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Research on Failure Mechanism of Abrasive Belt and Effect on Sanding of Medium-Density Fiberboard (MDF)

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Abstract: Sanding is a very important process in MDF production. In this study, abrasive belts (P60 and P120) and MDF were used to conduct sanding experiments, and mass variation, surface morphology, and surface roughness of the abrasive belts were measured to analyze the failure process of the utilized abrasive belts. It is found that the mass of the abrasive belt mainly increased in the sanding process. The increase range of P60 is mainly within the scope of 0~0.02 g, while for P120, the mass change mostly fluctuates within 0~0.01 g. The surface roughness (*S*a and *S*ku) of abrasive belts presents a down-and-up trend as sanding times increase, and *S*a and *S*ku of P60 are both larger than those of P120. Wood fibers with adhesive blocked the space among grits and led to a "grits gathering" phenomenon. When the area of "grits gathering" is larger, it forms an abrasive belt "blocking". Grit wear (dropping-off, fracture) and "blocking" constitute the two predominant patterns of the failure mechanism. This study is helpful to further improve wood-material-sanding theories, provide insights to investigate wear forms of other abrasive belts, and determine and extend the life of abrasive belts.

Keywords: medium-density fiberboard; sanding; abrasive belt; failure mechanism

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1. Introduction

Medium-density fiberboard (MDF) is a kind of versatile wooden composite material widely used in furniture manufacturing, construction, packaging, and other fields [1–3]. Sanding is used for thickness calibration, inhomogeneity smoothing, and surface polishing [4,5], which play an important role in MDF and MDF products manufacturing [6].

Some problems during MDF abrasive-belt sanding are hard to solve, such as the inconsistency of theoretical and actual calibrating thickness, short lifespan of abrasive belt, low sanding efficiency, burnt surface, poor surface accuracy, and so on [7]. The main reason is the abrasive belt losing its sanding ability.

Sanding ability includes two aspects: material-removal ability and surface-smoothing ability. Most of the time, these two kinds of abilities do not reach the limitation at the same time. The combined action of grit dulling and chip-space narrowing results in the failure of the abrasive belt [8]. The failure mechanism varies for materials due to different sanding mechanisms.

For metallic and brittle materials, the surface-creation process can be generally divided into three stages, namely rubbing, ploughing, and cutting [9]. In the rubbing and ploughing stages, the material-removal efficiency is relative to the wear width on the rake face (a grit can be simplified as a blade), and the grit fracture and abrasion of cutting-edge corners can improve the material removal to a certain extent [10]. The abrasive belt presents different wear forms at each sanding stage, which means the abrasive-belt wear mechanism is relatively complicated [8,11]. The wear modes of abrasive-belt grinding generally contain abrasion, chipping, and pull-off [12]. After grinding for a period of time, the blades of abrasive grits are continuously blunted, and the grits originally at the bottom gradually

start to participate in grinding [13]. Theoretical models can be established to analyze the influence of radial force, abrasive shape, and other factors on grinding efficiency and chip formation, as well as to predict abrasive belt wear and failure [14–16].

However, as a kind of natural-fiber composite material with porosity and heterogeneity, the ploughing stage of wood material is not obvious or even does not exist; instead, the densification stage occurs and cannot be neglected [17]. Moreover, the removal mechanism of wood material is not similar to metallic material, and the density and porosity variations exert visible influence on the surface creation [18,19]. Fiber bundles of high-porosity wood species are mainly faced with a compressive crush, while tensile rupture is the general pattern for low-porosity wood [19]. Wood defects (knots, decay, annual ring irregularities, etc.) are common in sawn wood, and the porosity and density of areas around the defects is different from the typical structure areas [20]. Sanding improves the surface quality of wood veneers with defects, and makes them equally valuable [20,21]. Thus, the dulling process of grits deteriorates due to the increased frictional force between grits and wood material. From the viewpoint of the wear mechanism, there are generally three basic wear forms of abrasive grit: pull-out, fracture, and abrasion [8]. Fracture and abrasion were the predominant wear patterns of the involved grits. Abrasion is the result of the friction between the cutting edge and wood [22]. Cutting with a negative rake angle leads to large chip-removal resistance, hence the front blade surface will be subjected to greater friction and abraded easily.

