Journal of Machine Engineering, 2019, Vol. 19, No. 4, 5–26
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received: *20 November 2019* / Accepted: *04 December 2019* / Published online: *20 December 2019*

wood machining, process optimisation, monitoring and control

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EN ROUTE TO INTELLIGENT WOOD MACHINING – CURRENT SITUATION AND FUTURE PERSPECTIVES

Wood materials are an important part of our daily life. Besides furniture, doors and window elements, parquet floors, veneering, ply wood, chip- and fibreboards, also structural elements for buildings are typical products. Due to the specific properties, variety and complexity of natural wood, wood materials and wood composites, the machining of parts made out of these materials exhibits specific challenges. In order to further improve productivity, quality and efficiency in wood machining, innovative solutions with respect to tool technology, process planning, machinery, process monitoring and intelligent control are necessary. This keynote paper reviews and summarizes scientific developments in wood machining in recent years. Furthermore, exemplary current an ongoing research activities are introduced. Finally, the paper presents and discusses future potentials regarding new approaches for intelligent process control in wood machining.

1. INTRODUCTION

Machining of wood and wood materials differs significantly from the machining of metals. In this regard, natural wood (e.g. beech, spruce, oak, fir tree, etc.) and wood materials, which consist of wooden particles or components combined with other materials (especially composites, plastics and metals), have to be considered separately. Natural wood is characterised by its biological or organic structure (Fig. 1) and the resulting inhomogeneity (caused by the layers of growth, channels of natural resin, mineral inclusions, water and moisture) as well as anisotropy due to the cylindrical growth and fibre orientation. Commonly used wood materials can be classified as Oriented Strand Board (OSB) and Fibre Boards (Fig. 1b), Multiplex (Fig. 1c), High Pressure Laminate (HPL) (Fig. 1d), uncoated or coated Medium Density Fibre Board (MDF) or High Density Fibre Board (HDF) (Fig. 1e), and compound materials (e.g. Corian©) (Fig. 1f).

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https://doi.org/10.5604/01.3001.0013.6227

In addition, wood materials are often combined with plastic or metal plates and inlays. Each of these materials requires a specific layout and optimisation of the machining technology, including the cutting tools, process setup and parameterisation.

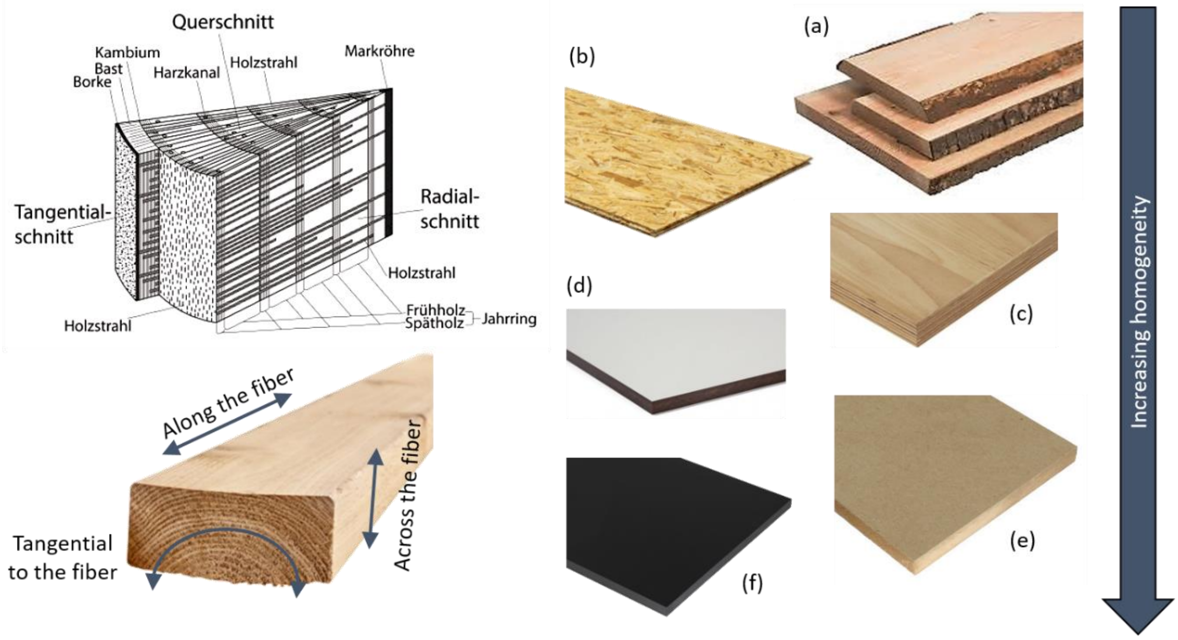

Fig. 1. Fundamental properties of wood with respect to machining characteristics [1]

Whereas, depending on the individual material, wood materials are mostly regarded as quasi-homogeneous and isotropic, in machining of natural wood the cutting direction relative to the orientation of the wood fibres and the cellular structure of the material must be taken into account (Fig. 2, Fig. 3). Table 1 summarises typical cutting speeds in wood machining.

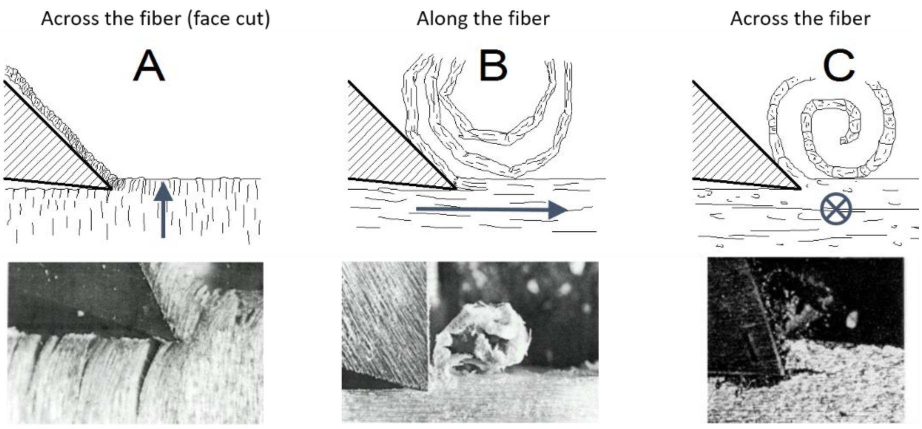

Fig. 2. Characteristics of wood cutting depending on the fibre orientation [2, 3]

The primary wood machining industry (saw mill technology) can be distinguished from the secondary wood machining industry (furniture industries, building elements industries, carpenter handcraft applications). Besides stationary machine tools, in handcraft applications, hand-operated power tools establish an important industrial sector with respect to wood machining. In addition to the core machining technology (machinery and tools), specific peripheral systems are essential in wood processing. Due to the high cutting speeds (table 1) and feed velocities, sophisticated machine enclosures and safety features are necessary [5]. Furthermore, chip and dust evacuation systems are required.

