2)$ as $a \to 0$, calculated with accuracy of a constant $2k$, defines the average dimension of microcracks: $l = \sqrt{l_R l_T}$ in the cross-section $RT$ of tested samples. The probability $p$ of crack creation on a surface $hl$, appearing in a sample of cross-section $ha$, determines the number of dissociated bonds ratio to a total bonds number i.e. $hl$ to $ha$ ratio. Due to the above $p = l/a$, and referring to the Bolzman formula

$$p = \frac{l}{a} = \exp\Big(-\frac{\Delta E}{RT}\Big) \tag{2.3}$$

where

$\Delta E$ – activation energy of one mole of bonds dissociation

$R$ – gas constant

$T$ – temperature in Kelvin scale.

Taking the above in to consideration, the number of $AE$ signals generated by soaking wood should be related to temperature as follows

$$N = 2k\exp\Big(\frac{2\Delta E}{RT}\Big)\exp\Big(-\frac{a}{2}\Big) \tag{2.4}$$

The results of temperature measurements shown in Fig.16, reveal due to theoretical expectations, linear course of $\ln N$ versus $1/T$ plot within the temperature range $0° \div 50°$C. The slope of linear function represents activation energy $\Delta E$ of bonds dissociation in a crack area. Its value is ranking above 12.5 kJ/mol which equals to hydrogen bonds energy.

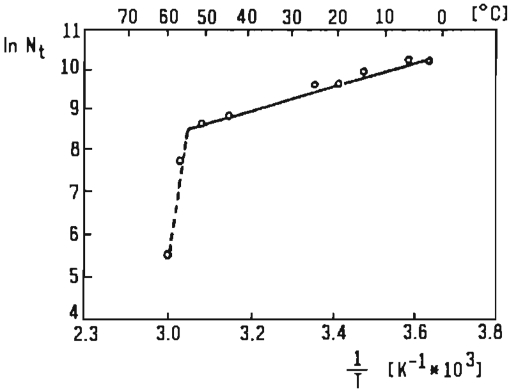

Fig. 16. Temperature dependence of the total number of $AE$ signals recorded while soaking beech wood in water (cf Poliszko et al., 1991/92)

## 3. Conclusion

In Poland, research into acoustic activity of wood was undertaken in the

Chair of Wood Science at Agricultural University in Poznań. The specialized measuring track for the $AE$ recording was completed there in co-operation with Professor J. Ranachowski from the Institute of Fundamental Technological Research Polish Academy of Sciences in Warsaw. The laboratory stand was designed to use the Polish apparatus type "DEMA" and then developed later to its modified version "EA-3" which was adapted to use the digital measuring track with an IBM compatible computer. Tests conducted with the aid of Polish devices on wood and wood based materials were successful and are being continued. The results of research are gradually introduced into international scientific circulation.

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## References

1. ADAMS R.G., 1969, *Fracture development in wood resulting from and detected using the acoustic emission phenomenon,* M.Sc. Thesis, Dept. of Forestry Univ. Br. Columbia, Vancouver
2. ANSELL M.P., 1982a, *Acoustic emission as technique monitoring fracture processes in wood,* Proc.of Symp. "Structural uses of wood in adverse environments" Vancouver B.C. (1978) Society of Wood Sci. and Technol, New York, Cincinnati, Toronto, London, Melbourne, 451-466
3. ANSELL, M.P., 1982b, *Acoustic emission from softwood in tension,* Wood Sci. and Technol., **16**, 1, 35-58
4. BEALL F., 1985a, *Effect of moisture conditioning on AE from particleboard,* Proc. 2nd Int.Conf of Acoustic Emission, Las Vegas
5. BEALL F.C., 1985b, *Relationship of acoustic emission to internal bond strength of wood-based composite panel materials,* J.Acoustic Emission, **4**, 1, 19-29
6. BEALL F.C., 1986, *Effect of resin content and density on acoustic emission from particle-board during internal bond testing,* Forest Prod.J., **36**, 7-8, 29-33
7. BEALL F.C., 1989, *Acoustic emission and acousto-ultrasonic characteristics,* In: Schniewind A.P. (ed.), *Concise encyclopedia of wood and wood-based materials,* Pergamon Press, Oxford et al., 1-4
8. BEALL F.C., WILCOX W.W., 1987, *Relationship of acoustic emission during radial compression to mass loss from decay,* Forest Prod.J., **37**, 4, 38-42
9. DEBAISE G.R., PORTER A.W., PENTONEY R.E., 1966, *Morphology and mechanics of wood fracture,* Material Research and Standards, **6**, 10, 493-499
10. GIBSON L.J., ASHBY M.F., 1988, *Cellular solids: Structure and Properties,* Pergamon Press, Oxford

