

## Prediction and Analysis of Surface Quality of Northeast China Ash Wood during Water-Jet Assisted CO<sub>2</sub> Laser Cutting

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**Abstract:** As a natural and environmentally friendly renewable material, Northeast China ash wood (NCAW) (*Fraxinus mandshurica* Rupr.) was cut by water-jet assisted CO<sub>2</sub> laser (WACL), the surface quality was evaluated by surface roughness of cut section. The surface roughness was measured by three-dimensional (3D) profilometry. Furthermore, the micromorphology of machined surface was observed by scanning electronic microscopy (SEM). Carbon content changes of machined surface were measured by energy dispersive spectrometer (EDS). A relationship between surface roughness and cutting parameters was established using response surface methodology (RSM). It is concluded that the cutting speed, laser power and water pressure played an important role in surface roughness of cut section. The surface roughness increased as an increase in laser power. It decreased caused by increasing of cutting speed and water pressure. Measurements revealed that the surface quality of NCAW part was improved using the optimized combination of cutting parameters. The established quadratic mathematical model of a good prediction is helpful for matching suitable cutting parameters to obtain expected surface quality.

**Keywords:** Green machining; water-jet assisted CO<sub>2</sub> laser cutting; northeast China ash wood; response surface methodology; surface quality

### 1 Introduction

One challenge in modern manufacturing is to phrase down environmental pollution and thus green technologies and manufacturing methods need to be adopted [1]. Laser processing was used for cutting, engraving, drilling, and surface treatment on wood [2–4]. However, the traditional laser processing for wood is based on laser beam of high energy density, causing big heat affected zone on machining area and smoke dust during the process, which affects the surface quality of machined parts [5]. Water-jet assisted laser process can overcome these shortcomings of traditional laser processing, and it has been successfully used to process ceramics of better surface quality, nearly without complex post processing [6]. Therefore, this technology is widely applied in micromachining field [7,8]. Water-jet assisted laser



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processing will be a potential technology for wood cutting because of its environmental protection and good machining quality.

As a natural and environmentally friendly renewable material, wood is widely used in furniture, building materials, wood products and other fields [9,10]. Especially, some delicate and fine wood products are widely needed, thus, numerous researchers have focused on surface quality of wood. Fukuta et al. [11] studied drilling on wood with lasers of different wavelengths and obtained holes with little ablation. Yusoff et al. [12] used CO<sub>2</sub> laser to cut different kinds of wood to study the influence of different cutting parameters on process indexes. The optimal cutting quality was obtained under the optimal cutting conditions. Eltawahni et al. illustrated that the effects of laser power, cutting speed and focusing position on the cutting parameters using CO<sub>2</sub> lasers to cut MDF of different thicknesses. Cutting quality was evaluated by measuring kerf width and surface roughness of machined part [13]. Kačík et al. [14] used CO<sub>2</sub> laser to radiate the surface of beech through, the surface composition changes of wood were analyzed by Fourier transform infrared spectroscopy (FTIR). Kubovský et al. [15] studied the surface of lime wood through ultraviolet radiation, measured the composition changes of wood surface by ATR-FTIR spectroscopy and observed changes in lignin and cellulose. Barcikowski et al. [16] used microscopy and UV microspectrophotometry to study the heat-affected areas of the cut kerf of particleboard and plywood. The results showed that the size of the heat-affected zone depended on the material and cutting parameters. Yang et al. [17] proposed water-jet assisted YAG laser processing on Korean pine wood, the water jet washed away the residues that remained on the surface of the kerf to improve the surface quality of machined area. Subsequently, they researched the mechanism of water-jet assisted YAG laser processing on wood, and good processing effect was obtained [18]. However, with in-depth research, it is found that wood has better absorption rate of CO<sub>2</sub> laser wave and CO<sub>2</sub> laser has the advantage of low price [11,19]. Meanwhile, northeast China ash wood (NCAW) is a type of precious hardwood in northeast China with a high density. It is widely applied in the furniture industry because of its beautiful texture and good resistance to decay. Therefore, it is necessary to study the experiment of NCAW during water-jet assisted CO<sub>2</sub> laser (WACL) cutting.

