Triboelectric surface field strength of wood after brushing

Lena Maria Leiter¹ · Roman Myna² · Stephan Frömel-Frybort³ · Falk Liebner⁴ · Rupert Wimmer¹

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Abstract
Mechanical friction causes electrical surface charges on wooden surfaces. In this research, triboelectric activation of solid wood surfaces was investigated by using a wood brushing machine. The extent of activation and the potential influence of machine parameters, or the influence of various wood species are questions so far unanswered. The electrical surface field strengths were continuously detected by means of an electric field meter. Machine settings, such as feed rate and brush pressure, have been varied to better understand the effects on the resulting surface charges. Data showed that nylon and tynex brushes lead to strong positive electric surface field strengths while natural fibers lead to less positive surface field strengths. In contrast, steel wire brushes showed negative electrical field strengths for oak wood, slightly positive field strengths for beech wood and stronger positive field strengths for softwoods. Overall, the tendency that a higher brush pressure led to higher recorded electrical surface field strengths while a faster feed rate reduced the field strengths was observed. As these findings were influenced by wood species and brushing materials, a better understanding of specific triboelectric interactions is essential for future applications. Tailoring surface charges can be an asset for new technical applications, such as chemistry-free primer treatments prior to wood coating.

Lena Maria Leiter
lena.leiter@boku.ac.at

1 Institute of Wood Technology and Renewable Materials, University of Natural Resources and Life Sciences, Vienna, Austria
2 Institute of Structural Engineering, University of Natural Resources and Life Sciences, Vienna, Austria
3 Wood Technology Department, Höhere Technische Bundeslehr- und Versuchsanstalt Mödling, Mödling, Austria
4 Institute of Chemistry of Renewable Resources, University of Natural Resources and Life Sciences, Vienna, Austria
Introduction

Surface activation is a major pretreatment strategy for the refinement of freshly created wood surfaces (Lohmann 2010), facilitating uniform application of paints or varnishes, further functionalization to impart specific properties, or to enhance the performance of adhesives (Wagenführ et al. 2012). Traditionally, surface activation is accomplished using appropriate chemical primers and liquid bonding agents, respectively, which are nowadays increasingly solvent-free or water based. Among the wide range of chemical primer systems both single and two component solutions have been patented (Böger et al. 2022), such as the poly(ethylene imine) (PEI)-based single-component primer patented by Weyerhaeuser Company (Tacoma WA, USA) or the two-component primer by Rhône Poulenc S.A. (Paris, France) relying on isocyanate/alkoxysilane chemistry. Further patented primers are based on hydroxymethylated resorcinol (HMR, US Department of Agriculture), or polyoxyethylene (20) sorbitan monolaurate (Polysorbate 20, Henkel AG & Co. KGaA, Düsseldorf, Germany), the latter featuring bonding capabilities to polyurethane adhesives. Interestingly, it was also shown that organic solvents, such as N,N-dimethylformamide can improve moisture-curing of polyurethane-bonded wooden specimens by swelling and partial dissolution of lignocellulosic surface layers. Next to better physical interlocking of the adhesive, it has been assumed that an additional quantity of formerly inaccessible water is released contributing to curing (Kläusler et al. 2014a, b).

