Effect of Wood Microstructure on the Quality of Gas-assisted Laser Cutting of Cherry

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To improve the processing quality of wood products, the effects of different wood microstructure on the cutting quality of cherry wood were studied in the experimental process of gas-assisted laser processing. Based on the absorption ability of wood relative to laser wavelength, the composite processing of CO_2 laser and inert gas was carried out. Kerf width and surface roughness were used as evaluation indexes, with analysis by factor experiments. The results showed that under the same parameter conditions, due to the difference in internal structure of wood, the cavity structure in the tracheid was more conducive to the diffusion and absorption of laser energy during perpendicular cutting. In addition, the kerf width and surface roughness of parallel cutting were smaller than that of perpendicular cutting. The microscopic morphology and surface carbon content of the kerf surface showed that during perpendicular cutting, due to the plugging effect of small holes, heat accumulation was not conducive to the flow of flue gas and carbide; thus carbon particles remained in the tracheid, and the carbon content of kerf surface was higher.

DOI: 10.15376/biores.18.4.7202-7211

Keywords: Gas-assisted; Laser cutting; Texture structure; Quality of cutting kerf; CO_2 *laser*

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INTRODUCTION

China is the largest production base and processing exporter of wood products in the world. Under the background of stable macroeconomic operation, the demand for wood industry products is growing rapidly (Penín *et al*. 2020). Wood products are favored in home decoration and other fields due to their rich style and elegant appearance (Ollonqvist 2011; Yang *et al*. 2016; Macak *et al*. 2020). At present, the comprehensive utilization rate of wood in the developed forestry countries has exceeded 80%, and the utilization rate of China is 63% (Tayal *et al*. 1994; Olakanmi *et al*. 2015). Due to the large gap, it is important to innovate the processing and production mode. Laser cutting is a kind of flexible non-contact machining method, which has the advantages of high machining precision, narrow incision width, low operating cost, and small area that is affected by thermal stress. Compared with traditional machining methods, the cutting speed of laser processing is very fast. Local heat treatment of parts can be carried out, and complex shapes and small parts can be processed. In addition, it is easy to realize automation by combining laser technology with computer technology.

Laser processing can overcome limitations of traditional tool geometry so that the selection of processing materials in material, size, shape, and processing links and other factors has great freedom and excellent control of space and time (Fukuta *et al*. 2016).

Therefore, it is widely used in material surface treatment, cutting, engraving, punching and micro-surface processing. However, the burning temperature of wood is low. Combustion reactions usually occur between 250 and 300 °C, which is affected by beam mode and laser output power. When the high energy laser beam impinges on the material, the beam power density in some irradiated areas is lower than the energy required for material vaporization, and the heat-affected zone increases due to combustion reaction on wood processing surface (Li *et al*. 2011; Jiang *et al*. 2016; Gaff *et al*. 2020). Serious carbonization phenomenon not only affects the physical properties and visual beauty of wood, but also affects the surface quality of wood products due to the increase of surface roughness caused by carbonization. Many factors limit the application of this technology in the field of wood processing (Yilbas *et al*. 2000; Kutsuna and Marya 2003).

To reduce the defects of laser processing, gas-assisted processing was combined with laser processing technology. The auxiliary gas serves as the only substance in contact with the workpiece, and the physical properties and flow characteristics of gas are used to protect the processing interface and achieve high quality processing of materials (Barcikowski *et al*. 2006; Flaviana *et al*. 2013; Li *et al*. 2018). To verify the advantages of gas-assisted laser processing wood, the authors conducted a preliminary study of 0.5 mm thick veneer (Liu *et al*. 2020). The results showed that, due to the protective effect of an auxiliary gas jet, the kerf width and carbonization area were reduced significantly. At the same time, due to the strong quenching ability of inert gas, the kerf was relatively straight and the inside of the tracheid was relatively smooth through scanning electron microscopy (Liu *et al*. 2020). Based on the above theoretical basis, the effect of auxiliary gas on the processing quality of wood veneer with a certain thickness during laser processing was studied in the present work. Laser power, cutting speed, and gas pressure were selected as processing parameters. The kerf width and surface roughness as evaluation indexes, and the influence law of different texture structure on cutting quality were analyzed by factor experimentation. The selection of processing methods in the practical application of laser processing wood are provided as a theoretical reference.