Most published papers results revealed the effect of process parameters on forming quality during laser processing. However, these variation law of laser processing may be not suitable for the experiment of NCAW during WACL cutting, and the detailed relationship between cutting parameters and forming quality was not quantitatively evaluated. The cutting speed, laser power and water pressure as process parameters to discuss the surface quality of NCAW during WACL cutting. The surface quality of cut section was evaluated by surface roughness. The model for surface roughness were established by RSM to evaluate quantitatively the connection of input parameters and output parameters. The model will be helpful for obtaining suitable cutting parameter.

## 2 Materials and Methods

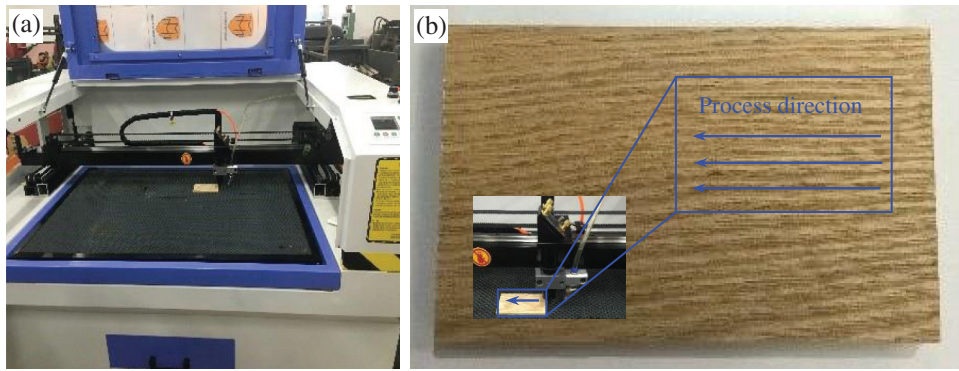
### 2.1 Materials

Northeast China ash wood (NCAW) (*Fraxinus mandshurica* Rupr.) was selected for experiment. NCAW specimens (moisture content of 12.42% and dry density was 0.78 g/cm<sup>3</sup>) were 100 mm × 60 mm × 2 mm (Length × Width × Thickness). Tangential section was chosen for WACL cutting experiment. Specimens were sanded using sandpaper (grit size no. 240).

### 2.2 Experimental Procedure

WACL cutting experiments were conducted using WACL equipment (Fig. 1a). The equipment mainly consists of CO<sub>2</sub> laser cutting machine and water-jet assisted CO<sub>2</sub> laser device. The laser system is a CO<sub>2</sub> laser cutting machine (Baomei Technology Ltd., Jinan, China) equipped with a CO<sub>2</sub> laser generator (wavelength of 10.6 μm and maximum laser power output of 80 W). Lens focal length is 63.5 mm. The water-jet assisted system is designed and manufactured by our group. The model of water pump is QL-380 (Hongyuan

company, Harbin, China). The diameter of the water jet nozzle is 0.5 mm and the nozzle angle is adjustable. The principle of WACL cutting is to fix NCAW on the working table with a special fixture, move the water-jet assisted CO<sub>2</sub> laser system to the processed area by controlling the feed system, turn on the power switch of the water pump, and turn on the laser switch at the same time. The laser beam radiates from the laser to the processing area of the NCAW, and the water-jet in the water pump sprays to the NCAW through the nozzle, and finally the NCAW parts with a certain geometric shape are obtained. In the processing, the distance water-jet focal point lagging behind the laser focal point about 1 mm, which can reduce the direct contact between water jet and laser beam, and prevent the water jet from absorbing too much laser energy, thus avoiding heat loss. The cooling and washing effect of water jet provides a guarantee for improving the size accuracy and surface quality of NCAW during WACL cutting. The process direction was along the fiber of NCAW by a single pass. The specimen and process method are shown in Fig. 1b.