Moreover, for some wood materials containing glue, such as MDF, the chip adheres more easily to the chip space and is harder to flow away. Adhesive in chips will be softened when the temperature rises during sanding. The softened adhesive covers the fiber and adheres to the abrasive grits, filling the sanding gaps and resulting in a so-called "blocking" effect [23,24]. This effect will reduce the removal ability of the abrasive belt and increase the sanding force and temperature [25,26]. In the early stage of sanding, there is sufficient space for containing chips. The small gaps of the abrasive belt are gradually blocked during sanding. At the end of sanding, the blocking is serious and the abrasive belt fails to remove the workpiece material [27].

At present, there are few studies on the abrasive-belt failure mechanism of wood materials, and the failure process of the abrasive belt is not clear, which is not conducive to finding methods to slow abrasive-belt failure and acquiring an accurate abrasive-belt lifespan. Given this, the sanding experiment on MDF was carried out to explore the failure mechanism of the abrasive belt. The obtained results can provide theoretical support for determining the lifespan of the abrasive belt and developing abrasive-belt sanding technology suitable for wood materials.

2. Materials and Methods

2.1. Materials

Medium-density fiberboard (MDF) with an air-dry density of 0.73 ± 0.05 g/cm^3 and an equilibrium moisture content (EMC) of about 11% was selected to prepare samples in this study. The selected MDF boards were bought from a factory in the same batch, and they were sawn into samples with the same dimensions of 50 mm (L) × 40 mm (W) × 40 mm (H). The surface of samples was smooth without obvious defects. The samples were replaced when sanded for a certain number of times (2000 times), to eliminate the influence of density change along MDF thickness direction.

Ordinary cloth-based and closed-coating abrasive belts with brown alumina grits (P60, granularity is 60; P120, granularity is 120) were used in the study. A large enough dimension of abrasive belt, 300 mm (L) × 60 mm (W), results in MDF uniform sanding.

2.2. Equipment

As shown in Figure 1, the experimental device is mainly composed of a driving mechanism that makes the workbench perform a linear reciprocating motion and a pneumatic device that provides constant sanding pressure. The samples were placed in the fixture

and tightened by adjusting the lock nut. The abrasive belt was flattened and fixed under compression device by adjusting the tensioners on both sides. A rubber pad was placed between the compression device and the belt. The vertical cylinder with linear guides (ADNGF-50-40-A, FESTO, Esslingen am Neckar, Germany) provided a constant sanding pressure of 100 N for the samples. As the sample material was continuously removed, its thickness decreased gradually, and the abrasive belt could move down along the vertical slide rail within the stroke of the cylinder guide rod, so that the abrasive belt was always in contact with the sample surface. The drive system is a crank slider mechanism driven by a motor. When the motor rotates, it drives the connecting rod to rotate and make the sample move. The sample reciprocated on the horizontal rail with an average moving speed of 0.3 m/s. When the sample returned, the compression device was lifted to ensure one-way sanding of the sample. The photoelectric counter completed the recording of the sanding times. The sample reciprocated once and the counter counted 1 time of sanding (one-way).

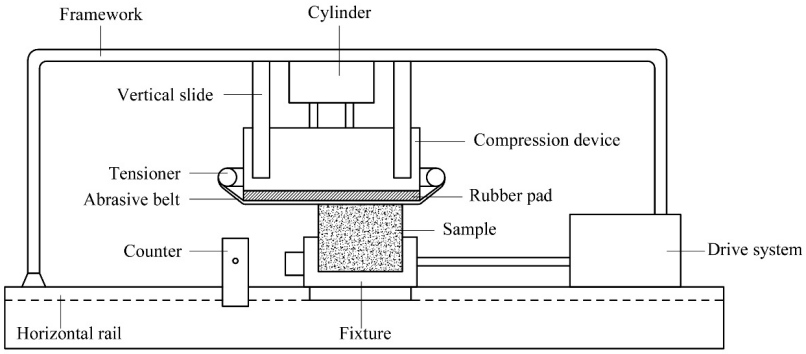


Figure 1. Schematic diagram of abrasive-belt sanding device.