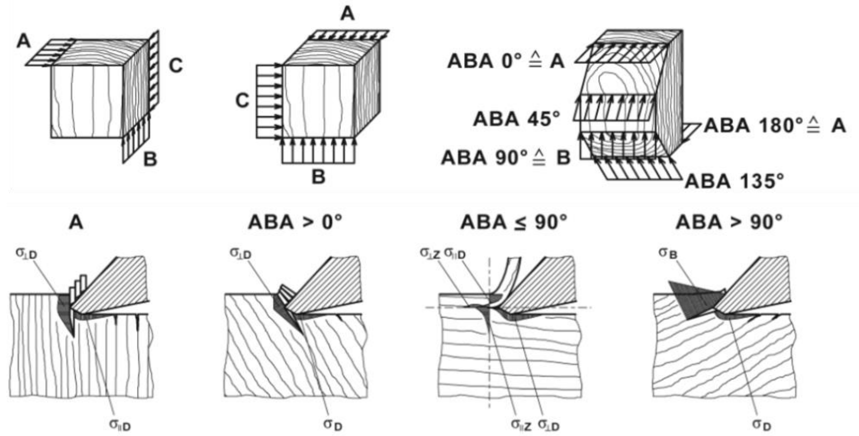

Fig. 3. Chip building mechanisms in wood machining [1, 3]

Table 1. Cutting speed v_c in sawing of wood and wood materials [4]

	Soft wood	Hard wood	Veneer	Treated wood	Ply wood	Veneer plates	HPL	MDF (raw)	Coated plates	Medium fibre board	Porous fibre board	Thermoplast plates	Thermoset plates	Hard paper, laminated fabric
v_c [m/s]	60 – 100	60 – 90	70 – 100	40 – 65	50 – 90	55 – 85	50 – 80	60 – 90	60 – 80	50 – 80	60 – 100	30 – 70	15 – 50	40 – 60

It can be recognized that an intelligent optimization of wood machining is a challenging task that involves various aspects and requires multi-disciplinary approaches. In this paper, exemplary technologies contributing to intelligent wood machining are discussed.

2. INDUSTRY 4.0 IN WOOD MACHINING

The wood machining industry is characterised by an extreme variety of products and companies of different size and structure, from individual single piece production in crafts enterprises up to highly industrialised mass production (e.g. in furniture production) but also mass customization. However, most of the companies belong to the Small and Medium

Sized Enterprises (SME). An ongoing development of innovative solutions in the segments of cutting tools, machines, automation, as well as information technology systems can be recognised. Nowadays, continuous solutions to provide a seamless information chain from product design via process setup to the implementation of the machining tasks is available (Fig. 4). Furthermore, highly automated production lines and flexible autonomous cells incorporating several production steps can be realised (Fig. 5). In-process data acquisition and integrated data processing up to wood machining specific ERP- (Enterprise Resource Planing), MES- (Manufacturing Execution System) as well as process planning and control systems are state-of-the-art. This also applies to image processing and scanning technology for quality control and optimization of processes like blanking. Also cloud connectivity (e.g. with tapio©, www.tapio.one) is already available.

Regarding a complete information chain, digitalisation and self-optimisation of wood machining process chains, an integrated and continuous observation of the material characteristics is essential. This starts with an acquisition of the wood properties in sawmills. By means of industrial computer tomography X-ray scanning, cross sections of trunks can be analysed with respect to inhomogeneity inside the wood, knotholes, cortex, natural resin inclusion, decay and rotting as well as the core channel (Fig. 6). Thus, an optimal cutting and segmentation of the trunk can be computed and the resulting wood volume is calculated online. In addition, in wood machining plants, the wooden boards and blocks can be scanned again, e.g. in order to adjust further sawing and blanking of useful parts out of cortex and deficient sections [www.homag.com].

In [6] four different wood species are evaluated regarding their orthotropic properties by means of tension tests and digital image processing. Studies of the material properties are a pre-requisite for the digitalisation of the wood machining process (see chapter 4).

Finally, the quality of produced wooden parts can be assessed automatically, e.g. with respect to geometric features or failure and damages of edges [7]. An insight into quality issues in wood machining is given by Csanády et al. in [8]. In [9], the use of Artificial Neural Networks (ANN) for modelling the surface quality of machined solid wood in terms of roughness is investigated. The effect of wood species, feed rate, cutting depth, wood zone (earlywood – latewood) and grain size of abrasives were analysed. The effects of feed rate, cutting depth and rake angle on the surface roughness and power consumption in wood machining were investigated and modelled by means of the Neuro-Fuzzy methodology in [10]. The surface roughness in machining of sweet cherry wood was investigated in [11]. The analysed roughness parameters increased with an increase in milling speed and feed rate. The surface quality was improved by the application of a climb way of cutting. In [12] the surface evaluation in high-speed milling of wood by a non-contact method using a confocal sensor. The surface roughness in drilling of MDF composite was analysed in [13]. The effects of sawing, planning and sanding on the surface roughness of wood are investigated also in [14]. Data gathered e.g. by stylus methods can be used for quality control with respect to subsequent process steps such as finishing or gluing. In [15] the influence of rake angle and feed speed at constant cutting depth in planning of various wood species on the resulting surface roughness was analysed. With decreased feed speed or rake angle, the performance of the specimen increased. The surface roughness sensitivity was higher regarding the rake angle but very low regarding the feed speed. Pinkowski and

Szymanski investigated the influence of tool wear on the surface roughness in profile milling of solid oakwood in [16]. Varying relationships were identified depending on the annual ring distribution of the wood. In [17], the effect of cutting conditions and chip formation in orthogonal wood cutting on the surface and subsurface structure was investigated by means of X-ray measurements. Damages of the subsurface cellular wood structure sensitively depend on the chip formation processes.