Besides chemical priming, plasma and corona discharge are two well established surface activation technologies. Both are energy intensive processes that rely on high frequency, high voltage ionization of suitable gases, such as argon, oxygen, nitrogen, or respective mixtures (e.g., air, H₂/N₂). As a result, a low-temperature cloud of excited gas atoms, molecules, metastable compounds, radicals, cations, electrons, and energy-rich photons is generated between the two electrodes, facilitating chemical surface alteration of a given material (oxidation, bond cleavage to release volatiles, radical formation for subsequent modification) that is placed into the plasma beam. Different from plasma treatment which requires high frequency voltage (up to several MHz) for low-pressure gas ionization (typically 100 Pa), significantly lower voltage and near-ambient pressure conditions are used in corona discharge technologies. The specific setup of the latter circumvents the inset of avalanche, i.e., charge carrier multiplication, which occurs when the dielectric strength or disruptive potential of the non-conducting medium (usually air) is surpassed. Along with the fact that corona discharge can be conducted at near ambient air pressure using high flow rates of (ionized) air, surface activation can be accomplished at high throughput and in a more controlled manner. This is feasible due to the relatively low electrical power corona which allows for better fine tuning of surface energy. Further advantages include the possibility of treating much larger surfaces as well as inner surfaces and recesses of three-dimensional pieces. Formation of strongly oxidizing, toxic or corrosive gases from air, including ozone, nitric oxide or nitric dioxide (nitric acid in the presence of moisture) is probably one of the most critical...
disadvantages of the corona process (Ebnesajjad and Landrock 2015). Nevertheless, both plasma and corona discharge technologies are well established for surface activation in many material processing sectors. Hitherto, this is however not the case for industrial wood processing even though significant gain in wettability has been demonstrated (Avramidis et al. 2009; Podgorski et al. 2000) which would improve adhesion of water-born printing inks or adhesives.

In this work, a novel surface activation method based on triboelectricity is introduced. The nature of triboelectricity and options to employ this effect for certain technical applications have been researched to some extent as reviewed elsewhere (Pan and Zhang 2019; Zhang and Olin 2020). Mechanical disintegration processes, like sawing, cutting, chipping, shredding, and sanding are key processes in the wood industry. Next to impact and cutting, friction is one of the principal mechanical forces occurring between the respective tool and the wooden material. The high energy introduced by cutting tools and partially transferred through primary or secondary friction easily disintegrates macroscopic, microscopic or supramolecular assemblies, cleaves chemical bonds and causes materials to change their electronic states. As a result of excitation (and boosted by thermal activation), electrons are transferred between the materials leading to opposite electrical charging. Its extent and the question which one of the materials paired in friction acts as electron donor (and becomes positively charged) depends on many factors, but is significantly influenced by the difference in surface work function (minimum energy required to remove a valence electron). This process of electron transfer continues until the Fermi levels of the two materials coincide (Matsusaka et al. 2010). The direction of electron transfer between two materials depends on their individual readiness to act as an electron donator or acceptor. Respective lists referred to as “triboelectric series” can be found somewhere else, ranking materials according to their tendency to become positively or negatively charged when brought in intimate contact with another material prior to their separation (e.g., Diaz and Felix-Navarro 2004; Park et al. 2008; Burgo et al. 2016; Zou et al. 2019). A triboelectric series, however, does not provide any information about the amplitude of charging due to many interfering effects, such as electrical resistance, conductivity, moisture content, contact time and area, among others. Still it is worth noting that materials located far apart in a triboelectric series tend to build-up higher charge differences than materials being in closer proximity to each other (Diaz and Felix-Navarro 2004).

Wood as an electrically semi-conductive material is commonly positioned near the center of a triboelectric series. This implies that it can act as both electron donor and acceptor (Diaz and Felix-Navarro 2004; Reches et al. 2009). The individual behavior largely depends on its moisture content, bulk density, anatomical structure, and ambient humidity (Skaar 2012). Processing of wood with metal tools typically affords positively charged wood surfaces (Greason 2013) while both positive (e.g., polyamides) and negative charging (e.g., polyethylene) can occur with synthetic organic polymers (Liu et al. 2015).

Different from metals and polymers, only little is hitherto known about triboelectrical charging of wood particles and surfaces, as well as the mechanisms involved (Karner and Urbanetz 2013). Among the few studies investigating triboelectric charging of wood particles (e.g., Zhang et al. 2013; Myna et al. 2021a, b, c), in particular the
latter reports are worth noting. Using the example of different types of wood and wood composite materials it was demonstrated that hand-held circular sawing produces dust that is either always positively or negatively charged. It has been furthermore shown that coating of sawing blades, such as with chromium, is an efficient means to promoting charge neutralization (Myna et al. 2021a), eventually leading to reduced dust cloud formation. This can be of great benefit to many powder-handling operations where electrostatic charging is a critical issue (Amyotte and Eckhoff 2010; Mehrani et al. 2005), such as coal dust (Nifuku et al. 1989), malt grain (Nifuku and Enomoto 2001), or wood dust (Calle et al. 2009) generation, transportation or air purification.