2.3. Mass Variation of Abrasive Belt

During the MDF sanding experiment, precision analytical balance (BSA4235, Sartorious, Göttingen, Germany) was used to weigh abrasive belt per 2000 times of sanding. In addition, the mass change of abrasive belt was determined. In order to improve the measurement accuracy, a high-pressure air gun (rated pressure 3.0 MPa) was used to remove chips on the surface of abrasive belt before each mass weighing.

2.4. Surface Morphology of Abrasive Belt

After every 2000 sanding times, 3D surface profilometer (VR5000, KEYENCE, Osaka, Japan) was used to scan the central part (24 mm × 18 mm) of the surface of abrasive belt with a Z-axis resolution of 1 μm, and the subsequent measurement positions were consistent. Then, surface roughness was measured with the matched professional analysis software (VR Series version 3.2.0.277, KEYENCE, Osaka, Japan). Scanning electron microscope (Hitachi S-3400N, Tokyo, Japan) was used to analyze surface morphology of abrasive belt.

In this study, in order to better observe the surface flatness and abrasive grits' sharpness, following the previous research on wear characteristics of abrasive belt [8], the surface roughness can be characterized by two parameters according to ISO 25178-2 (2012):

1. *S*a: arithmetical mean height of the scale-limited surface, which means the arithmetic mean or geometric mean of the distance between the point within the outline and the center plane. When the height distribution and frequency tend to be consistent, the *S*a is lower, and when the height distribution and frequency consistency is weaker, the *S*a is higher. In other words, a low *S*a means a good surface flatness.
2. *S*ku: kurtosis of the scale-limited surface. Its figure can judge the sharpness of the grits. The higher the *S*ku, the sharper the distribution of girts; the lower the *S*ku, the flatter the distribution. In general, when *S*ku < 3, the height distribution is higher to the mean surface; *S*ku = 3, the height distribution is regular (sharp and slow parts coexist); *S*ku > 3, the height distribution is extremely sharp [28].

The calculation formulas of these parameters can be expressed as:

$$Sa = \frac{1}{A}\iint_A |z(x,y)|dxdy \quad (1)$$

$$Sq = \sqrt{\frac{1}{A}\iint_A z^2(x,y)dxdy} \quad (2)$$

$$Sku = \frac{1}{Sq^4}\left[\frac{1}{A}\iint_A z^4(x,y)dxdy\right] \quad (3)$$

where A means the measurement area, x and y represent the boundary of the measurement area, z (x, y) refers to the machined surface height.

3. Results and Discussion

3.1. Mass Variation and 3D Morphology of Abrasive Belt

With the increase in sanding times, the abrasive belt did not lose quality for grit wear, as shown in Figure 2. On the contrary, the quality of the abrasive belt increased in most cases. For P60, the mass variation of the abrasive belt had certain randomness, and the change trend was not particularly obvious. The mass of P60 basically increased in the sanding process, and the increase range was mainly within 0~0.02 g. For P120, the mass increase in the abrasive belt was large at the beginning, and gradually decreased with the increase in sanding times. The mass change of P120 mostly fluctuated within the scope of 0~0.01 g.

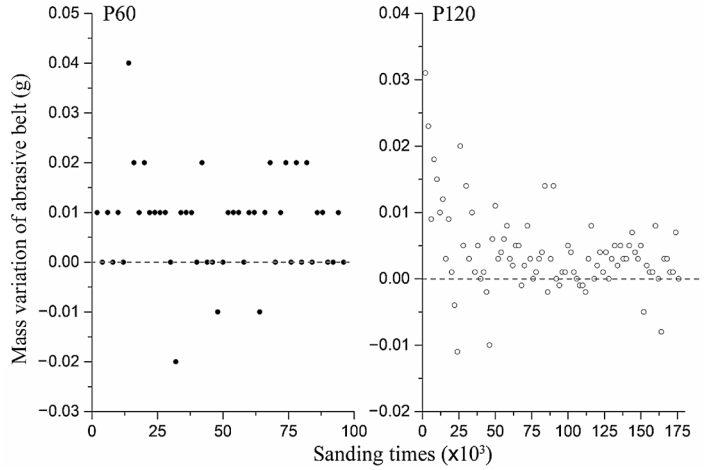


Figure 2. Mass variation of abrasive belts (P60 and P120) during MDF sanding.

