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WOOD ADHESION: STATUS AND TRENDS FOR FUTURE DEVELOPMENT

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Abstract
This paper presents an overview on the role of wood adhesion as joining and bonding technology in the forest products industries. As key factors for the development of wood products and wood composites, wood adhesives, their application and processing technologies are expected to be of prime importance for the future of the whole sector. The development of adhesive technology was driven by continous adaptations and demand for higher adhesive qualities and competitiveness, but also increasing requirements from the costumer sectors in terms of reliability, process ability as well as environmental and safety issues. This trend is expected to continue, because the realisation of a maximum ressource efficiency in our industry is essentially linked to adhesion as joining processes. In order to improve the technologies, some emerging challenges especially for the wood adhesion industries are sketched, and current research questions and their relevance for the future advancement are delineated.

Key words: *wood adhesion; wood adhesives.*

INTRODUCTION

Worldwide the market and demand for adhesives is constantly increasing, regardless of current political and economic turbulences. Adhesive bonding will be an indispensable joining and connecting technique in the paper, construction, automotive, transport, medicine and wood working industries. On a global perspective sales of approx. 60 billion €/year are realized with adhesives, sealants and adhesive tapes. The German Adhesive Industries have produced in 2013 in total 877´000 to of adhesives, their activities result in a turnover of 1.55 billion €. A specifically vivid and positive dynamic can be identified for the business markets construction (+ 4.7%) and wood and furniture industries (+ 5.8%). In its forecasts on the upcoming years, the German Association of Adhesives e.V. identified wood construction industries as sector with superior growth potential. According to several market research studies these markets will grow annually by up to 8%, thus the demand on wood adhesives will rise accordingly.

Looking back to the history of wood based products, components, and engineered wood products in the past 100 years it becomes obvious that adhesives, their application and processing technologies have been key factors for the development of the whole industrial sector (Firhart 2013). While the first sticking components used for plywood and early glulam fabrication were based on natural proteins (casein, glutin) the industrial adhesive technology was initiated in the first quarter of the 20th century using synthetically formulated resins and adhesives based on fossil hydrocarbons. The following development of adhesive technology was driven by constant adaptations and demand for higher adhesive qualities and competitiveness, but also increasing requirements from the costumer sectors in terms of reliability, process ability as well as environmental and safety issues. This trend is not expected to change in the near future, so there is a need for further development and refinement of adhesives properties and qualities.

To summarize, many of the contemporary trends in wood products and wood industry are very closely linked to adhesive bonding technologies: lightweight materials and their application in systems, material combinations in composite technologies, the striving to higher resource efficient materials based on residues of cascaded materials.

On the other hand these rather optimistic visions of the adhesive producers and processing industries need to be reflected critically, in order to formulate strategies and action plans for adequate research and development activities, which are definitively needed to escort the outlined processes. In the following sections, some emerging challenges especially for the wood adhesion industries are sketched, and current research questions and their relevance for the future advancement are delineated.

CALLENGES FOR THE WOOD ADHESION INDUSTRIES

Future perspectives of the wood adhesive industries are closely linked to four directly related and interacting challenges.

AVAILABILITY OF RESOURCES AND RELATED ECONOMIC BOUNDARIES

The economics of adhesive technology are decisively defined by the secured availability and the costs of the adhesives and the processing and handling costs (production, application, maintenance, and disposal). Adhesives costs are directly determined by the delivery costs of the crude materials, energy costs for refining and processing. Today 95% of the input materials used for production are common wood adhesives (PVAc, UF, MUF; PRF, PUR; EPI, EP) are fossil petrochemicals, which implies that both the raw material basis and the directly energy depending processing and transportation expenditures are closely correlated to the costs for crude oil and natural gas as energy and material feedstock. These basic direct costs are additionally superimposed by effects of short term market influences (e.g. changes in production capacities for specific intermediates), which results in shortage of supply and rising costs.