**Figure 1:** Equipment and process method. (a) Equipment, (b) Specimen and process method

Surface roughnesses of the cut sections of NCAW parts with different cutting parameters were measured using three-dimensional (3D) profilometry (Zeiss Axio Scope. A1 microscope, Carl Zeiss AG, Oberkochen, Germany). The cross sections of NCAW parts were sputtered with gold first because specimens were non-conductive. Then they were scanned using a FEI Quanta200 SEM (Dutch company, Amsterdam, Netherlands). A part of specimen was observed. The SEM figures of the NCAW parts morphologies were obtained. In order to reveal the mechanism of surface quality change, energy dispersive spectrometer (EDS) was used to analyze the content changes in chemical composition of machined surface.

### 2.3 Experiment Plan

The effects of cutting parameters on surface roughness of NCAW kerf was investigated by Box-Behnken design (BBD). The experimental plan was conducted by Design-Expert Software (V8.0.6). Eq. (1) shows a model of the WACL cutting.

$$Y = b_0 + \sum_{i=1}^k b_i X_i + \sum_{ij} b_{ij} X_i X_j + \sum_{i=1}^k b_{ii} X_i^2 \quad (1)$$

where  $b_0$  represents the free term of the regression equation;  $b_i$  and  $b_{ii}$  stand for the linear and quadratic terms;  $b_{ij}$  represents the interacting terms [20]. The effects of cutting speed, laser power and water pressure on surface roughness during WACL cutting were assessed.

In this study, the WACL cutting experiments on NCAW were processed at three levels. Tab. 1 demonstrated the factors and levels.

**Table 1:** Factors and levels of water-jet assisted CO<sub>2</sub> laser (WACL)

Levels	Factors		
	Cutting Speed (mm/s) $X_1$	Laser Power (W) $X_2$	Water Pressure (MPa) $X_3$
-1	24	45	1.0
0	27	50	1.3
1	30	55	1.6

### 3 Results and Discussion

The surface roughnesses of cut section measured using three-dimensional (3D) profilometry are shown in [Tab. 2](#). Experimental data is shown in [Tab. 2](#).

**Table 2:** Experimental data

Standard	Run	Factors			Response
		Cutting speed (mm/s) $X_1$	Laser power (W) $X_2$	Water pressure (MPa) $X_3$	Surface roughness Ra ( $\mu\text{m}$ )
1	8	30	50	1.6	1.75
2	14	27	50	1.3	2.23
3	13	27	50	1.3	2.17
4	1	24	45	1.3	1.44
5	15	27	50	1.3	2.15
6	9	27	45	1.0	1.77
7	16	27	50	1.3	2.14
8	4	30	55	1.3	1.96
9	7	24	50	1.6	3.21
10	8	27	55	1.6	3.08
11	9	24	55	1.3	3.27
12	10	27	55	1.0	2.75
13	17	27	50	1.3	2.18
14	11	27	45	1.6	1.02
15	5	24	50	1.0	3.15
16	2	30	45	1.3	0.83
17	6	30	50	1.0	2.56

#### 3.1 Analysis of Variance

Analysis of variance was performed to indicate that the factors have significant effect on the surface roughness of WACL cutting WACL. [Tab. 3](#) showed that the selected model was significant (probability of <0.0001).  $p$  value (<0.05) represented the model terms are significant. Variables  $X_1$ ,  $X_2$ ,  $X_3$ ,  $X_1X_2$ ,  $X_1X_3$

and  $X_2X_3$  are important for predicting of surface roughness, and they affect the surface roughness of machined surface during WACL cutting.