EXPERIMENTAL

Transmission Process of Laser Energy

The physical basis of laser processing is laser energy conversion and absorption of that energy by the material. Wood is an anisotropic and porous material. Laser absorption is uneven on the surface of wood when laser is used to process wood; as a result, the laser beam exhibits multiple and repeated absorption and reflection behaviors in the kerf (Gao 2015; Lorenz *et al*. 2015; Guo *et al*. 2021). Figure 1 shows the process of multiple reflections of the laser beam in the kerf.

At the initial stage, the wood surface was irradiated by laser beam and heated mainly by heat conduction. At this time, the absorption of heat was mainly Fresnel absorption, most of the laser energy was reflected off the wood surface, and the utilization rate of laser energy was very low (Kačík *et al*. 2006; Gao 2019). With the continuous increase of irradiation time, small incisions were gradually formed on the wood surface. Due to the change of radial vaporization flux caused by laser intensity distribution, a certain pressure gradient $\bar{F}$ was formed on the kerf surface, and the laser energy was reflected by the kerf wall many times before reaching the bottom (Kubovsky and Kacik 2009). In the reflection process, part of the laser energy would be absorbed by the plasma that was generated by ionization in the kerf and the kerf wall, and a certain depth kerf would be formed with the relative motion of the laser beam and the wood workpiece (Arshed *et al*. 2014; Zimmermann *et al*. 2019).

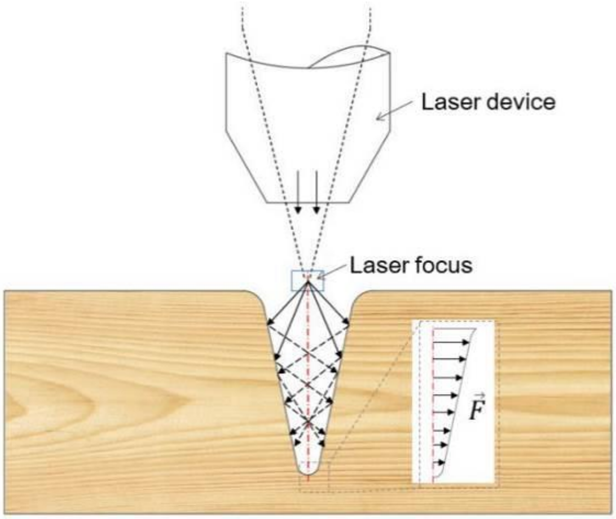


Fig. 1. Multiple reflection process of laser beam in slit

Thus, in the process of laser cutting wood, the laser energy presented a gradual attenuation trend. Affected by the texture structure of wood, when cutting along the fiber, the laser beam passed through an aggregate of numerous fiber bundles in the direction of the grain, and when cutting cross the fiber, the laser beam passed through the wood ray composed of thin-walled cavity tissue. Because of the difference in the wood's local structure, the size of the kerf in different cutting directions was inconsistent. Therefore, it is necessary to consider both the direction of parallel cutting and perpendicular cutting in order to obtain the optimal processing size.

Materials and Methods

Cherry (*Prunus serotina*) wood was selected as the test material. Cherry wood is a highly valued wood with moderate hardness, fine and clear texture, and tight particles. The samples size was 120 mm × 80 mm × 2 mm (length × width × thickness). The moisture content was 11%, and the dry air density was 0.85 g/cm^3. At the early stage of the experiment, the surface of the sample was polished by 240# sandpaper to ensure that the surface of the wood was smooth, without cracks, blemishes, knots, decay, and other defects. Table 1 shows the technological parameters of factor experiments.

Table 1. Process Parameters of Gas-assisted Laser Processing of Cherry Wood

Process Parameters	1	2	3	4	5	6	7
Laser power (W)	30	35	40	45	50	55	60
Cutting speed (mm/s)	25						
Gas pressure (MPa)	0.1						

Whether the wood could be cut with a laser depended on whether the laser wavelength could be better absorbed. The study showed that cellulose molecules in wood have the strongest absorption capacity in the range of 8.30 to 10.00 μm for laser wavelength, and the wavelength of CO_2 laser is 10.6 μm, which is closest to the wavelength absorption range of cellulose molecules. Compared with fiber lasers and YAG lasers, CO_2 lasers are more suitable for cutting non-metallic materials. The CO_2 laser also uses continuous emission, which can provide a smooth cutting surface, good cutting quality, and low purchase cost.