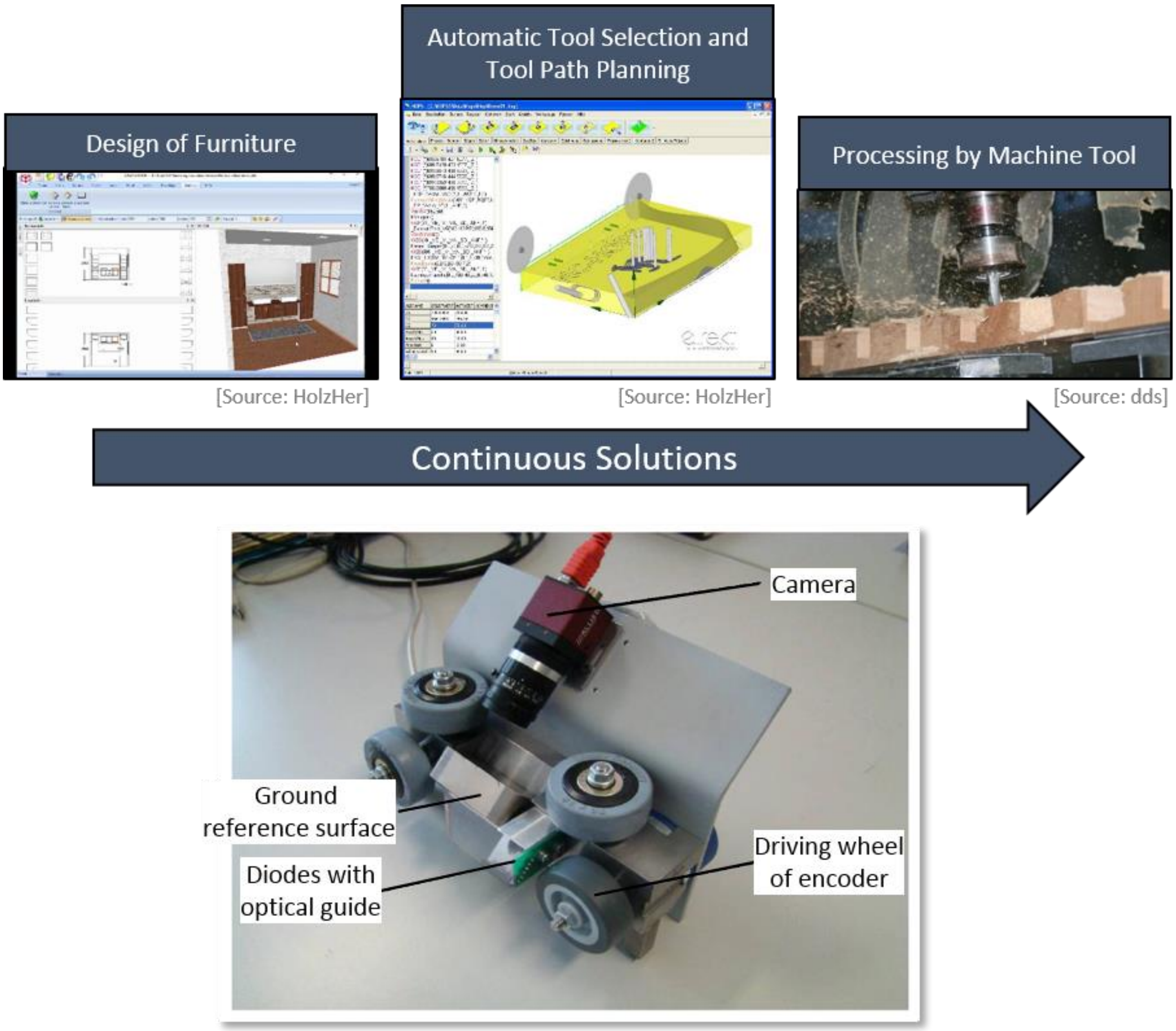

Fig. 4. Information chain in wood machining for furniture production [sources: HolzHer, dds, IfW]

In [18] the influences of machining and air exposure on the wettability of some wood species were analysed. It was shown, that machining has an appreciable influence on the wettability. The effect of the cutting direction on the bonding strength of wood-to-wood joints was investigated in [19]

By means of a mechatronic system based on piezo actuator or magnetic bearings, in [20] the surface damage in terms of cutter marks in peripheral milling of wood is diminished. In [21] the development of a control strategy for the compensation of structural vibration and cutting tool inaccuracy affecting the quality of planed wood surfaces is introduced. Besides active vibration control using a specific spindle unit with piezo actuators, the cutting tool trajectory is modified in real-time.

Fig. 5. Automated wood processing production line [source: HOMAG]

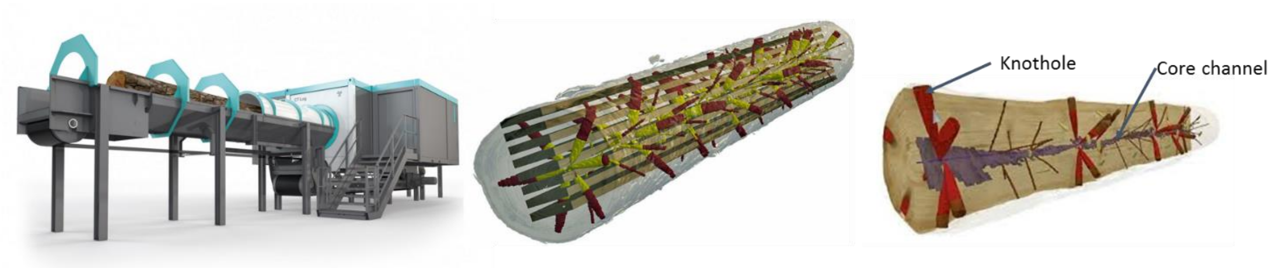

Fig. 6. Acquisition of wood properties by X-ray scanning [source: Microtec]

Latest research at the IfW in Stuttgart in terms of material characterisation is focused on the identification of the type and properties of wood materials during the cutting processes in order to allow for adjusting the process parameters online autonomously and without a priori information [22]. In Fig. 7, acoustic emission (AE) signal patterns for various investigated wood materials are presented together with the normalized amplitudes of three different classification parameters $f1$, $f2$ and $f3$ (see [22]). The milling tests were carried out using a 20 mm carbide tool with one cutting edge. The feed velocity was 8 m/min, spindle speed was 18.000 min^{-1} and the cutting depth was 10 mm. The AE signals were gathered with a sampling frequency of 800 kHz, thus enabling a signal pattern acquisition in a very high bandwidth. The medium cutting forces ranged from 27.6 N up to 60.4 N depending on the wood material. It was found that a material identification is possible based on the AE signals. In order to distinguish between different thicknesses of the same material, multiple classification steps are necessary. A multi-criteria signal analysis and data based approaches are content of the ongoing research.