11. HÄNSEL A., NIEMZ P., 1989, *Untersuchungen zur Schallemission von Holzwerkstoffen bei Biegebeanspruchung,* Holztechnologie, **30**, 2, 92-95

12. KAISER J., 1953, *Erkenntise und Folgerungen aus Messung von Geräuschen bei Zugbeanspruchung von metallischen Werkstoffen,* Archiv für das Eisenhüttenwesen, 24, 43-45

13. KOVALCHUK L.M., GURIN O.W., 1991, *Kontrol kachestva faniery akusticheskimi metodami,* Derevoobr.Prom., 1, 9-11

14. KOVALCHUK L.M., ZHUKOVA A.S., KOVALCHUK S.L., 1988, *O mekhanizme razrusheniya cemento-struzhechnykh plit,* Derevoobr.Prom., 5, 4-6

15. MELZOW D.T., PFEIFFER T., THEIS K., 1986, *Einige Ergebnisse der Schallemissionsanalyse während der Schnitholztrocknung,* Holztechnologie, **27**, 1, 19-26

16. MOLIŃSKI W., RACZKOWSKI J., POLISZKO S., RANACHOWSKI Z., 1991a, *Mechanism of acoustic emission in wood soaked in water,* Holzforschung, **45**, 1, 13-17

17. MOLIŃSKI W., RACZKOWSKI J., SUCHORSKI P., 1991b, *Effect of initial moisture content on acoustic emission in wood during its swelling under mechanical restraint,* Drev.Vyskum, 130, 1-9

18. MORGNER W., NIEMZ P., THEIS K., 1980, *Anwendung der Schallemissionsanalyse zur Untersuchung von Bruch- und Kriechvorgängen in Werkstoffen aus Holz,* Holztechnologie, **21**, 2, 77-82

19. NAKAO T., 1990, *Waveform analyses of acoustic emissions in wood by the wave propagation theory,* Mokuzai Gakk., **36**, 10, 819-827, (Jap.)

20. NIEMZ P., BEMANN A., WAGENFÜHR R., 1990, *Untersuchungen zu den Eigenschaften von immissionsgeschädigtem Fichtenholz,* Mechanische Eigenschaften und Schallemissionsanalyse, Holztechologie, **30**, 2, 70-71

21. NIEMZ P., BERNATOWICZ G., MATEJAK M., 1990, *Orientierende Untersuchungen zur Anwendung der Schallemissionsanalyse bei der Holztrocknung,* Proc. VIII International Symp. "Fundamental Research of Wood", Warszawa, 202-206

22. NIEMZ P., BERNATOWICZ G., MATEJAK M., 1991, *Wstępne badania nad analizą emisji dźwięku przy suszeniu drewna,* Przem.Drzewny, **42**, 5, 7-8

23. NIEMZ P., HÄNSEL A., 1987, *Untersuchungen zum Verformung und Bruchverhalten von Spanplatten,* Holztechnologie, **28**, 3, 139-141

24. NIEMZ P., HÄNSEL A., 1988a, *Untersuchungen zur Ermittlung wesentlicher Einflussfaktoren auf die Schallemission von Vollholz und Holzwerkstoffen,* Holztechnologie, **29**, 2, 79-81