As can be seen from Figure 3, the maximum grit-protrusion height of the initial abrasive belt of P60 is about 0.23 mm. Before 40,000 times, the maximum grit-protrusion height decreased significantly, while the changing range thereafter was not that significant. The height consistency of the new abrasive belt was not good. It can be clearly seen that the area with high points on the abrasive belt was formed from single or multiple grits. As sanding times increased, the abrasive grits adjacent to the high points were gradually connected, and the area of grits in the cluster gradually expanded, forming new "grits gathering" high points. This phenomenon became more and more significant as sanding times increased. In the sanding process, the abrasive grit wear caused the evident decrease in the maximum grit-protrusion height of the abrasive belt. Moreover, the fiber chips stuck to the adhesives of the abrasive belt during MDF sanding, and became worse with further "grits gathering". The overall mass increase in the abrasive belt indicated the predominance of the "grits gathering" phenomenon in this case.

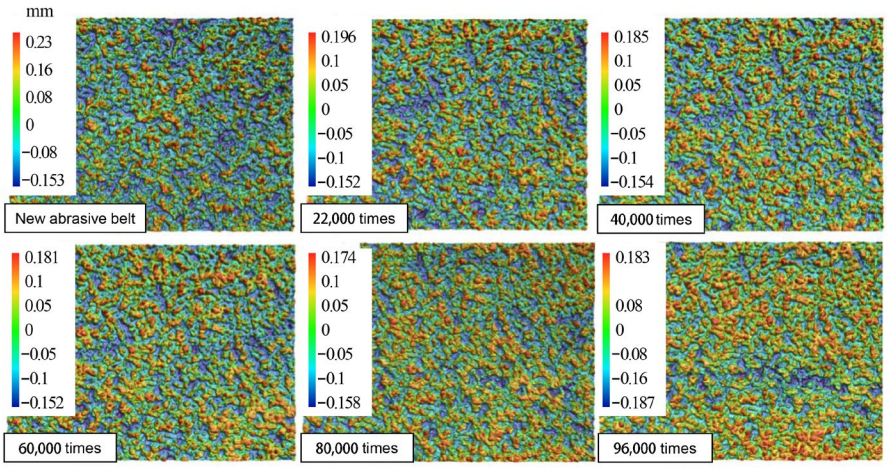


Figure 3. Surface topography of abrasive belt (P60) in MDF sanding.

It can be seen from Figure 4 that the maximum grit-protrusion height of the initial abrasive belt of P120 is about 0.15 mm. Before 25,000 times, the maximum grit-protrusion height decreased significantly with the increase in sanding times, while the change range was not big after that. P120 had a certain amount of the "grits gathering" phenomenon at the initial high point, but the boundary between abrasive grits was relatively clear. With the sanding times increasing, the "grits gathering" diffusion was more significant and had an obvious directionality.