Intentional triboelectrical charging as a means of wood surface activation is an opportunity that has hitherto received little attention. This is surprising since it bears obvious economic advantages compared to traditional (additional) secondary activation processes, such as chemical priming, plasma or corona discharge. In addition to considerable savings related to energy and equipment, the earlier mentioned release of volatiles (O₃, NOₓ, HNO₃, solvents) harmful to both environment and equipment could be avoided. In view of these considerations, the goal of this work was to prove whether or not wood surfaces can be intentionally triboelectrically charged. It was hypothesized that triboelectric charges can be introduced through brushing of wood surfaces, creating either a positive or negative electric surface field strength which was anticipated to be evenly distributed across the entire surface. It was also expected that the amplitude of introduced electrical charges and, hence, of field strength could be controlled to a certain extent by: (a) different brushing materials, (b) different wood species and (c) variation of machine settings, without changing the polarity of the electrical field.

Materials and methods

Wood samples

Various defect-free wood samples with a radial annual ring orientation (close to 90° to processing surface) were prepared. Samples had an initial size of 93 mm × 45 mm, at a length of 600 mm. All the samples have been conditioned in a standardized climate (20 °C, 65 relative humidity), until weight constancy was reached. The wood species fir (Abies alba Mill.), beech (Fagus sylvatica L.), spruce (Picea abies L. [Karst]), pine (Pinus sp.) and oak (Quercus sp.) were chosen for the experiments. The wood density was determined at a wood moisture content of 0%, following ISO 3131. Considering mean density (\(\bar{\rho}\)), the wood species have been split into two groups of species: (1) hardwood: beech \(\bar{\rho} = 0.71\) g/cm³ and oak \(\bar{\rho} = 0.64\) g/cm³, and (2) softwood: fir \(\bar{\rho} = 0.45\) g/cm³, pine \(\bar{\rho} = 0.50\) g/cm³ and spruce \(\bar{\rho} = 0.53\) g/cm³.

Brushes

Brushes (Koti Kobra GmbH, Austria) with different bristle materials (Fig. 1) were used. The structuring brushes had a body length of 300 mm, and an initial outer diameter of 150 mm. The plastic bristles were made of different polymers as
substrate material, with inserted silicon carbides acting as abrasive grit to achieve the brushing effect. Nylon (NY) and Tynex® (TY) were used as substrate materials. Tynex® is an abrasive filament made by extruding a mixture of nylon and abrasive grit (DuPont Company, Delaware, USA). Brushes with the grain sizes K46 for nylon and K80 for TY were used for testing. The individual letters in the brush code at the beginning of the combination for the grain size indicated the hardness of the abrasive grit in alphabetical order. Names from A to K stand for grits being soft, L to O being medium and P to Z for a particularly hard grit. The number after the letter indicates the grain size of the abrasive grit. The higher the grain size, the finer the grit and thus the lighter the brushing pattern. The numbers are given in the unit of measurement mesh, which indicates the mesh size of a sieve per one inch (ISO 6344).

Besides structuring brushes (NY and TY), which have the main purpose of creating structured surfaces, also roller brushes (steel wire (ST) and natural fiber (NF)) were used. The latter has the purpose of modifying the surface without leaving big indentations. The steel wire brushes were made out of brass-plated cord wire with a copper content of 63.5 ± 2.5% and the natural fiber brushes out of mexico fibers, with the trade name tampico-fiber from Agave lechuguilla and Agave funkiana from the area of Jaumave, Mexico. For those brushes, no grain size could be determined. However, reading the manufacturers specification (Koti Kobra GmbH, Austria), the brushes are designed in a way that the grain size would be similar to K80.