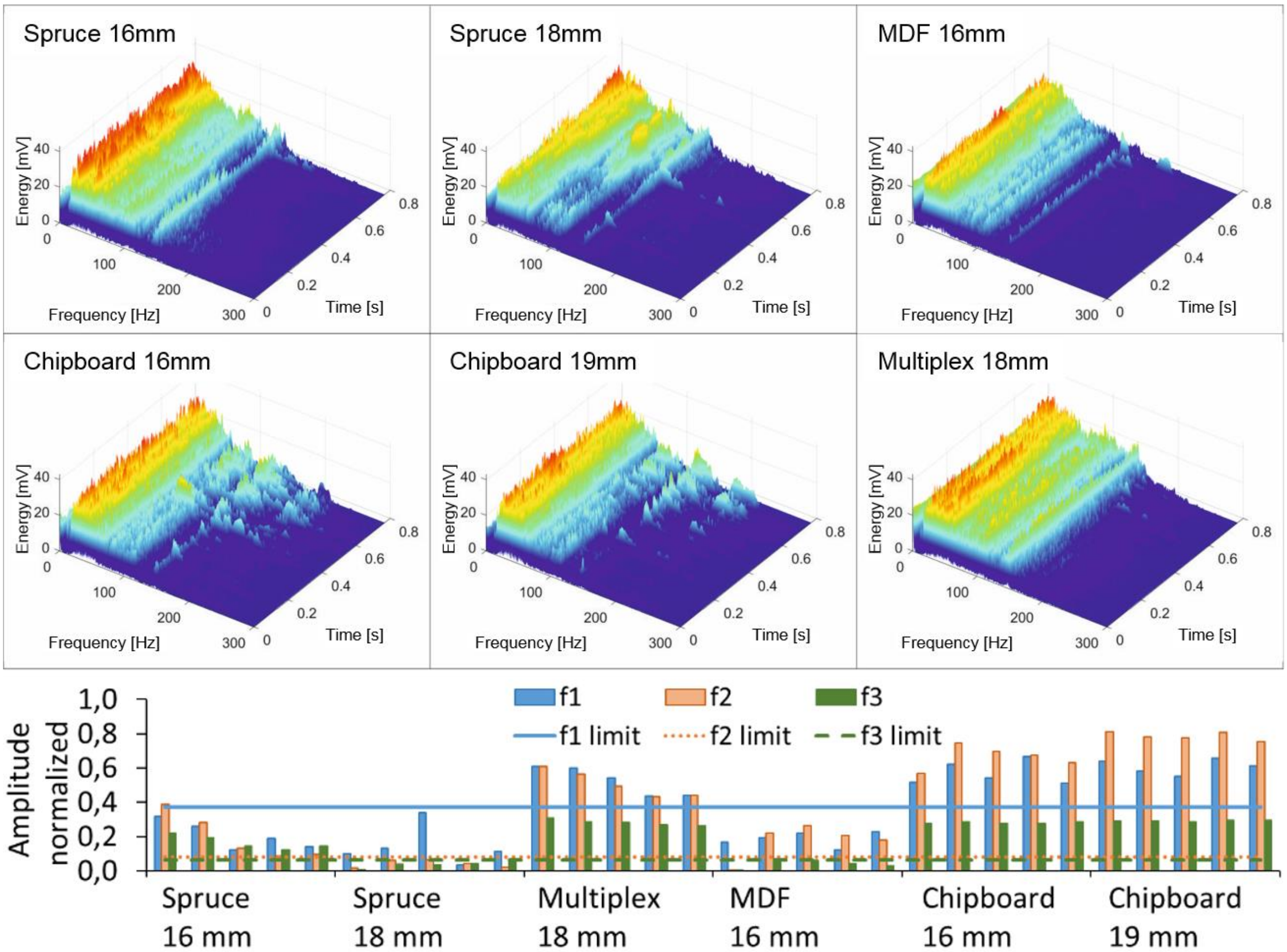

Fig. 7. Acoustic Emission signal patterns for material identification in wood machining [22]

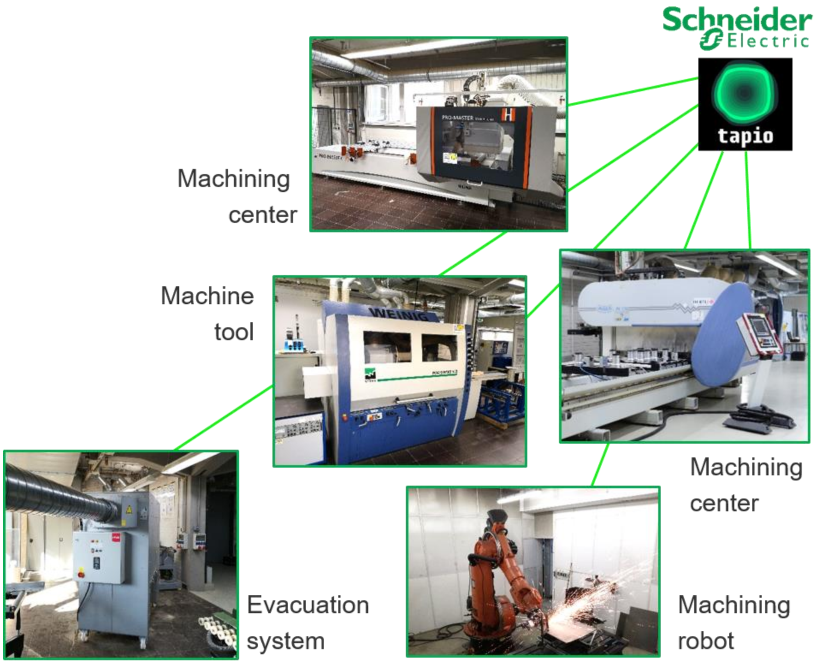

Fig. 8. Connectivity of wood machining facilities [IfW]

A fundamental pre-requisite for Industry 4.0 implementations in wood machining is the connectivity of machines and production systems. This means the interconnected communication of process and machine state information as well as workpiece data throughout the entire production for central but also decentral information processing, digitization, visualization, documentation and adaptive production control purposes. Exemplarily, this can be realized by the “tapio” technology platform (www.tapio.one) and digital services dedicated to the wood machining industry. Just as recently implemented at the IfW, even “used” machines and facilities can be connected by means of a retro-fit (Fig. 8). The open platform allows for the creation of user-specific application software (“Apps”) for data processing and visualization as well as the provision of digital services (e.g. process optimisation, material and tool management, maintenance).

3. CUTTING TOOL DEVELOPMENT

Intensive development and improvement of cutting tools for wood machining applications was achieved in industry. The range of cutting tool materials expands from Stellite and high speed steel up to uncoated and coated tungsten carbide as well as diamond tools, cermets and ceramics [1]. Recently, fine grain carbides with small portion of binder were developed that provide high hardness but also high impact strength and wear resistance. Nowadays, rake angles of 36° can be produced [23]. Cutting tool materials with high hardness are particularly required for machining of coated or layered wood composite materials. In wood machining, abrasive wear dominates but also corrosive, cracking and chipping wear occurs [24–28]. [29] gives an overview of tool wear of tungsten carbide tools in wood cutting processes. The wear mechanisms under different working conditions as well as techniques for tool wear determination were discussed.

In addition to the mechanical properties of the wood, hard particles and inclusions have a severe effect on the tool wear. The influence of wood properties and variations in terms of salt content and mechanical characteristics on the wear behaviour of tip-inserted bandsawing tools was analysed e.g. in [30]. The cutting tools were made out of Stellite and High Speed Steels and TiN coated. The proportion of mineral salt in wood samples as well as their mechanical strength have an effect on the wear progress. In [31], the influence of the grain size of tungsten carbide tipped circular saws in machining particleboard was studied. The work revealed the longest tool life for the coarse grain size compared to the medium and fine one. Abrasive, corrosive, cracking and chipping wear mechanisms on band saws were investigated in [32] with respect to machining of pine wood. For this, an analogy test was implemented with a circular plate carrying two saw teeth and a test setup in a milling machine.

By means of a specific machine learning (ML) algorithm, a wear prediction of woodworking cutting tools, depending on individual process conditions and machine characteristics acting on the tool, was developed in [33]. In [34], an automatic measuring system was used for determining tool wear and implementing an adaptive control system for grooving with respect to improving the machining accuracy in terms of burr formation corresponding to the progression of tool wear.

In [35] the behaviour of cutting tools modified by ion nitriding, hard coating and combined treatments in peeling of beech and pulp chips production is analysed. The treatment showed improved wear and shock resistance properties as well as improved quality of the final product. Significant work has been conducted regarding mono- and multi-layered coatings of cutting tools for wood machining applications [36–41] and only some examples can be mentioned here. The application of Cr_2N/CrN multilayer coatings deposited on HS6-5-2 substrates using cathodic arc evaporation was analysed in [42]. Multilayer coatings containing 7 bilayers were compared to monolayer coatings. An increase of the tool life by two times was achieved in planing of wood. In addition, the surface quality was improved. PVD multilayer chromium nitride coatings were studied in [43]. Beneficial performance was found regarding the anti-wear-resistance and workpiece surface quality. For machining of three different types of MDF, the application of ternary CrAlN hard layer coatings on carbide tools was tested in [44]. Coating of cutting edges generally results in a (micro-) rounded edge geometry which possesses drawbacks regarding the cutting performance and machined surface quality. Therefore, at the IfW, plasma sharpened CVD coated cutting edges were investigated (Fig.9). The cutting edge radii was reduced from 10–20 µm to 0.5 µm. Significant increase of tool life was observed.