This dominant dependence from non-renewable, fossils is one of the driving forces for the current trend towards higher shares of natural, biogenic and renewable resources for the production of wood adhesives. Despite some good progress with tannins and soy proteins, on a short to midterm it is hardly conceivable to expect that they will gain relevant proportions (>50%) in the formulation of load bearing adhesives, because the moisture stability especially of proteins is not sufficiently high to compete with the technical performance of classified synthetic adhesives. However, for the application in the paper industries and in the furniture and interior products industries it is most likely that bio-based adhesives will get accepted, thus the market share of adhesives formulated with glutin, casein, dextrin and other proteins will increase significantly (today 8% on the German market). The prices, however, will only be competitive on the midterm, because the process steps for the treatment of bio-based materials are technically complex.

In addition, industry has to focus the availability of biological input materials. Germany has used in 2008 in total 3,6 Mio to of renewables (excludes wood) for a diversity of products (Raschka, Carus 2012). Approximately one fifth of these renewable are converted in the paper industries to starch and polymers. Comparing these quantities to the current production volumes it becomes obvious that the use of renewable resources in adhesives will be a niche application, at least in the next decades.

At short notice also any increase in efficiency of synthetic adhesives has to be targeted. A higher cross-linking of the polymeric network by catalytic reactions might increase the performance level, allowing reduced spreading rates and gains in materials efficiency. However, such developments need to be driven carefully, when structural applications are concerned securing the necessary reliability and safety levels.

SYSTEM SECURITY

Adhesively bonded products have been successfully in wood construction because the technical reliability under both short-time and long-term impacts is sufficiently guaranteed. National and international standards have been established which define performance criteria for the individual system-components (adhesive, wood) and their products (Neumüller 2014). In line with current efforts to enhance the efficiency of timber building and its products several parties are demanding to reduce the performance requirements of fest standards and the approval processes, arguing that this could make the wood construction processes more competitive in regards to costs and environmental profile. Generally these claims need a very careful handling, they are justified only in those cases where regulations are not directly relates to safety issues. Nevertheless, a specific streamlining of the bureaucratic processes might be helpful to enhance process efficiency. In most cases, however, the challenging technical requirements formulated in the testing procedures are legitimated to guarantee system security, and sustainability, because wood adhesion is a complex process influenced by several parameter, which all can contribute with a certain variability to the system security.

As in other industries, there is a certain risk that product and process innovations in the field of wood adhesion are restrained by established approval procedures. Although the European Construction Products regulation allows that special solutions are regulated by European Technical Approvals, most of the criteria considered in the approval processes are based on established procedures. In order to better support that innovations find their way into the industrial application, system based assessments as recently done in the context of fire regulation for multistory wood housing need to be accepted. Efficient and meanwhile accepted techniques of building element monitoring can be used to continuously supervise critical details of constructions, which combined with the expertise of specialists might result in reduced technical precaution work, without jeopardizing the construction system security.

Actual research is ongoing to enhance the electric conductivity of adhesive layers by incorporating fillers or fibers (black carbon, carbon fibers at nanoscale) to allow electrical conductivity and using the bondline as sensor. By connecting electrical voltages one can use the bondline for structural health monitoring, signalizing physical strains or deformations in the constructions which would allow timely measures when critical limits are passed. Similarly moisture and temperature monitoring can be incorporated in the adhesive layers at local and presumably critical points of the constructions, using cheap wireless data transfer, data logging, and automated controlling routines. These passive monitoring systems can be used to responsibly reduce some of the established safety measures in structural bonding, efficiently combined with expert inspection plans which are indispensable especially for new materials and engineering solutions and demonstrators.

In addition, operational and accepted design guidelines for wood-to-wood and wood-to-non wood assemblies are urgently needed. Vallee et al. (2014) claim to apply the available principles to realize reliable, safe, economical and esthetical joints and connections.