**Surface charging**

To charge the surfaces, mechanical friction was applied by means of a commercial brushing machine (TWINGO 300 B, Houfek a.s., Czech Republic). During pre-testing it was seen that the surfaces of some wood species tended to get covered with wood dust. For better suction results, an air pressure system (Fig. 2) was installed to keep the dust in motion and therefore ensure dust free surfaces.

The machine settings feed rate and brush pressure offset were varied (Table 1). Brush pressure was adjusted by the height difference (offset) between the wood surface and the bristles of the brush. A brush pressure offset of 3 mm was set as the low brush pressure level (low BP), while an offset of 6 mm represented the high brush pressure level (high BP). Considering that the bristles of the steel wire brush bend less than those of the other brushing materials, an offset of 6 mm resulted in slightly burnt wood surfaces. Therefore, for this brush type a 1 mm
A 3 mm offset was used as the low brush pressure (low BP), while the 3 mm offset was set as the high brush pressure (high BP). The feed rate settings given by the manufacturer were 4.5 m/min for the slow feed rate (slow FR), and 9 m/min for the fast feed rate (fast FR).

**Table 1** Varied machine settings for brushing materials NY…nylon, TY…Tynex, NF…natural, fiber ST…Steel, for the wood species AA…fir (*Abies alba*), FS…beech (*Fagus sylvatica*), PA…spruce (*Picea abies*), PS…pine (*Pinus* sp.), and QS…oak (*Quercus* sp.)

| Brush | Wood species | Brush pressure [mm] | Feed rate [m/min] |
|-------|--------------|--------------------|-------------------|
|       |              | Low    | High   | Slow  | Fast  |
| NY    | AA           | 3      | 6      | 4.5   | 9     |
|       | FS           | 3      | 6      | 4.5   | 9     |
|       | PA           | 3      | 6      | 4.5   | 9     |
|       | PS           | 3      | 6      | 4.5   | 9     |
|       | QS           | 3      | 6      | 4.5   | 9     |
| TY    | AA           | 3      | 6      | 4.5   | 9     |
|       | FS           | 3      | 6      | 4.5   | 9     |
|       | PA           | 3      | 6      | 4.5   | 9     |
|       | PS           | 3      | 6      | 4.5   | 9     |
|       | QS           | 3      | 6      | 4.5   | 9     |
| ST    | AA           | 1      | 3      | 4.5   | 9     |
|       | FS           | 1      | 3      | 4.5   | 9     |
|       | PA           | 1      | 3      | 4.5   | 9     |
|       | PS           | 1      | 3      | 4.5   | 9     |
|       | QS           | 1      | 3      | 4.5   | 9     |
| NF    | AA           | 3      | 6      | 4.5   | 9     |
|       | FS           | 3      | 6      | 4.5   | 9     |
|       | PA           | 3      | 6      | 4.5   | 9     |
|       | PS           | 3      | 6      | 4.5   | 9     |
|       | QS           | 3      | 6      | 4.5   | 9     |

**Fig. 2** Brushing section between the two fixing rollers with a self-designed air pressure system directly after the nylon K80 brush.
Electric field detection

Immediately after brushing the cumulated electrical surface field strengths were measured using the electric field mill EFM 115 (Elektrofeldmeter, Kleinwächter®, Germany), which is a small fieldmeter with high sensitivity detecting the electric direct voltage field. For continuous wood surface measurements using the EFM 115, the experimental setup shown in Fig. 3 was established.

According to Baytekin et al. (2011), surface potential measuring instruments assume that the object to be measured has an infinite size. This means that valid values are delivered when the measured object is significantly larger than the detection area of the measuring sensor. As seen in Fig. 3, the detection unit was adjustable, to set the right position above the wood surface to be measured.

The measuring sensor, a part of the detection unit, was designed as a Faraday cage to shield from possible surrounding electrostatic charges. The use of a Faraday cage is well established for measuring triboelectrification (Burgo et al. 2016; Zhou et al. 2020). Electromagnetic fields ($E$) striking the box from outside are causing a force effect $\vec{F} = Q \times \vec{E}$ on the freely moving charges ($Q$) of the sheet metal. There is a spatial redistribution of the charges on the surface until the external electric field component tangential to the surface becomes zero. This results in an equalization and the electric flow ends (Schwab 1996).