The effects of wood moisture content, processing heat value, and thermal conductivity were considered. A CO_2 laser cutting machine (Jinan Baomei Technology Co., LTD., China) was used in the experiment of gas-assisted laser processing wood. Figure 2 shows the equipment for gas-assisted laser processing wood. The wavelength of the CO_2 laser was 10.6 μm, the rated power of laser was 80 W, the maximum cutting speed was 200 mm/s, and the focal length of lens was 63.5 mm, which provided a focus spot diameter of 0.1 mm. The auxiliary gas was industrial helium with purity ≥99.999%. The gas flow was regulated and stabilized through the pressure reducing valve, and then it entered the nozzle through the guide pipe and jet to the wood surface coaxial with the laser beam. The auxiliary gas pressure at the nozzle could be up to 2.5 MPa. The laser beam was reflected and focused by the optical system and entered the processing area. The relative position of the gas-assisted laser processing device and the processed wood was controlled by a private motor driven X-direction and Y-direction feed system.

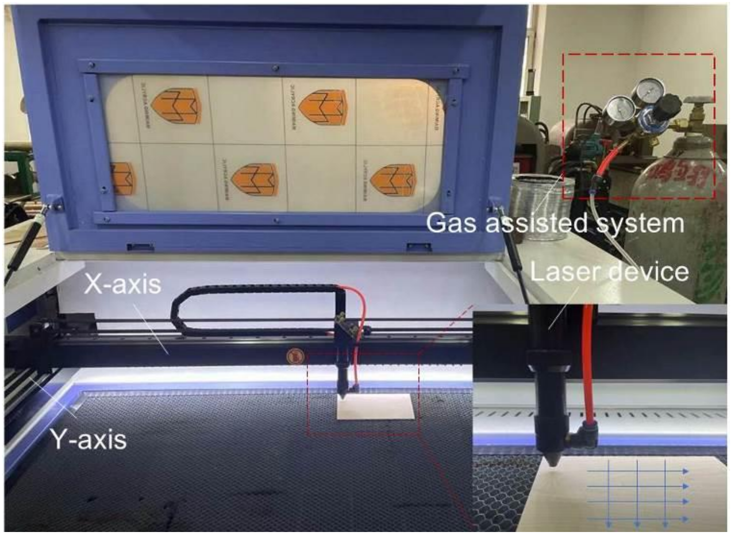


Fig. 2. Gas-assisted laser processing equipment

The auxiliary gas was introduced through the nozzle and uniformly ejected to the wood surface with the laser beam coaxial. This allowed for the synchronization of the laser beam and the auxiliary gas. Laser cutting was carried out along the two directions of parallel cutting and perpendicular cutting, and the influence of wood texture direction on processing quality was analyzed. The cross section of cherry wood specimen cut by gas-assisted laser was measured by optical microscope. The width of the top and bottom of the kerf was measured, and the average value was taken as the kerf width. The upper surface roughness of molded parts under different process parameters was measured by Axio Scope.A1 laser microscope (Zeiss GMBH). In order to ensure the accuracy of measurement results, each incision was measured three times, and its average value was taken. FEI Quanta200 scanning electron microscope (Hillsboro, OR, USA) was used to observe the micro-morphology of wood incision section under different cutting methods and analyze the surface principal component.

RESULTS AND DISCUSSION

Influence of Texture Direction on Kerf Width

Figure 3 shows the influence of laser process parameters on the kerf width of gas-assisted laser processing wood in two ways: parallel cutting and perpendicular cutting. When the cutting speed was constant, the kerf width increased with the increase of the laser power, regardless of whether it was parallel cutting and perpendicular cutting. This was attributed to the fact that when the laser power was low, the laser irradiated on the wood surface and transferred less heat, wood removal was relatively reduced, so the kerf width was small. With the gradual increase of laser power, the heat generated on the wood surface accumulated rapidly, and the temperature rose rapidly to the effective boiling point of the biomaterial to vaporize the wood. The wood ablated at the kerf increased, the kerf width also increased, and the heat affected zone around the incision increased.