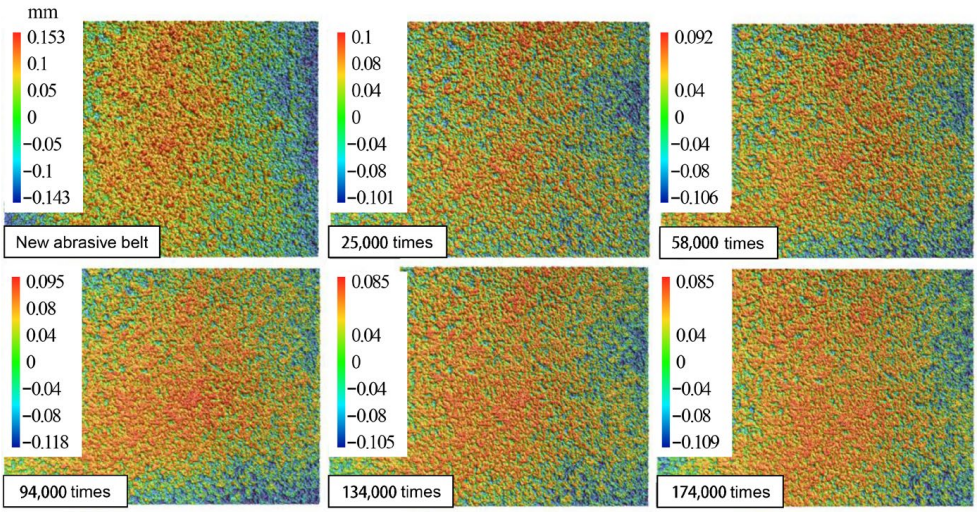


Figure 4. Surface topography of abrasive belt (P120) in MDF sanding.

As the density of the coating grit increases, the "grits gathering" effect becomes more pronounced. The coating grit density of P120 is higher than P60, and the dispersion of P120 grit is worse than P60 grit. The small chip space of P120 makes it easier to be blocked up. Therefore, the abrasive grits tend to clump together because of the action of the adhesive, which makes P120 have a significant "grits gathering" high point in the initial stage. With the sanding times increasing, the "grits gathering" phenomenon becomes more significant. Similar to P60, the "grits gathering" phenomenon has more influence than the wear mass loss, resulting in the overall mass increase in P120. Though the mass increase in P120 is great at the beginning, with "grits gathering" and chip space narrowing, the abrasive belt was gradually blocked up and the mass growth gradually decreased.

The "grits gathering" phenomenon increases the equivalent size of the cutting edge and affects the sanded surface to a certain extent. Dispersed initial abrasive grits means that the equivalent size of each cutting edge is small. As shown in Figure 5, a small equivalent

size of cutting edge would leave sharp and slender marks on the sanded surface. When the equivalent size of the cutting edge becomes larger, the tip angle of the cutting edge is larger, which means a larger negative rake angle, flattening the wood fibers on the sanded surface. When the equivalent size of the cutting edge is too large, friction between the sample and the cutting edge is dominant. When the surface fibers of MDF sample were crushed to a certain degree, they were violently rubbed, causing the wood fibers to be pulled and warped [19]. Thus, the "grit gathering" phenomenon shows significant influence on the cutting mode and surface-creation process. With the area of "grits gathering" becoming larger, the space among abrasive grits was increasingly blocked and resulted in abrasive-belt failure in MDF sanding.