25. NIEMZ P., HÄNSEL A., 1988b, *Zerstörungsfreie Prüfung der Festigkeitseigenschaften des Holzes,* Holz-Zbl., 117, 1667

26. NIEMZ P., WAGNER M., THEIS K., 1983, *Stand und Möglichkeiten der anwendung der Schallemissionsanalyse in der Holzforschung,* Holztechnologie, **24**, 2, 91-95

27. NOGUCHI M., 1985, *Acoustic emission from wood and wood-based materials,* J.Soc.Mater.Sci.Jap., 34, 383, 896-904

28. NOGUCHI M., KAGAWA Y., KATAGIRI J., 1980, *Detection of acoustic emissions during hardwood drying,* Mokuzai Gakk, **26**, 9, 637-638

29. NOGUCHI M., FUJII Y., IMAMURA Y., 1985a, *Use of acoustic emission in the detection of incipient stages of decay in western hemlock wood,* Acoust.Letters, **9**, 6, 79-81

30. NOGUCHI M., OKUMURA S., KAWAMOTO S., 1985b, *Characteristics of acoustic emissions during wood drying,* Mokuzai Gakk., **31**, 3, 171-175 (Jap.)

31. NOGUCHI M., NISHIMOTO K., IMAMURA Y., FUJII Y., OKUMURA S., MIYAUCHI T., 1986, *Detection of very early stages of decay in western hemlock wood using acoustic emissions,* Forest Prod.J., **36**, 4, 35-36

32. NOGUCHI M., KITAYAMA S., SATOYOSHI K., UMETSU J., 1987, *Feedback control for drying Zelkova serrata using in-process acoustic emission monitoring,* Forest Prod.J., **37**, 1, 28-34

33. OHYA S., KITAYAMA S., KAWAGUCHI M., 1989, *The effect of veneer quality on the bending strength of laminated wood,* Mokuzai Gakk., **35**, 10, 905-911 (Jap.)

34. OKUMURA S., KAWAMOTO S., MORI T., NOGUCHI M., 1986a, *Acoustic emission during drying of japanese oak (Quercus mongolica var. grosseserrata),* Bull. Kyoto Univ. For., 57, 300-307 (Jap.)

35. OKUMURA S., KAWAMOTO S., NAKAGAWA M., NOGUCHI M., 1986b, *Relationship between drying stresses and acoustic emission in wood,* Bull. Kyoto Univ. For., 58, 251-259 (Jap.)

36. OKUMURA S., KIYOTAKI T., NOGUCHI M., 1987, *A few experiments on acoustic emissions during wood drying,* Bull. Kyoto Univ. For., 59, 283-291 (Jap.)

37. OKUMURA S., KAWAMOTO S., TOYOTA M., NOGUCHI M., 1988, *Propagation properties of AE waves in wood,* Bull. Kyoto Univ. For., 60, 299-309 (Jap.)

38. POLISZKO S., MOLIŃSKI W., RACZKOWSKI J., 1991/92, *Acoustic emission of wood during swelling in water,* J.Acoustic Emission, **10**, 3/4, 107-111

39. RACZKOWSKI J., 1969, *Der Einfluss von Feuchtigkeitsänderungen auf das Kriechverhalten des Holzes,* Holz als Roh- und Werkst., **27**, 6, 232-237

40. RACZKOWSKI J., CEGIEŁA J., 1992, *Determination of wood tension strength perpendicular to the grain in radial compression test,* Proc. IUFRO All-Div. 5 Conference, Nancy August 23-28, 1992, **1**, 322-323

41. RACZKOWSKI J., POLISZKO S., MOLIŃSKI W., SUCHORSKI P., 1990, *Emisja akustyczna w procesach wysychania drewna: Wpływ temperatury suszenia na niektóre parametry emisji akustycznej w drewnie,* Maszynopis sprawozdania z badań koord. przez IPPT PAN (CPBP 02.03. 1.18), Poznań, 1-50