By magnifying the kerf with a microscope at 200X, when the laser power was 30 W and the cutting speed was 25 mm/s, the minimum kerf width of the parallel cutting of gas-assisted laser processing wood was 0.27 mm, and the minimum kerf width of the perpendicular cutting of gas-assisted laser processing wood was 0.36 mm. The kerf width of the parallel cutting of gas-assisted laser processing was obviously smaller than that of perpendicular cutting, and it could be clearly seen that the carbonization phenomenon near the incision had been significantly improved. Thus, the carbonization layer was smaller, and the color difference varied greatly. These effects were attributed to differences in the internal structure of the wood. When cutting along the grain, the moving direction of the laser beam was the same as the direction of the wood texture, and the smoothness of the kerf was better. When cutting across the grain, as the wood was mainly composed of tracheids, the cutting angle of the laser beam was perpendicular to the wood fiber, which was more conducive to the diffusion and absorption of laser energy. As a consequence, the kerf width was relatively large.

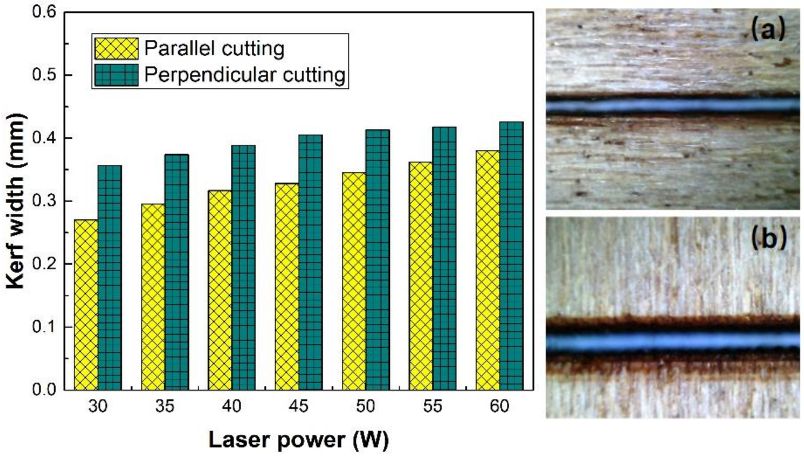


Fig. 3. Influence of laser parameters on kerf width: (a) parallel cutting (b) perpendicular cutting

Influence of Texture Direction on Surface Roughness

Figure 4 shows the influence of laser parameters on the surface roughness of gas-assisted laser processing wood in the process of parallel cutting and perpendicular cutting. When the cutting speed was constant, the surface roughness increased with the increase of laser power, no matter whether parallel cutting and perpendicular cutting was being done. This was because when the laser power was low, the laser energy acting on the wood surface for heat transfer was less, the ablative ability of the wood at the kerf was weakened, the surface roughness of the kerf was better, and consequently the surface roughness was small. With the increase of laser power, the energy acting on the wood surface accumulated rapidly in unit time, and the heat at the cutting kerf was too large to be absorbed timely and fully, which led to burning. Thus, a large amount of carbide and residue formed on the kerf surface, so the surface roughness also increased.

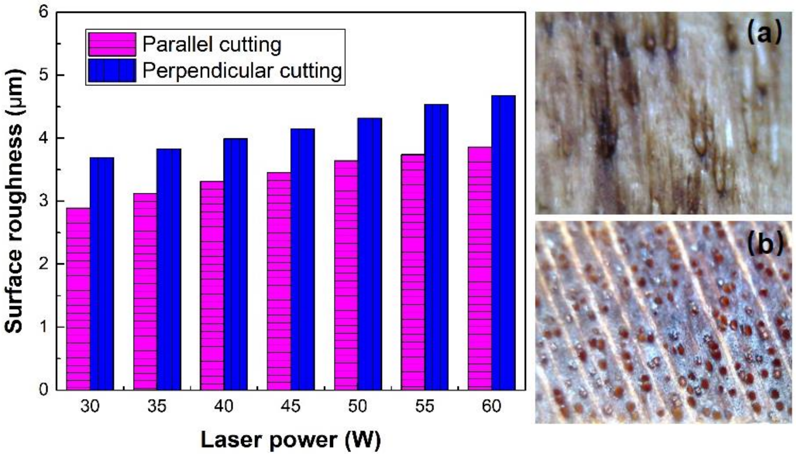


Fig. 4. Influence of laser parameters on surface roughness: (a) parallel cutting (b) perpendicular cutting