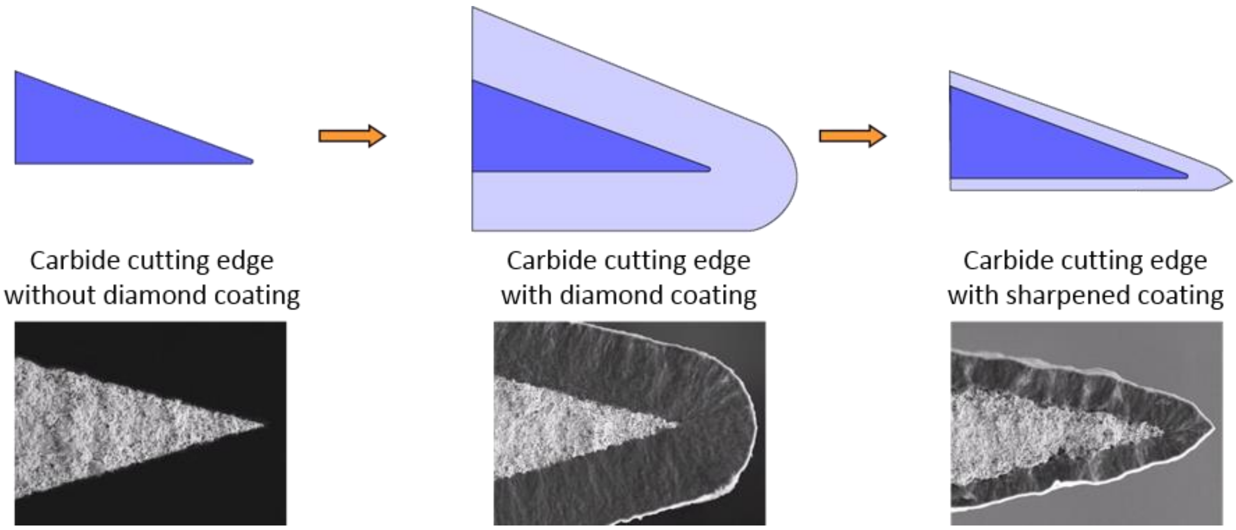

Fig. 9. Plasma sharpened cutting edges for wood machining tools [45]

In wood machining, the use of ceramics cutting materials shows some interesting potential [46]. Besides the cutting and wear performance, the lightweight characteristics could lead to higher cutting speeds [47]. In [48], the use of Al_2O_3 ceramics tools in machining of wood-based materials was analysed. The microstructure of the ceramics influences its technological properties.

Philbin and Gordon characterise the wear behaviour of polycrystalline diamond tools in machining of wood-based composites [49]. Investigations at the IfW showed lower roughness values when machining with polycrystalline diamond tools compared to carbides and revealed an improved tool life when introducing a chamfer to the polycrystalline diamond tools (Fig.10).

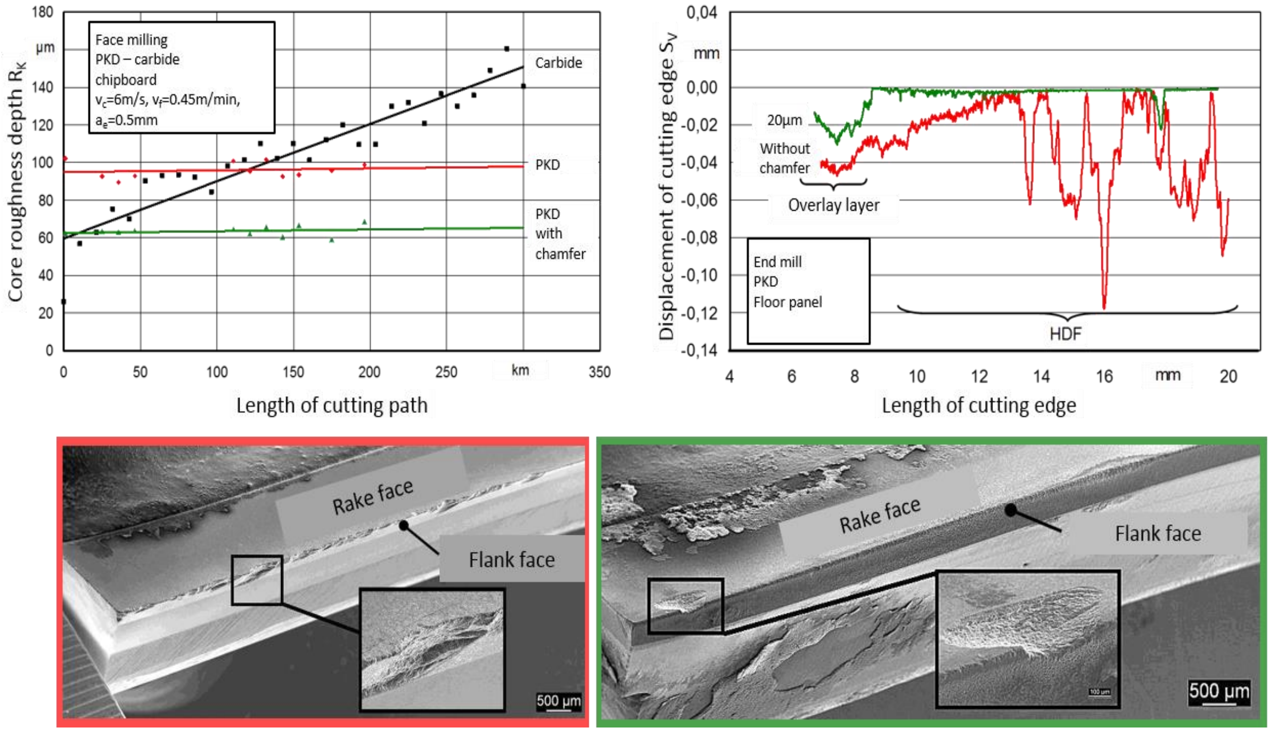

Fig. 10. Tool life and quality investigations with poly crystalline diamond tools [50, 51]

Also, the (macro-) geometric properties of the cutting tools have been studied in terms of helix angle and its influence on chip formation and energy consumption [52] as well as helix angle and its influence on cutting forces [53]. Company LEUCO introduced and patented milling tools with extreme helix angle leading to a decorticating and oblique shearing cutting (Fig. 11). In Fig. 11, also an exemplary serrated milling tool by company LEITZ is shown. Although a lot of research and development was carried out, still optimisation potentials for the design and treatment of wood cutting tools have to be exploited.

Since the evacuation of chips and dust is an essential task in wood machining, further developments in tool and machine equipment concern the suction systems. Regarding tool technology, chip evacuation turbines have been developed which provide a suction air flow directly at the working zone (Fig. 12).

Furthermore, the design of lightweight tool bodies leads to important advantages in wood machining. Due to the high cutting speeds and tool rotation frequencies, any unbalance of the spindle and tool system provokes a remarkable decrease of surface quality and increase in dynamic spindle loading leading to a faster wear progress of the spindle bearings. In horizontal tool applications, gravitational effects amplify the influence of unbalance. In addition, the tool mass influences the natural frequencies of the whole spindle system (incl. the clamped tool) and lighter tools shift the first eigenmodes to higher frequencies. Last but not least, the power consumption is less when accelerating a lightweight tool to the required spindle speed for machining of wood and wood-based materials. Therefore, the development of lightweight tool bodies is of particular interest (Fig. 13).