VARIABLE SYSTEM PARAMETER

Principally the overall performance of most wood-adhesive systems are directly influenced by the quality of the adhesive and adherents, the detailed process quality applied in the adhesion procedure, and the impacts on the bonded assemblies during use. Indeed there are numerous system components affecting the overall performance – some experts are listing more than 30 influences. Albeit recent scientific progress in the physical and chemical interaction of the main components, especially on the microscale level, the wood-adhesion system still cannot be modelled sufficiently well as is the case with competitive joining technologies. It is postulated that most historic and recent developments in wood adhesion technology have been based on try-and-error concepts, because a comprehensive understanding of the various influencing factors is missing. It is anticipated that the variability of influencing factors is going to increase in future, because more complex (hard)wood species will enter the market, more recovered and thus aged wood will be used in cascading routines, and adhesives will be formulated with different and renewable feedstocks. Frequent adaptations of adhesive formulations are originated by changing environmental and health related regulations, which often directly impact and change the products properties. Effects of these variable influencing factors on the performance of the bondline have to be determined empirically in laborious standard tests. Certainly much more research and advance is needed to combine relevant system parameters in mechanistic models aiming to forecast the performance of adhesively bonded connections as a function of inputs and expected impacts and exposures, including creep and fatigue.

LEGISLATION AND POLITICAL DIRECTIVES

Emission thresholds

In the European Union the essential requirements of construction products in terms of health and safety are regulated by the Construction Products Directive. One essential element of the system is the CE marking of products, which is a declaration by the manufacturer that a given product meets certain public safety requirements. Among the six essential requirements to be addressed by a product prior to being put on the market are hygiene, health and the environment. In the context of adhesively bonded products especially gaseous emissions of aldehydes or volatile organic compounds (VOCs) during processing and use of the products are regulated internationally on increasingly intensified level. Early 2012 the Official Journal of the European Community announced the classification of formaldehyde as carcinogenic for humans, with regard to reports of GHS (Globally Harmonized System of Classification and Labelling of Chemicals) and IACR (International Agency for Research on Cancer). This raises concerns that the European Chemicals Agency (ECHA) prepares to further tighten the emission thresholds for HCHO below the current E1 level. Such a measure would especially affect the wood panels industries which still uses predominantly urea-formaldehyde resins for the production of commodity products applied in the furniture and interior product markets. Producers of engineered wood products have already changed the adhesive technology of aminoplastic or phenoplastic resins towards higher cross-linked, however more expensive adhesive systems, showing reduced formaldehyde emission potentials. However, a total ban of formaldehyde as crosslinking agent in adhesives would certainly existentially menace to majority of the wood products industry. Resins like PUR and EPI are based on polyaddition reactions to build up crosslinked polyuria networks. They are free of any formaldehyde, and are using aromatic diisocyanates as their reactive component. As all isocyanates, MDI is an allergen and sensitizer, and its handling requires strict safety controls and personal protective equipment, but its human a relatively low human toxicity is low compared to other organic cyanates. Completely cured bondlines or adhesive films of polyaddition resins usually show MDI emissions below the limits of detection.

Environmental impacts

An important task for both adhesive producers and processors are the requirements to disclose the environmental effects of the adhesives and the adhesively bonded products (Lopes Silva et al. 2015). To be able to meet requirements of the European Construction Products Directive which also demands a sustainable use of bio based products, the building products industry has initialized together with certification bodies a regulative framework for a standardized environmental assessment of building activities (EN 15978 Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method) defining Environmental product declarations (EPDs) as the backbone for the implementation. Based on LCA data they assemble all relevant environmental issues of a building product and serve as information source for building product certification and assessment of sustainability of constructions. Both individual producers and industries are asked to deliver reliable and transparent data for their specific products. These processes are standardized by Product Category Rules (PCR) which serve as guidelines for operationalization, transparency and comparability of the product EPDs.