When the laser power was 30 W and the cutting speed was 25 mm/s, the minimum surface roughness of the parallel cutting of gas-assisted laser processing wood was 2.89 μm, and the minimum surface roughness of perpendicular cutting of gas-assisted laser processing wood was 3.69 μm. The surface roughness of the parallel cutting of gas-assisted laser processing was obviously smaller than that of perpendicular cutting. This was attributed to the fact that the perpendicular cutting was more conducive to the absorption of laser energy, and at the same time, the wood as a cavity structure which composed of tracheid, due to the disordered and complicated structure of the pores, the residue and carbide after vaporization were not easy to discharge and accumulate in the pores under the action of air flow, which led to greater surface roughness of the wood during the perpendicular cutting.

Influence of Texture Direction on Surface Carbon Content

Figure 5 shows the micro-morphology of gas-assisted laser processing wood in the process of parallel cutting and perpendicular cutting. As can be seen from the figure, when cutting along the grain, the flame-retardant area was formed on the kerf surface due to the flame-retardant effect of helium, which prevented the combustion reaction. There was almost no residue on the kerf surface and inside the tracheid, and the surface quality was good. In the process of cutting across the grain, the kerf surface was smooth, the cell wall was completed, and the pores were scattered and ordered, but some of the pores with small diameter had carbon particles remaining. This was due to the flame retardant and cooling effect of auxiliary gas, which reduced the damage to cells caused by heat generated from combustion reaction. The heat-affected zone was effectively reduced and the surface quality was improved. However, due to the influence of wood texture structure, there was a blocking effect in the pores during heat transfer, and the heat was accumulated in the pores; thus the carbonization phenomenon occurred.

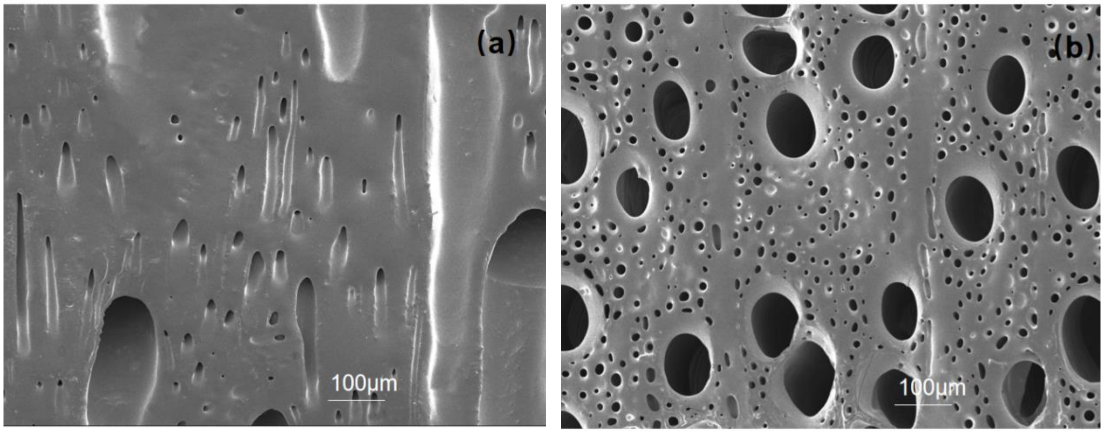
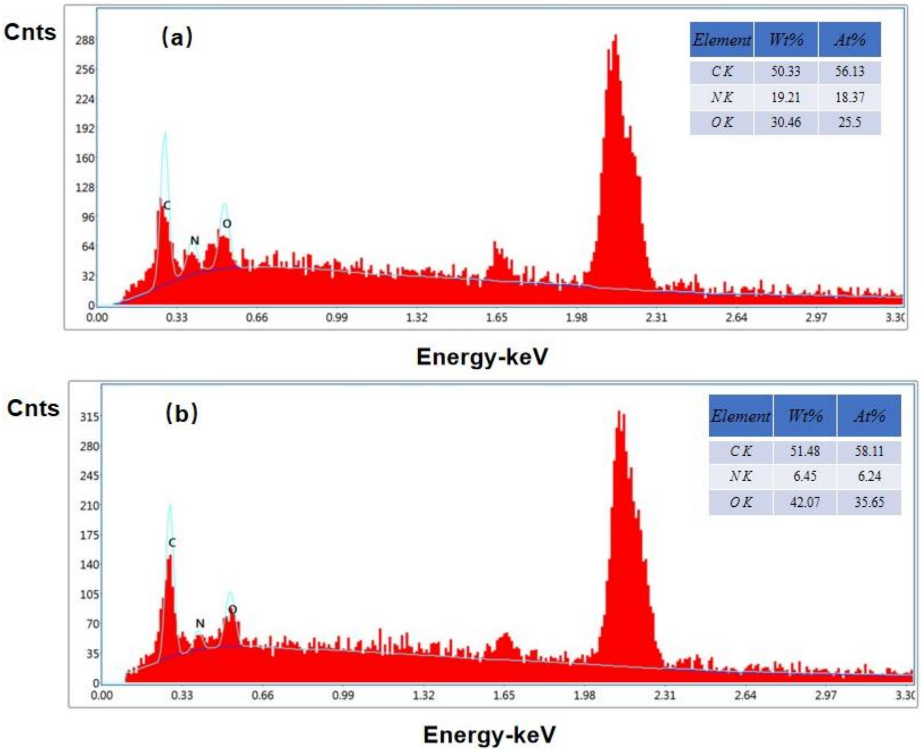