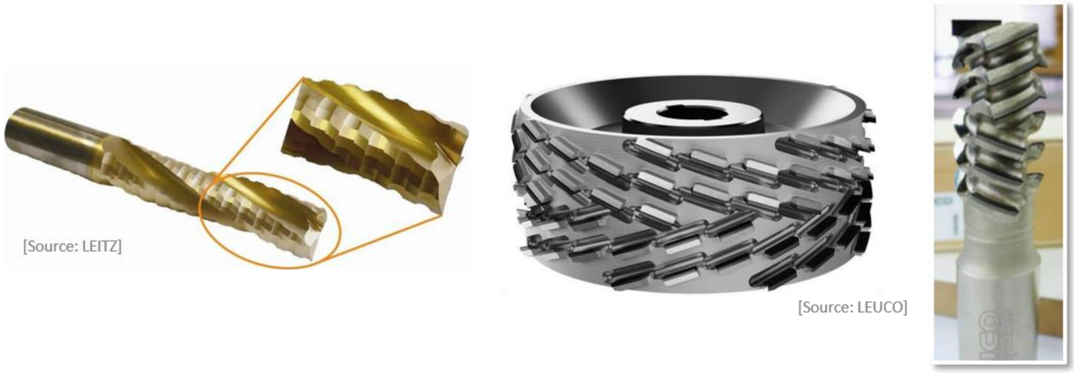

Fig. 11. Modern tool geometries for wood machining [LEITZ, LEUCO]

Fig. 12. Turbine shaped chip evacuation systems at wood machining tools [LEUCO, IfW]

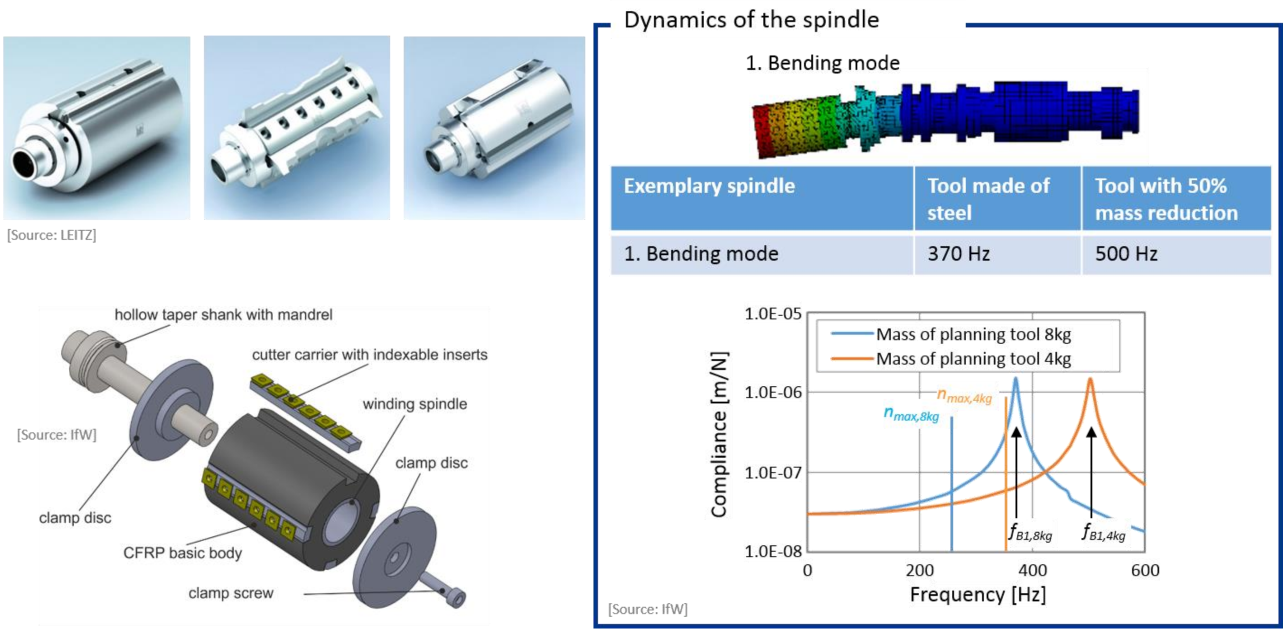

Fig. 13. Lightweight design of a wood machining tool [IfW]

An important instrument for knowledge-based tool and process development is established by wood machining process simulation. However, wood machining simulation still necessitates fundamental research in order to understand and model significant influences on process conditions as well as application oriented development in order to make simulations useful for industry.

4. WOOD MACHINING SIMULATION

Nearly 100 years ago, the components of the resultant force in the machining of wood and wood-based products were analysed for the first time [54–59]. Later on, investigations were conducted into the influences of tool and process parameters on the components of the resultant force [60–63]. Kivimaa [3, 64] described the relation between the cutting force F_c and the apparent density ρ of wood to be almost linear and largely independent of the direction of primary motion. However, the direction of primary motion has a very great effect on cutting force [65]. Not only the material properties but also the geometry of cutting edge (especially the tool orthogonal rake angle) greatly influence the components of the resultant force [66–69]. The effect of the kinematic input variables can be described by means of the mean undeformed chip thickness h_m [70]. Gottlöber reported a largely linear to slightly degressive increase in cutting force with growing mean undeformed chip thickness [71]. There are different analyses regarding the influence of cutting speed v_c. Kivimaa [3, 64] detected no dependence of cutting force and normal force on cutting speed up to 50 m/s. Pahlitzsch analysed the cutting forces for a series of wood-based products up to a rotational speed of 6000 min^{-1} for tool diameters of 125 mm. The course of the cutting force depending on cutting speed hardly changed except for a slightly decreasing tendency in the case of low rotational speeds [60]. Pahlitzsch and Jostmeier detected that the cutting force is minimal at a cutting speed of about 40 m/s [63, 72]. Thunell and Weber determined a cutting force minimum at a cutting speed of about 15 m/s [73, 74]. According to Weber [73], the values of cutting force are on a slightly increasing straight line within a cutting speed range between 40 and 90 m/s, as usual in practice. Sandvoß [69] detected that the cutting force F_c increased from about v_c = 40 m/s up, yet hardly changed at lower cutting speeds.

Material removal processes of metal materials have already been simulated successfully [75], assuming an isotropic material behaviour as well as plastic flow and cutting processes in the shear zones. However, the material behaviour and the process conditions cannot be applied to the machining of wood and wood-based products. Wood materials are inhomogeneous, porous and usually anisotropic. Their mechanical properties vary depending on moisture and time. Other machining conditions, defects and tool loads occur in the cutting of wood materials [2, 4, 76]. Regarding wood materials with a high anisotropy, the machining direction and the material structure must be taken into account [77, 78]. These properties require modified simulation approaches including the anisotropic character of the material (process forces and friction work depending on machining direction) as well as the cutting behaviour during highly dynamic loading [1]. In contrast to natural wood, the wood-based products of MDF and chipboard have partly or rather quasi-isotropic and quasi-homogeneous material properties, depending on the respective material variant though. Up to now, it has not been completely established to what extent the assumption of isotropic and homogeneous material behaviour in the calculation of resultant force components leads to errors or deviations from the real conditions.