For several relevant adhesive types the German Association of Adhesives has supported EPD compilations, thus master EPDs for epoxies and some polyurethane products already are published (epd.klebstoffe.com) – however progress for polycondensation resins is low. It is anticipated that transparency and reliable communication of environmental issues will gain even more importance in the future (Milner 2009). Up to now voluntary certification systems might became mandatory in the next decades, and the comprehensive and independently controlled procedures are expected to support bonded wood products, especially when used in long-lived constructions, in substantiating they favorable life-cycle impacts.

CURRENT AND FUTURE RESEARCH

Referring to the challenges briefly addressed above, the current wood adhesive research is focusing several key areas to further improve the reliability and competitiveness of bonded wood products.

STRUCTURE-PROPERTY RELATIONSHIPS

Most of the fundamental research initiatives aiming at systematically understanding and elucidating the relationships between die complex system parameters acting at the wood adhesive bondline are focusing on the micro- and nanometer level (e.g. Custodio and Broughton 2009. Central question still is to have a persuading scientific concept of the adhesion mechanisms between wood and polymer molecules, and how these mechanisms can be influenced in the bonding procedure. Wood cell wall diffusion by low molecular weight components of phenolic adhesives will modify the physical and chemical cell wall properties and is a key to promote and engineer technically the bonding performance especially for extreme impacts (Kamke and Lee 2007). It is still unclear how different wood species and cell-wall tissues react with different adhesive types and formulations, and how primer technology can be used to match the wood surfaces chemistry for specific adhesive types and formulations. The complex field of fatigue and creep in the interphase zone is yet not fully understood, but parametric information about time-dependent properties is needed in addition to the nano- and micro level data to feed the mechanistic models for the bondline behavior under defined stresses and impacts. Information of the model calculation has to be verified, up scaled in applied research and finally shall support development of more efficient adhesives, their applications and the management of the bonded products along the service life.

ADHESIVE MODIFICATIONS, "GREEN" ADHESIVES

Focal goal of any adhesive modifications are substantially better product performances, better product economy, or improved environmental profile. Recent and current developments focusing on the reduction of formaldehyde emissions are summarized by Marutzky (2014). Examples for physical modifications are illustrated by Vioel et al. (2014) and Gindl-Altmutter et al. (2014). The incorporation of nano- or microscaled particles aiming at functionalizing the adhesives, adapting their rheology during the penetration phase, and controlling the curing and setting of the polymer is main objective of many research projects.

In addition to such physical modifications, the admixture of bio based components to the reaction of synthetic compounds is actually the most dynamic field of adhesive modification research (e.g. Pizzi 2006, Umemura 2014). Biobased proteins (e.g. elastin, keratin), polysaccharide (e.g. cellulose, starch, chitin), polyphenols (e.g. Lignin, and lipids (Terpene, Terpene acids) are admixed to existing formulations in order to substitute fossil compounds or to reduce formaldehyde emissions. A main challenge of natural byproducts, however, is to overcome their reduced activity and crosslinking tendency. The use of catalysts, specific hardeners and higher reaction temperatures are current strategies to create the targeted higher moisture resistance of the cured films (Ding and Matharu 2014). While more and more bio based resins are being used for furniture and indoor-used products, it is doubtful if those resins can be used at higher extends in cold setting construction products – because the required moisture stability, as well as a constant and secure market availability has to be guaranteed.

Furthermore, modifications of individual resin compounds are being targeted, aiming at using new functionalities for the setting and crosslinking, as well as for a debonding of the components at the end-of-life operations. Conductive particles or encapsulated materials are being used, which are triggered by externally applied signals or stimuli (magnetic forces, vibration) and act in the desired way. Main challenge is to guarantee the overall safety of the bondline over the lifetime, and to avoid any misuse. By spreading encapsulated reactive chemicals in the resin, which are released on demand or at specific temperature conditions, the deformation ability of the bondline might be influenced, changing from brittle to more ductile or vice versa.