The electric field meter was connected to the detection unit, and data were transferred to a computer. Prior to a set of six measurements, a zero-calibration was done by grounding the entire device. In addition, the measurement range was set by varying between the system from 5 to 25 kV/m. To ensure measurements of freshly brushed wood surfaces and avoid data acquisitions coming from the conveyor belt before and after the sample has passed the sensor, a photosensor was placed between the brushing sector and the detection unit. The photosensor

Fig. 3 Experimental setup to continuously measure electrical surface field strength of wood samples due to surface brushing. left: front view, right: side view of the used setup
was used to deactivate grounding, i.e., zero-calibration, as well as to trigger elec-
tric surface field strength measurement as soon as a sample was recognized.

The measurement setup allowed the quantification of the accumulated electro-
static surface field strength at zero energy transfer. The principle of electrostatic
induction is used for measuring the electric field strength generated (Zhou et al.
2020), expressed in V/m with a resolution of ±5 V/m.

**Experimental design and data evaluation**

A full-factorial experimental design was used, with six specimens per wood species and all of them were brushed eight times with four
machine settings (low BP|slow FR; low BP|fast FR; high BP|slow FR;
high BP|fast FR). The number of conducted experiments was therefore:

\[6 \text{ specimens} \times 8 \text{ turns} \times 5 \text{ wood species} \times 2 \text{ brushpressures} \times 2 \text{ feed rates} \times 4 \text{ brushes} = 3.840.\]

An analysis of variance (ANOVA) using main and 2-way effects was applied, to
test for the significance of the wood species, the brushing material, the machine set-
ting (brush pressure and the feed rate), and the interactions thereof. Homogeneity
of variances was tested with a Levene test, which showed significant differences.
Therefore, for the multiple mean comparisons the Bonferroni post hoc test was
employed, with \( p < 0.0001 \) as the probability of error.

**Results and discussion**

Overall, it was possible to triboelectrically charge the surfaces of all tested wood
species by using different brushing materials (Fig. 4). Nylon (NY) and Tynex®
(TY) brushes resulted in strong positive cumulated electric surface field strengths
for all wood species, whereby the highest mean field strengths were recorded for
pine wood brushed with TY (9.36 ± 1.69 kV/m), and for beech wood brushed
with nylon (8.53 ± 1.86 kV/m). While brushes made from natural fibers (NF) lead
to mainly positive cumulated surface field strengths for all wood species with an
overall mean field strength of 2.06 ± 0.80 kV/m, the steel brush (ST) data showed
a negative mean field strength for oak wood (−1.3 ± 1.22 kV/m) and positive field
strengths for all the other species, corresponding to Greason (2013) who stated that
wood charges positively when colliding with metals. The post hoc test showed sig-
nificant differences \( p < 0.0001 \) between all wood species brushed with natural fiber
and steel wire bristles, but no significant difference was found between fir and oak
wood brushed with TY K80 (sig 0.007) or NY \( p < 0.000 \), and between pine and
oak wood brushed with NY \( p < 0.004 \).

To understand how the brushing material influences the electrical surface field
strengths it was important to quantify factors such as grain and bristle size since
they influence the surface texture. It is well known that during sanding a finer grit
size, which translates to a smaller bristle diameter and a smaller grain size in brush-
ing, will lead to finer wood particles and smoother surfaces. During brushing an
increased removal of earlywood tissue takes place, while the latewood remains
rather unaffected. A larger bristle diameter of the brushes is therefore leading to a rougher surface profile, since larger particles get removed from the earlywood. Finer brush bristles result in less wood removal, and therefore to a lower brushing profile with a smoother surface.