The way MDF and chipboard are produced has a great influence on their characteristics. The respective wood-based product is characterised by the raw materials, the size, orientation and fixation of particles as well as the cavity systems. Niemz [79] gave an overview of the relevant structural characteristics for different observation levels. The production process (especially hot pressing) leads to changes in the material moisture and a characteristic density distribution in the thickness of the board. This vertical apparent density profile causes relevant characteristics, e.g. elastic and strength properties, machinability as well as coating of the board (cf. DIN EN 312:2010-12 and DIN EN 622-5:2010-03). Resulting from the production process, undesirable variations in the apparent density may arise parallel and diagonally to the machining direction. As wood-based products are hygroscopic materials, the material moisture varies with the ambient climate leading to changes in size and moisture gradients within the board as well as changes in the elastomechanical properties [80–82]. Hence, cutting experiments of wood-based products make it necessary to characterize them by means of suitable test methods [83]. When evaluating the surface quality in the machining of MDF boards, it showed that a high apparent density results in a better surface quality [84]. Beer analysed the specific cutting energy in the machining of chipboards by means of wedge splitting and microtome tests [85]. The material failure was characterised by friction and pressure energy. The friction processes occurring during machining influence the process heat and thus the material behaviour. Since the actual conditions during machining are not known with sufficient accuracy, the friction process is an unsolved matter [86]. In the machining of metal as well as wood, the friction coefficient is mainly determined by means of empirical approaches and fundamental laws of friction. The friction coefficients are mostly adjusted by using process forces measured by experiment. Several friction coefficients for defined material pairs in wood machining were established in early investigations [87–89]. Regarding the influence of the friction between wood and steel in material removal processes, the essential parameters such as material pairing and wood moisture were already mentioned and characterised in [89]. In addition, the coefficients for static and sliding friction were established for both dry and moist wood depending on feed rate. McKenzie examined the friction coefficients for various density layers in an MDF board during milling [90], detecting only slight variations in the friction coefficients.

Fischer, Sitkei and McKenzie developed the first model approaches of wood machining. In [91–93], Fischer reported on the mechanics in wood machining and elaborated a complex model for predicting cutting force. He assumed that the force actually required for cutting is low compared with the influences of friction, deformation, chip acceleration and wear. Sitkei presented a calculation approach based on the notion that the cutting edge deforms a chip on the tool wedge surface at a particular radius [94]. Equations for cutting and normal force were derived from the balance of the bending moments. The influencing factors are the directionally dependent mechanical parameters of the wood type, the undeformed chip thickness and width, the deformation radius of the chip as well as the cutting angle. A linear term in the calculation approach takes the cutting edge rounding into account. The „Wood Cutting Simulation“ program, developed by Fischer at the Chair of Materials Technology at the TU Dresden, provides the simulation of machining processes for solid wood and wood-based products. Different material pairings, tool geometries and process parameters can be adjusted in this software. Unfortunately, one cannot access the fundamental physical principles and the sources for creating the parameters compiled in the wood database. Using regression equations, McKenzie described a cutting force model for milling 19 mm thick MDF boards with a total apparent density of 0.778 kg/dm^3 [90]. In the case of a constant tool orthogonal rake angle and a constant undeformed chip thickness, the model requires the apparent densities and friction coefficients of the three individual layers within the total MDF thickness. The model assumes that the sum of the process forces in the individual layers amounts to the total process force. Dippon and Altintas presented another analytical force model for MDF machining using orthogonal cutting [95]. In this model, the process forces are described by means of the pressure on the rake face, the tool geometry as well as the apparent MDF density. Then the cutting coefficients are established from that. The influence of the friction between rake face and cutting edge was considered to be low and hence neglected. Due to the quasi-isotropic behaviour of MDF, Tani used a force model from metal cutting for the milling of MDF [96]. The model assumes that there is a linear correlation between resultant force and feed. The force model requires data of feed, tool geometry, tool entry angle and the calculation of process parameters. Bouzakis presented a possible concept for the FE simulation of chipboard machining [97, 98]. Based on the simulation results, the chip forming processes in the machining of chipboard were analysed in the area of both dense and loose chip layers. The implemented material models were developed from stress-strain diagrams of standardized bending tests for low strain rates. The mechanical properties of the chipboard were determined by experimental measurements and supplemented by the simulation results of indentation hardness tests. The established material models were optimised by force measurements in milling tests. In the simulations, the good agreement of the process forces in the machining of the different layers were used to characterize the mechanical properties of the material layers. The material model by Wong takes the influence of particle size, wood type, particle orientation and the imperviousness of chipboard into account [99]. Compared with experimental measurements, this model shows deviations concerning the process forces. Further investigations into the analysis of wood machining are the studies by L-Ngoc, Caughley and Sheikh-Ahmad. L-Ngoc and Caughley examined the collapse of the cell structures of wood under cutting conditions [100, 101]. Sheikh-Ahmad investigated how the tool temperature can be established by means of specially developed FE simulation models [102].

Summing up the modelling approaches for the machining of wood, it can be found that individual modelling approaches on empirical and analytical basis already exist for different types of wood. There are, however, no material models for chipboard yet. The few modelling approaches for MDF apply approaches usual for metal or rather isotropic materials. For the machining of MDF and chipboard, there are, however, no material models including their production-related isotropy group. The modelling approaches presented do not take account of the aspects of friction processes nor of the material behaviour under the highly dynamic loads during cutting processes.

The FE software LS-Dyna is a simulation environment often used in practice for analysing wood behaviour. In this software, material cards are already available to enter directionally dependent material parameters for simulating the orthotropy of wood-based products [103]. Maillot compared the available material models in LS-Dyna [104]. Vasic combined the theory of fracture mechanics for orthotropic wood-based products with linear and nonlinear approaches [105]. The models require different assumptions and data (e.g. crack orientation, stiffness and strength parameters) influencing the direction and the size of crack propagation. Until now, several material and damage models have been developed and combined concerning the analysis of wood behaviour under highly dynamic loads. Adalian and Morlier analysed the behaviour of poplar wood under multiaxial compression load by using a drop hammer for static and dynamic processes. The macroscopic deformation conditions were approximated in empirical models using initial density and strain rate as input variables [106].

The state of the art shows that there are no material models for chipboard and only few modelling approaches for MDF. The models for MDF use approaches from the area of metal cutting and of isotropic materials [95–98]. These models have already provided good results owing to the rather isotropic properties of MDF. Nevertheless, they have to be supplemented and consolidated further. Further research is needed here with regard to the material behaviour for highly dynamic loads (as in material removal processes) and a more precise analysis of friction and cutting processes. The great majority of already existing studies and developed material models are orientated towards models with cellular structures and high anisotropy under quasi-static loads.