BIOMIMETIC EFFECTS

Nature offers numerous examples of very efficient and adaptive bonding and adhesion principles even between different materials, in wet and even saltwater atmosphere, and at hot or very cold temperatures. Some of them are even reversible, as the Gecko foot and the barnacle attachment mechanisms. It is obvious that many research is done to use those effect in our technological adhesion processes. It has been elucidated that the Gecko-effect is not based on chemical, but on physical adhesion principles, originated by complex, highly hierarchically topographically structured design. Could this be transferred to wood bonding mechanisms, by uncovering the nanoscaled cellulose fibrils on the wood surfaces, using those structures as reversible Velcro® fasteners? A further identified concept of natural bonding mechanisms is that nature often uses many bonding mechanisms similarly (mechanical interlocking, capillary forces, van de Waals forces, covalent bonds). Wood bonding also follows this concept, thus there are similarities which need further understanding to use the biomimetic principles to its full potential. In a recent COST action TD0906 potentials and trends in biomimetic adhesion have been discussed. De Campo et al. (2012) evaluate the synergies for manmade bonding and conclude a transfer of the interesting and more and more identified mechanisms found in nature still is far away from being used industrially, including self-healing processes. Nevertheless, the potential for adaptation, not simple copying, is high, especially for bonding mechanisms found in technology and in medical/surgery.

ALTERNATIVE APPLICATION PROCESSES

Application, spreading and surface wetting are indispensable components of the system wood-adhesive. It is feasible that in future wet application in structural wood bonding, today the dominant technology, could partly be substituted by the application of pre-synthesized adhesive films. Such a process might bring advantages in safety, on-site application, economy and ecology. As further technology, vaporized application and airborne application could be developed for specific applications.

A future technology already applied in concrete and plastic industries is adaptive manufacturing, or 3-D printing. There is a trend that in future more and more freeformed products based on wood fiber or powder will be mixed with binders (organic or inorganic) and printed simultaneously or alternating in 3 D-printers. There is a need for research allow sufficiently intimate as well as long term adhesion.

ADDITIONAL FUNCTIONALITIES

Most of the following concepts are highly visionary. They are based on the logic that as more functions are provided by one product or concept, the more attractive and smart is the product. Resins and the related cured adhesives certainly can serve more than just as a binder. In future adhesion properties will be combined with other functions, as

- Design (Color, optical effects)

- Conducting (Light, signals, voltage)
- Storage (Digital data)
- Damping (Vibrations, Acoustics)
- Acclimatizing (Cooling, heating, PCM)
- Separation (Barrier effects, shielding)

OPPORTUNITIES FOR ADHESIVE DEVELOPMENT

The necessity and importance of adhesive development will continue in the upcoming years. Recent research, mostly under applied focus, into adhesive chemistry and technology has enhanced the understanding of principle mechanisms and has secured that adhesively bonded wood products perform well and on a high level of reliability. However, there are many open challenges to be addressed properly to cope with the future challenges (e.g., Zhao et al. 2011, Miyamoto 2015). Wood adhesion research shall put more focus on fundamental questions, using and combining principles of all disciplines in natural sciences and applying high level microscopic, analytic and spectroscopic technologies to better understand and elucidate to interaction of the influencing parameter. Adhesive research has to be realized as part of material science.

Joining and bonding mechanisms of alternative technologies, industries, medical applications biological principles of adhesion have to be further studied to identify principles that can be transferred to wood adhesion.

It can be expected that progress in big data handling and management will also impact the advance in wood bonding. If the prospects in data logging, storage, and analysis of signals are used accordingly in R&D including monitoring, direct and positive effects for safety and health control can be anticipated. In addition the systematic assessment of information is a foundation for knowledge and expert systems, which are urgently needed to better cope with the complexity of adhesive bonding technologies. Combined with knowledge of human experts, which will remain to be an indispensable factor for the overall security, systematic combination and modelling of the influencing parameters will allow to enhance the efficacy and efficiency of wood adhesion processes.

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