Nylon and TY brushes lead to more expressed brushing profiles, while natural fiber and steel wire bristles show little to no indentations. The present data revealed that the amount of wood removal is directly linked to the accumulated triboelectric surface field strength. These surface field strength differences can be explained by the fact that the diameter and number of bristles are representing different contact area sizes. Nylon bristles (K46) are thicker than TY bristles (K80), while steel wires are thin compared to TY bristles. The natural fiber bristles were by far the thinnest. Therefore, brushes with thicker bristles (lower grain size) had fewer but bigger points of impact, thus smaller contact areas. This not only affected the amount of the wood removed, but also the electrical field strength generated while brushing. The results correspond to findings by Williams (1976), who observed that with a larger contact area (thinner bristles) a higher amount of surface damages may occur, which complicates the electrical charge transfer that is leading to a reduced surface field strength.

Another explanation for the achieved electrical surface field strengths as related to the used brushing material can be found with the triboelectric series (TS). It has been observed that materials that are positioned very distant from each other in the TS have the tendency to get charged more strongly, compared to materials that are more adjacent (Diaz and Felix-Navarro 2004). According to Liu et al. (2015) cotton is located in the middle, nearby steel, wood and amber on the negative side, while polyamide is not directly adjacent on the positive side of the series. Wood as
a material is not precisely specified within the series, as the used wood species is not documented in Liu et al. (2015) Regarding the results shown in Fig. 4, it appears that Liu et al. (2015) have possibly experimented with beech wood. For beech wood, the surface field strength with steel was positive at a low level, while natural fibers cause more intensely cumulated field strengths. It can be assumed that both natural fibers and cotton mainly consist of cellulose, which will behave similar during triboelectric charge transfer. TY and nylon both refer to polyamide within the TS of Liu et al. (2015), which has led to stronger positive surface field strengths for all wood species. In Fig. 4, it can be seen that only oak wood brushed with steel wires has reached a negative mean surface field strength. Therefore, in a triboelectric series that includes oak wood, the positions of steel and wood would be opposite to Liu et al. (2015).

**Machine settings effects**

To investigate the effect of brushing material (Brush), machine setting (Setting) and wood species (Wood species), an ANOVA was calculated. Within the model (Table 2) all factors showed significance, and the $R^2$ was 92.7%. For further investigation, the machine settings have been separated to brush pressure and feed rate to analyze how these factors influence the cumulated electrical surface field strength. Table 3 summarizes mean surface field strengths for each brushing material at the various machine settings separated by wood species.

There are clear differences (Table 4) between machine settings, which also explain the relative wide scattering in Fig. 4. While Table 4 concludes that the softwoods fir and spruce showed 17 out of 20, pine wood showed 16 out of 20 significant differences, the hardwoods beech and oak showed 15, respectively, 16 out of 20 significant differences between the settings. When looking at the brushing materials, nylon showed 16, TY 15, steel wire 14 and natural fiber 16 out of 20 significant differences. Therefore, neither the wood species nor the brushing materials resulted

### Table 2 Tests of between-subjects effects for cumulated electrical surface field strength

| Source                     | Type III sum of squares | df | Mean square | $F$   | Sig  |
|----------------------------|-------------------------|----|-------------|-------|------|
| Corrected Model            | 36,127.459$^a$          | 43 | 840.173     | 1128.771 | .000 |
| Intercept                  | 57,888.299              | 1  | 57,888.299  | 77,772.769 | .000 |
| Brush                      | 26,031.824              | 3  | 8677.275    | 11657.894 | .000 |
| Setting                    | 2604.032                | 3  | 868.011     | 1166.170  | .000 |
| Wood species               | 642.782                 | 4  | 160.696     | 215.894  | .000 |
| Brush * Setting            | 976.237                 | 9  | 108.471     | 145.730  | .000 |
| Brush * Wood species       | 4989.608                | 12 | 415.801     | 558.627  | .000 |
| Setting * Wood species     | 319.895                 | 12 | 26.658      | 35.815   | .000 |
| Error                      | 2858.956                | 3841 | .744       |       |
| Total                      | 98,038.595              | 3885 |           |       |
| Corrected Total            | 38,986.415              | 3884 |           |       |

$^a R^2 = 0.93$
in a distinct increase in the number of significant differences between the different machine settings. This corresponds to the results by Myna et al. (2021c) where wood species was found insignificant, meaning there was no overall difference in triboelectric charging between their investigated species spruce and beech. However, they reported differences between solid wood and wood composite materials and suggested that the used urea–formaldehyde resin as binder might be influential.