**Table 3:** Results of the analysis of variance for surface roughness

Source	Sum of squares	Degrees of freedom	Mean square	<i>F</i> Value	<i>p</i> Value
Model	8.55	9	0.95	310.05	<0.0001
$X_1$	1.97	1	1.97	643.08	<0.0001
$X_2$	4.50	1	4.50	1468.87	<0.0001
$X_3$	0.17	1	0.17	55.85	0.0001
$X_1X_2$	0.12	1	0.12	39.99	0.0004
$X_1X_3$	0.19	1	0.19	61.77	0.0001
$X_2X_3$	0.29	1	0.29	95.18	<0.0001
$X_1^2$	0.048	1	0.048	15.66	0.0055
$X_2^2$	0.69	1	0.69	226.27	<0.0001
$X_3^2$	0.63	1	0.63	205.57	<0.0001
Residual	0.021	7	$3.064 \times 10^{-3}$		
Lack of Fit	0.017	3	$5.508 \times 10^{-3}$	4.48	0.0908
Pure Error	$4.920 \times 10^{-3}$	4	$1.230 \times 10^{-3}$		
Cor Total	8.57	16			

### 3.2 Regression Equations

The relationship between surface roughness and cutting variables using a quadratic model because of the high values of  $R^2$ . Tab. 4 shows that the values of  $R^2$  come near 1, indicating that the model has a high degree of fit and well predicting for the surface roughness of cut section during WACL cutting. Eq. (2) states the model equation for surface roughness of cut section during WACL cutting.

$$Ra = -37.4244 + 0.0916X_1 + 1.854X_2 - 14.1353X_3 - 0.0117X_1X_2 - 0.2417X_1X_3 + 0.18X_2X_3 + 0.0119X_1^2 - 0.0162X_2^2 + 4.2972X_3^2 \quad (2)$$

where  $X_1$  stands for cutting speed in mm/s;  $X_2$  represents laser power in W;  $X_3$  is water pressure in MPa.

**Table 4:** Results of ANOVA analysis

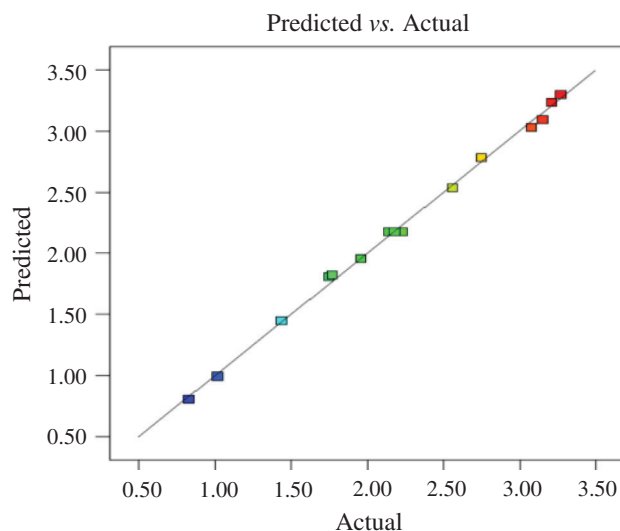
Responses	Source	Standard deviation	$R^2$	Adjusted $R^2$	Predicted $R^2$
Ra	Quadratic	0.055	0.9975	0.9943	0.9683

Fig. 2 shows the results of predicted and actual surface roughness of cut section. The predicted values come near the actual values of surface roughness, namely, the established model well predicts the surface roughness of cut section during WACL cutting.