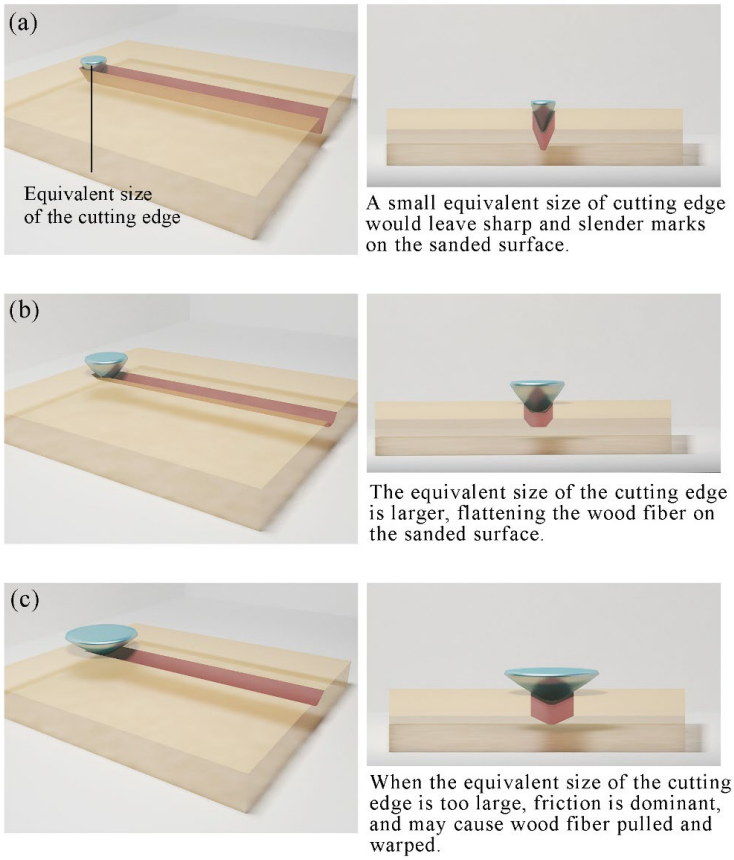


Figure 5. Surface morphology with different equivalent cutting-edge sizes: (**a**) small equivalent size; (**b**) large equivalent size; (**c**) excessive equivalent size.

3.2. The SEM Morphology and the Surface Roughness of Abrasive Belt

There are generally three patterns for abrasive-belt wear [8]. As shown in Figure 6, the fracture and pull-out of abrasive grits are the two main wear patterns in this study, which are more significant than the abrasion. The wear behavior of P120 is basically the same as that of P60 according to SEM images observed by Zhang et al. [8]. With respect to new abrasive belt, the abrasive grits are wrapped in adhesive and adhered to the abrasive-belt substrate. The cutting edges of abrasive grits are not directly exposed, and there are brittle cracks observed in the adhesive coating (Figure 6a,b). In the early stage of MDF sanding, some of the abrasive grits which bore large cutting forces were pulled out due to their large sizes and relatively high height. This was manifested as a partial rupture of the surrounding adhesive coating (Figure 6c). There were also some abrasive grits with lower penetration depth in the substrate. They were vulnerable to falling off during the MDF sanding process because of the subsequent weak adhesion, leading to the slight damage to the adhesive coating (Figure 6e). As sanding process continued, the height consistency of the abrasive grits became better than that in the early stage, and the cutting force on each

abrasive grit was more uniform. In this circumstance, some low-strength abrasive grits tended to be broken (Figure 6d). In addition, there were some abrasive grits that did not participate in the entire sanding process (Figure 6f).