Figure 5 shows the effect of varied brush pressure (BP) and feed rate (FR) and it can be seen that an increase in brush pressure leads to an increase in cumulated electrical surface field strength, while an increase in feed rate reduces the surface field strength for all brushing materials. Pan et al. (2018) investigated the time- and load-dependence of the triboelectric effect using aluminum and copper friction pairs. They concluded that the larger normal load will yield a more stable coefficient of friction. Furthermore, if the normal load is small, the roughness is hardly removed, and the effective contact area is small and, if the normal load is larger, the roughness is suppressed (or even removed), and the effective contact area is larger. It can therefore be assumed that a larger contact area will result in a higher surface field strength. Depending on the brushing material, the increase in contact area differs due to the ability of brush bristles to bend. Even though in absolute values the effect was strongest for nylon, where the estimated marginal mean of the accumulated surface field strength increased from 5.34 kV/m for the low brush pressure, up to 7.78 kV/m for the high brush pressure, in relative values natural fiber brushes lead to the highest increase, which was as high as 1.02 kV/m at the higher brush pressure.
TY brushes have led to an estimated marginal mean increase of 1.72 kV/m at the higher brush pressure. Overall, the effect of varied machine settings was lowest for steel wire brushes, where the estimated marginal mean of field strength increase at the higher brush pressure was 1.31 kV/m.

Table 4 Level of significance ($p<0.0001$) between brushing material, machine settings and wood species AA…fir (Abies alba), FS…beech (Fagus sylvatica), PA…spruce (Picea abies), PS…pine (Pinus sp.), and QS…oak (Quercus sp.)

| Brush | Brush pressure | Feed rate | AA | FS | PA | PS | QS |
|-------|----------------|-----------|----|----|----|----|----|
| NY    | Low            | Tested variable | * | * | * | NS | * |
|       | High           | * | * | NS | * | * |
| TY    | Low            | NS | * | * | * | * |
|       | High           | NS | * | * | NS | * |
| ST    | Low            | NS | * | * | NS | NS |
|       | High           | * | NS | * | NS | NS |
| NF    | Low            | * | * | NS | NS | NS |
|       | High           | * | * | NS | NS |
| NY    | Tested variable | Slow | * | * | * | * | *
|       |                | Fast | * | NS | * | * | *
| TY    | Slow           | * | * | * | * | * |
|       | Fast           | * | * | * | NS | * |
| ST    | Slow           | * | * | * | * | * |
|       | Fast           | * | NS | * | * | NS |
| NF    | Slow           | * | * | NS | * | NS |
|       | Fast           | * | * | * | NS | *
| NY    | Low BP|slow FR→high BP|fast FR | * | NS | * | *
| TY    | * | NS | * | NS | NS |
| ST    | * | NS | * | NS | NS |
| NF    | * | NS | * | NS | NS |

Fig. 5 Interaction between brush pressure (BP—left) and feed rate (FR—right), for the different brushing materials (NY…nylon, TY…Tynex, NF…natural, fiber ST…steel)
Williams (1976) concluded that a reduced contact time is leading to a higher induced surface field strength. This would mean that higher surface field strengths occur when the feed rates are higher. However, own data show that the cumulated electrical surface field strengths tend to decline at higher feed rate. For nylon, the field strengths decreased from 7.51 kV/m at slow feet rate, to 5.63 kV/m at the fast feet rate, that is the strongest effect of all brushing materials in absolute and relative terms. TY brushes showed less effect with a decrease of 0.81 kV/m at higher feed rate setting. For the natural fiber brushes at the faster feed rate, a reduction of 0.27 kV/m was recorded for the estimated marginal mean. Once again, the decrease was lowest for the steel wire bush where at the higher feed rate a decrease of only 0.15 kV/m was measured. A faster feed rate might also lead to a higher amount of surface damages, which complicates the electrical charge transfer and therefore might be responsible for the reduced surface field strength.