42. RANACHOWSKI J., REJMUND F., LIBRANT Z., 19, *Emisja akustyczna w zastosowaniu do wyznaczania propagacji pęknięć i oceny wytrzymałości mechanicznej materiałów kruchych,* in: J.Ranachowski (ed.), *Problemy i metody współczesnej akustyki,* PWN Warszawa-Poznań, 105-118

43. RICE R.W., SKAAR CH., 1990, *Acoustic emission patterns from the surfaces of red oak wafers under transverse bending stress,* Wood Sci. and Technol., **24**, 2, 123-129

44. SADANARI M., KITAYAMA S., 1989, *Waveform analysis of acoustic emissions generated in the wood-drying process,* Mokuzai Gakk., **35**, 7, 602-608 (Jap.)

45. SATO K., NOGUCHI M., FUSHITANI M., 1983, *The characteristics of acoustic emissions of wood generated during several types of loading,* Mokuzai Gakk., **29**, 6, 409-414 (Jap.)

46. SATO K., KAMEI N., FUSHITANI M., NOGUCHI M., 1984, *Discusion of tensile fracture of wood using acoustic emissions. A statistical analisis between the relationships of AE and fracture stress,* Mokuzai Gakk., **30**, 8, 653-659 (Jap.)

47. SATO K., OKANO T., ASANO I., FUSHITANI M., 1985, *Application of AE to mechanical testing of wood,* Proc. 2nd Int.Conf. on Acoustic Emission, Lake Tahoe, 240-243

48. SATO K., HONDA T., FUSHITANI M., 1986, *Fracture toughness and acoustic emission of wood,* Progress in Acoustic Emission III, The Japanese Soc. of NDI, 602-608

49. SKAAR CH., SIMPSON W.T., HONEYCUTT R.M., 1989, *Use of acoustic emission to identify high levels of stress during oak lumber drying,* Forest Prod.J., **30**, 2, 21-22

50. SUCHORSKI P., MOLIŃSKI W., 1990, *Detection of structural changes in wood during moistening using acoustic emission method,* Proc. of 8th Inter. Symp. "Fundamental Research of Wood", Warszawa 8-12 Oct. 1990, 214-218

51. WAGENFÜHR A., NIEMZ P., 1989, *Charakterisierung mikrobiologisch geschädigter Hölzer Teil 1: Untersuchungen zum Bruchverhalten mitels Schallemissionsanalyse,* Holztechnologie, **30**, 2, 84-85

52. WASSIPAUL F., VANEK M., MAYERHOFER A., 1986, *Klima und Schalemissionen bei der Holztrocknung,* Holzforsch. und Holzverwert., **38**, 4, 73-79

53. YOSHIMURA N., SHIMOTSU M., HONJOU K., KOTAKI M., OGASAWARA Y., OKUMURA D., NOTO F., 1987, *Detection of starved joints in plywood by acoustic emissions,* Mokuzai Gakk., **33**, 8, 650-653 (Jap.)

## Emisja akustyczna w mechanice pękania drewna

### Streszczenie

W pracy przedstawiono szereg zagadnień związanych z mechaniką pękania drewna. Osobno omówiono zjawiska towarzyszące destrukcji tego materiału pod obciążeniem mechanicznym oraz efekty wywołane zmianami wilgotności drewna. W artykule przedstawiono omówienie wyników badań wielu autorów jak i badania własne. We wszystkich przypadkach prezentowany materiał dotyczy wyników badań, w których podstawowym narzędziem do śledzenia zmian strukturalnych w drewnie była metoda pomiaru emisji akustycznej. Takie podejście do tematu wymagało szerszego omówienia źródeł sygnału emisji akustycznej w drewnie, a we wnioskach końcowych umożliwiło wyznaczenie energii pękania wiązań strukturalnych w oparciu o wyniki badań akustycznych.

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