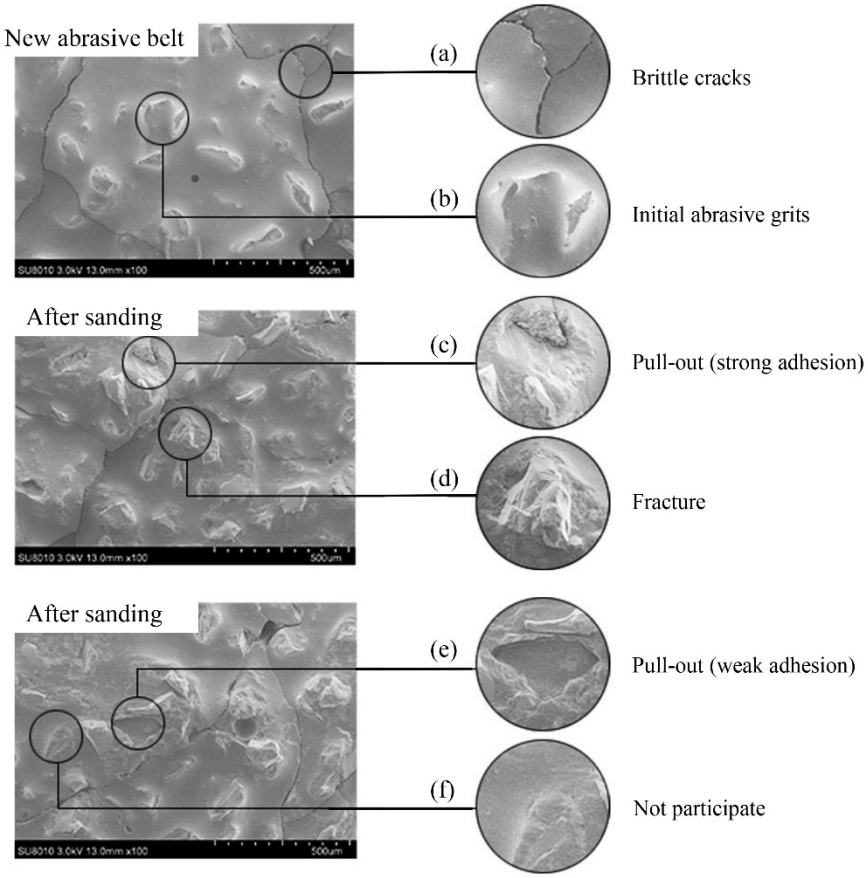


Figure 6. Typical wear behavior of abrasive-belt (P120) surface before and after MDF sanding through SEM observation. (**a**) brittle cracks in the adhesive coating; (**b**) initial abrasive grits wrapped in adhesive; (**c**) pull-out of abrasive grits with strong adhesion; (**d**) broken abrasive grits; (**e**) pull-out of abrasive grits with weak adhesion; (**f**) abrasive grits not participated in sanding.

Poor height consistency of abrasive-grit protrusion is equal to fewer abrasive grits involved in MDF sanding. The involved grits are subjected to greater stress concentration, performing a stronger material-removal ability. However, the sanding-removal efficiency does not improve by the reason of the small number of the involved grits. The height consistency of abrasive grits also has a significant effect on surface roughness of samples, which is taken as the principal quality indicator of the sanding process [29]. In the early stage of sanding, the surface roughness value of the workpiece was relatively big. In the mid-stage of sanding, when the height consistency of the abrasive grits was better, the surface roughness value of the workpiece was small and relatively stable. When the grit wear was severe, the abrasive belt slowly lost its cutting ability. In this case, the surface roughness of the workpiece would increase and even machining defects would appear, such as surface burning [6].

Overall, the average value (X) for Sa and Sku of P60 are both larger than that of P120 as shown in Figure 7, while the standard deviation (σ) for Sa and Sku of P60 are both smaller than that of P120.

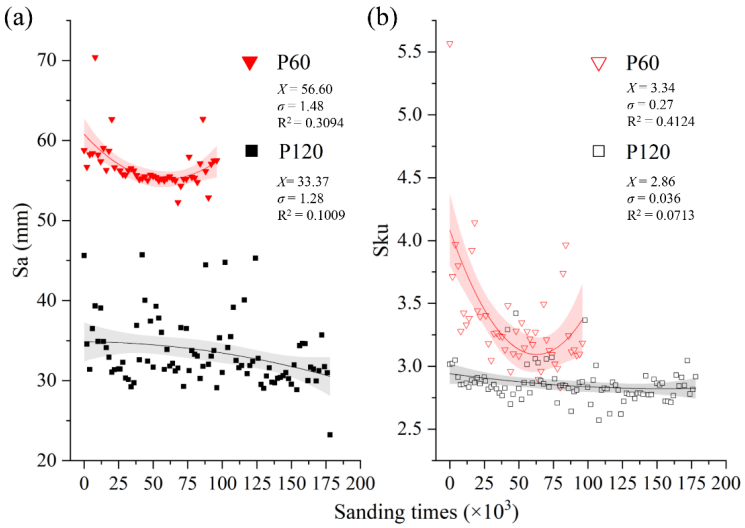


Figure 7. Surface roughness of abrasive belt during MDF sanding: (**a**) *Sa*; (**b**) *Sku*. Where *X* means the average value of surface roughness, σ means the standard deviation of surface roughness, R^2 means the correlation coefficient of quadratic fitting.

Seen from Figure 7a, the *Sa* of abrasive belts presents a down and up trend with the increase in sanding times. For P60, when the sanding times are from 0 to 70,000, the *Sa* gradually decreases. When the sanding times exceed 70,000, the *Sa* begins to increase, while the *Sa* of P120 is unstable and its change trend is not significant.