### Wood species effects

In Fig. 6 it can be seen that depending on the brushing material neither softwood nor hardwood showed a higher surface field strength.

While the model predicted higher field strengths with TY and steel wire brushes for softwood, higher field strengths for hardwood were shown when brushed with nylon or natural fiber brushes. A possible explanation is that abrasive TY and steel bristles have created more friction due to the denser hardwood. Steel and heavily silicon carbide reinforced TY bristles are known to be more conductive and therefore have donated more electrons than fully insulating nylon and natural fiber bristles. Further research to fully understand this effect is needed.

![Fig. 6 Interaction graphs for species group color filtered by brushing material (NY...nylon, TY...Tynex, NF...natural, fiber ST...Steel)](image-url)
Brushing sequence effects

It was observed that the brushing sequence (no.1 to no.6) affected the cumulated electrical surface field strength. This was observed with all brushing materials, especially at the higher feed rate. The sequence drift occurred from the first to the final specimen and could still be observed after switching the brushing order (no.4, no.1, no.5, no.2, no.6, no.3). Thus, the sequence of brushing had a higher impact on the field strength than the wood specimen itself. It was observed that the cumulated field strength drift for one wood species remains proportionally constant, with different machine settings and brushing materials only the intensity of the effect changed.

It could be observed that the measured field strengths of hardwood samples showed a declining trend, while the softwoods have shown the reverse. One explanation for this could be wood abrasion. While softwoods had a strong brushing effect even with at a lower brush pressure, hardwoods showed far less abrasion. With this difference it can be concluded that the brush bristles had to bend more when brushing denser wood. As the bristles got increasingly bent with each specimen, the actual BP on the wood surface has declined and led to a reduced surface field strength. Another explanation is that the temperature has increased when the specimens were brushed one after the other. Further research including temperature recordings during brushing is needed. Greason (2000) has studied the effects of temperature and air humidity on the triboelectric charges of metal and reported a charge decrease at higher temperatures. This corresponds to the tendency observed for beech and oak wood, but contradicts the trends found for the measured softwood species.

As for the steel brush data it is noticeable that the downward drift in the measured electrical surface field strengths, as observed from specimen no1 to no6, is in part responsible for the negative cumulated electric field strengths for beech wood. Zhang et al. (2013) investigated triboelectric charging of wood particles during pellet handling processes, including the interaction between wood particles and steel plates. Negatively charged particles were observed and it was concluded that this was due to the position of wood and steel in the TS. The negative cumulated electric field strengths measured for oak wood comply with the data reported by Zhang et al. (2013).

Conclusion

Within this work it was shown that triboelectric charges can be introduced to wood surfaces and measured with a continuous setup. Charges can be introduced to the wood surfaces by mechanical friction using a brushing machine Twingo 300 B (Houfek a.s., Czech Republic). The measurements of the field strengths were possible using an EFM 115 by the company Kleinwächter® (Germany) in combination with a self-designed detection unit built using the principle of a Faraday cage. It was relatively difficult to generate meaningful generalizations on the topic of triboelectric charges of wooden surfaces by brushing.

Overall, it was shown that wooden surfaces can be electrically charged, and that the introduced charges can be influenced by applied settings. A higher brush
pressure resulted in higher surface field strengths, while a faster feed rate tended to decrease the cumulated electric field strength. While different brushing materials and varied machine settings led to a change in quantity of the field strength, the polarity of the field strength did not change.

Moreover, differences in wood species did not lead to distinct field strengths. Even though at some machine settings certain wood species showed a significantly higher field strength than others, it was not possible to indicate a clear trend including variation of machine settings.

The knowledge about triboelectric charging of wood surfaces after conventional wood finishing processes could be used in the future to facilitate better wood coating applications. It is anticipated that complex coatings will be easier to apply, and in a future project it could be investigated whether or not tribo-activated wood surfaces still require chemistry-based primer treatments. Such a “tribo-primer” would make wood manufacturing even more environmentally friendly.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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