Fig. 5. Surface micro-morphology of gas-assisted laser processed wood slit: (a) parallel cutting (b) perpendicular cutting

Figure 6 shows the surface composition analysis of the kerf in the process of parallel cutting and perpendicular cutting.



Element	Wt%	At%
C K	50.33	56.13
N K	19.21	18.37
O K	30.46	25.5

Element	Wt%	At%
C K	51.48	58.11
N K	6.45	6.24
O K	42.07	35.65

Fig. 6. Surface composition of wood kerf processed by gas-assisted laser: (a) parallel cutting, (b) perpendicular cutting

As could be seen by energy spectrum analysis, in the process of cutting along the grain, the carbon content of the kerf surface was 50.3%, and in the process of cutting across the grain, the carbon content of the kerf surface was 51.5%. The carbon content of the surface was relatively reduced in the process of cutting along the grain. This was due to the introduction of inert gas, which formed an area that was resistant to the oxygen flame on the surface of the kerf. Thus, the carbonization phenomenon caused by surface ablation was reduced, and the range of heat affected zone was reduced. At the same time, the cooling and scavenging effect of the auxiliary gas of low temperature compression, the residue and residual carbon particles after vaporization were blown away, and the carbon content on the surface of the kerf was effectively reduced. Because the long and narrow cell wall was more conducive to the flow of flue gas and carbide in the process of cutting along grain, the carbon content on the kerf surface could be effectively reduced under the simultaneous of gas jet with certain pressure.

This study has certain limitations, and further research will be conducted on the multi-factor influence of different wood, different gas mixing and gas parameters, in order to fundamentally solve the carbonization and burning problems of laser processed wood molding parts and improve the processing quality.

CONCLUSIONS

1. In the process of gas-assisted laser cutting wood, the kerf width was increased with the increase of laser power, and in the processing of parallel cutting, the kerf width was significantly less than that of perpendicular cutting, while the carbonization area on the surface of the incision was significantly reduced.
2. In the process of gas-assisted laser cutting wood, the surface roughness was increased with the increase of laser power. Due to the difference in pore structure, in the processing of parallel cutting, the surface roughness was significantly less than that of perpendicular cutting, and the kerf surface was smoother.
3. The microscopic morphology and carbon content of the kerf were observed by scanning electron microscopy. In the processing of parallel cutting, the carbon content was significantly less than that of perpendicular cutting. Therefore, in the process of gas-assisted laser processing wood, the quality of the kerf obtained by the parallel cutting was significantly better than that obtained by the perpendicular cutting.

ACKNOWLEDGMENTS

The authors are grateful for Research Start-up Fund Project of Oriented Training (Introduction of Talents) of Heilongjiang Bayi Agricultural University (No. XYB202205), National Key R&D Program of China “Study on Fiber Preparation of Ultra-thin Fiberboard and Control System of Uniform Paving” (No. 2021YFD220060404) and The Special Funds of Fundamental Research Funds for the Central Universities (No. 2572020DR12).

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Article submitted: January 10, 2023; Peer review completed: January 21, 2023; Revised version received and accepted: August 14, 2023; Published: August 29, 2023.
DOI: 10.15376/biores.18.4.7202-7211