The investigation of the mechanisms of wood and wood-based material machining is conducted at the IfW (University of Stuttgart) since decades [107–123]. Großmann worked on the optimisation of sawing tools regarding an increase of quality and productivity in machining of spruce [124]. The sawing process was reproduced by an analogous milling experiment accompanied by cutting force calculations. Specific cutting force coefficients depending on cutting depth, feed per tooth and cutting speed were identified in experiments. For evaluating the medium cutting force, regression equations and correction terms were determined. The findings were transferred to pine wood, oak and beech. Furthermore, specific and medium cutting force values were gathered for varous moisture conditions. By means of the cutting force calculation, the influence of convex secondary cutting edge geometries was predicted and analysed. Enßle analysed the influence of micro geometry of diamond tools for wood and wood-material machining regarding tool life improvements [126]. Besides spruce and bech, also MDF and chipboard were regarded. For simulating the cutting conditions considering the micro geometry of the cutting edge, Enßle used a 2D Finite Element (FE) simulation. The material removal was simulated by erasing elements at the workpiece side. By this, effects of the contact of chips and the tool were not described accurately. A linear elastic material model and the Young's modulus and density of an exemplary MDF workpiece were assumed. With respect to wood machining simulation, the work of Martynenko regarding milling of MDF, chipboard, multiplex, spruce and beech wood have to be recognized [126]. As a bottleneck in force measuring, the limited bandwidth of conventional dynamometers and spindle power analysis became obvious. The actual force peaks have to be reconstructed based on a fundamental knowledge of the force characteristics. For cutting speeds of approx. 20 m/s, Martynenko identified a decreasing cutting force characteristics in machining of multiplex. For MDF and multiplex a linear relationship of feed per tooth and cutting force was observed. Furthermore, Martynenko analysed the influence of the rake and tilt angles as well as the influence of various process settings on the specific cutting force values. For the cutting force parameters in cutting, normal and passive directions, regression models were determined based on the medium depth of cut h_m. In addition, the influence of the filling of the chip space at the tool on the cutting force was investigated and modelled depending on different workpiece material properties and tool geometries. By this, an optimization of the tool shape for high performance machining was possible. For the analysis of chip generation and transport, a high speed camera and thermography were applied.

For simulating machining of wood materials, furthermore, intensive studies were carried out at the IfW. Thus, material models or MDF and beech were established and tested. These material models are based on the determination of elastic and thermal material parameters as well as tensile tests with low strain rates (Fig.14).

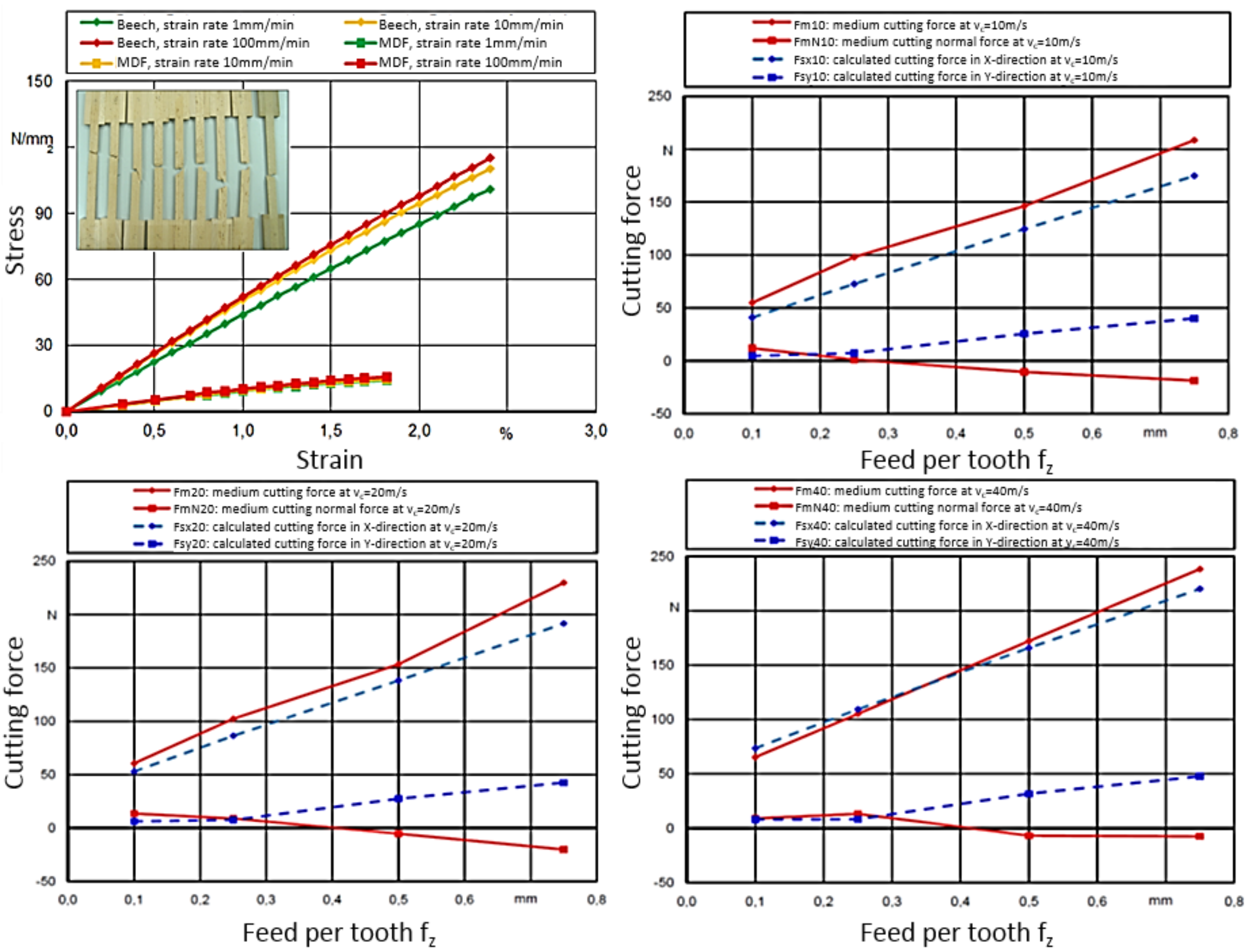

Fig. 14. Stress-strain diagrams of MDF and beech as well as cutting force simulation results [IfW]

Flow curves for higher strain rates were extrapolated. By means of the material model for MDF, an investigation of the Finite Element software systems ABAQUS and DEFORM was conducted for milling. A variation of the cutting depth showed a good agreement with experimental data. The availability of appropriate friction coefficients appeared to be inevitable.

5. SUMMARY AND CONCLUSION

This paper introduces and reviews essential technologies, which – in combination – enable the implementation of intelligent wood machining. Processing of solid wood and wood-based materials incorporates specific challenges that have to be considered carefully within the design of machining systems, tools and machines as well as for the layout and optimisation of the process setup and settings. Innovative sensors, measuring and monitoring techniques allow for an identification of wood material properties and the adjustment of the processes in principle. However, up to now, a remarkable effort is necessary for the identification of the individual specific characteristics of wooden parts which have to be treated by machining processes. A high potential can be observed regarding sophisticated process monitoring and control systems. Industry 4.0 scenarios and enabling technologies are already available in the wood machining sector. However, besides large industrial applications, still research and development work is necessary in order to integrate these approaches in small and medium sized enterprises that dominate the wood machining industry. Although intensive and comprehensive investigations have been carried out with respect to the optimisation of wood machining tools, still future potential can be observed. Further work is necessary in order to better understand the relationships between cutting forces, tool wear and workpiece surface and edge quality. A very interesting aspect is the further qualification of sophisticated machining simulations and an even more detailed and realistic modelling of the phenomena in wood material processing. This requires fundamental research as well as an intensive transfer to industry in order to establish the approaches for tool and process optimisation.

As a summary, obviously, science and industry are “en route to intelligent wood machining”. However, still intensive research and development is necessary in order to understand, describe, simulate and control the complex and varying phenomena in wood machining precisely and comprehensively.

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