In the early stage of MDF sanding, the height consistency of the abrasive belt was poor, which is related to its process of coating grit, so the new abrasive belt had a relatively high *Sa*. In addition, because P120 has a higher density of coating grit and a better height consistency than P60, for *Sa*, the *X* of P120 was smaller than P60. As the sanding times increased, some abrasive grits with extremely great protrusion height would fall off or fracture, and their height consistency became better, leading to a smaller *Sa*. Due to a poorer height consistency, *Sa* of P60 decreased more significantly, and σ of P60 was slightly larger than P120. During sanding, the tiny fibers of MDF filled the gap between the abrasive grits or cover the grits. Although a high-pressure air gun was used to remove sanding dust on the surface of the abrasive belt in this study, there were still some fibers containing adhesive that could not be removed completely. On account of its high density of coating grit, the "grits gathering" effect of P120 is more serious than P60. Therefore, the *Sa* of P120 is unstable and is greatly affected by "grits gathering". For P60, the influence of "grits gathering" on *Sa* is mainly reflected in the late stage of sanding. When the "grits gathering" effect is extremely serious, the chip space of the abrasive belt is not enough and the equivalent size of the cutting edge increases. Then, the fibers containing adhesive cover the abrasive grits, which can be called "blocking" and results in the increase in *Sa*.

As shown in Figure 7b, the *Sku* of abrasive belts decreases firstly and then increases, which is similar to the regular pattern of *Sa*. Most *Sku* of P60 are greater than 3, while those of P120 are less than 3. Thus, for *Sku*, *X* of P60 is larger than P120.

For P60, most of the time, the height distribution of abrasive grits is as sharp as needles (*Sku* > 3), which have good sharpness. However, the abrasive-grit sharpness of P120 is poor. With the increase in sanding times, the *Sku* of P60 decreased sharply, but it increased at around 75,000 sanding times. The *Sku* of P120 will have random fluctuations during the sanding process. In the sanding process, the abrasive grits will continue to break and produce new cutting edges. This phenomenon is called "self-sharpening" [4], which causes the *Sku* to fluctuate continuously. P60 has larger abrasive grits than P120, but the size of the new cutting edge produced after self-sharpening is smaller than P120. Therefore, the *Sku* of P60 is significantly reduced, which makes σ of P60 for *Sku* much larger than that of P120. Under the same pressure, the broken proportion of P120 is smaller than P60, so

its self-sharpening effect is poorer than P60. Moreover, the blocking of the P120 is more significant than that of P60, so its *S*ku is relatively stable.

The surface morphology and the surface roughness of the abrasive belt reflect the wear process of abrasive-belt sanding. The failure mechanism of the abrasive belt can be obtained through the influence of the grit wear and blocking on the surface roughness of abrasive belt.

4. Conclusions

The failure mechanism of the abrasive belt has been discussed by the means of the MDF sanding experiment and the analysis of the abrasive belt's mass variation, surface morphology, and surface roughness. The main findings can be summarized as follows:

1. With the sanding times increasing, the abrasive-belt mass mainly increased and the mass variation trend is not significant.
2. The initial maximum grit-protrusion height of abrasive grits for P60 is about 0.23 mm, and about 0.15 mm for P120. The maximum grit-protrusion height of abrasive grits dropped significantly in the early and mid stage of sanding, and remained basically constant in the late stage. As the sanding times increased, the "grits gathering" phenomenon appeared on abrasive grits adjacent to the high point, and this phenomenon is more obvious for P120.
3. The *S*a and *S*ku of P60 are larger than those of P120. When the sanding times increase, the *S*a of P60 first decreases and then increases, but the Sa of P120 does not change significantly. Most of *S*ku (P60) were greater than 3, while lower than 3 for P120. P60 had a significant self-sharpening effect.
4. With the increase in sanding times, the scope of "grits gathering" becomes larger, eventually leading to the severe "blocking" phenomenon. "Blocking" and grit wear are the predominant patterns in the failure mechanism of the abrasive belt. The height consistency of abrasive grits and the density of coating grit both have an important influence on abrasive-belt wear, failure, material removal, and surface-processing quality.

The abrasive-belt failure mechanism is a fertile area for the research of the abrasive-belt lifespan, and the approaches used in this study could provide insights to investigate wear forms of other abrasive belts and to extend the lifespan of the abrasive belt. However, further research is needed to fully explore the failure mechanism of different abrasive belt types and wood species, and the features of the abrasive belt suitable for wood materials.

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Conflicts of Interest: The authors declare no conflict of interest.

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