### 3.3 Effects of Input Parameters on Surface Roughness of NCAW during WACL Cutting

Fig. 3a shows the perturbation diagram of surface roughness of cut section during WACL cutting. Obviously, cutting speed, laser power and water pressure have significant influence on the surface

roughness of NCAW part. The influence of cutting speed and laser power on the surface roughness of NCAW part is greater than that of water pressure. The results show that the surface roughness increases with an increase in the laser power, because when the laser power increases, more heat is concentrated on the cut section of the NCAW part, so surface roughness increases. However, it decreases with the increase of cutting speed and water pressure, because when the cutting speed increases, the laser moves rapidly on the processing surface of the NCAW part. Due to the short action, only a small amount of heat concentrates on the surface of NCAW part, so surface roughness decreases. When the water pressure increases, the turbulence of the water increases and the interference intensifies, which affects the heating ability of the laser acting the material. The interference of water turbulence reduces the laser energy density, resulting in only a small amount of heat concentrated on the surface of NCAW part, so surface roughness decreases.



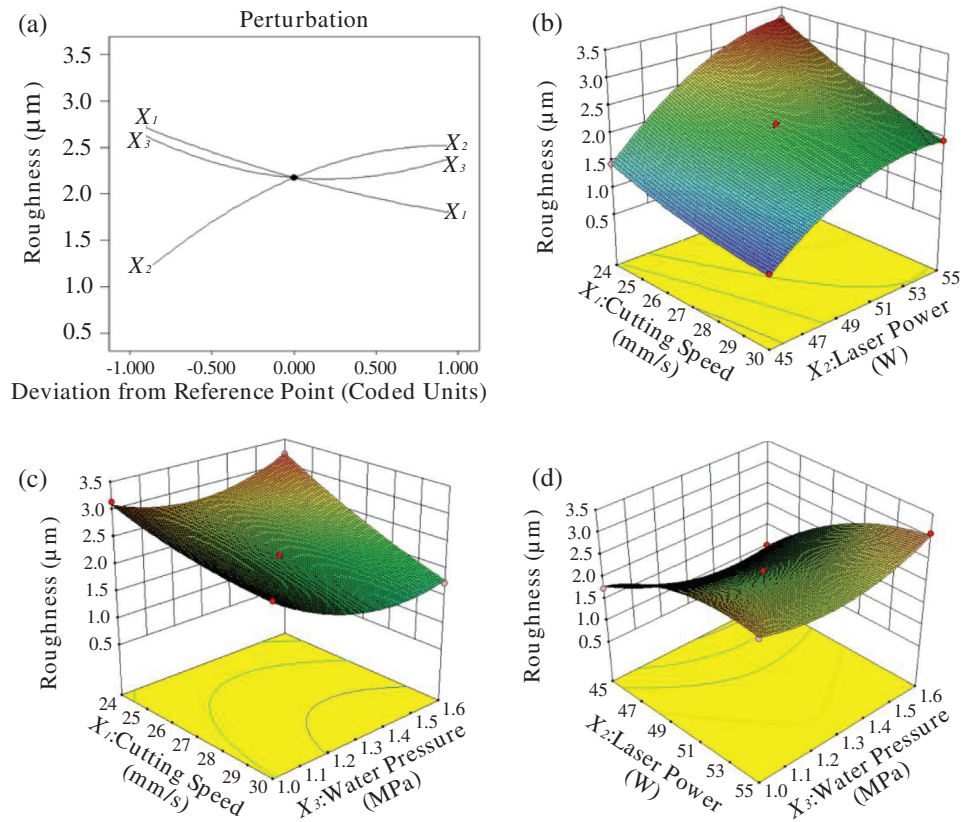
**Figure 2:** The graph of predicted and actual values of surface roughness

The interaction of cutting parameters also has a significant impact on the surface roughness of cut section, as shown in Figs. 3b–3d. As can be seen from Fig. 3b, in the range of selected parameters, when the cutting speed is at a low level, the surface roughness increases with the increase of laser power and the growth rate is relatively large. This indicates that the interaction between cutting speed and laser power has a great influence on the surface roughness after machining. When the laser power increases, more heat accumulates on the kerf surface of NCAW, resulting in increasing surface roughness. Fig. 3c illustrates that the value of surface roughness decreases with the increase of cutting speed and water pressure, and the effect of cutting speed on surface roughness is more significant than that of water pressure on surface roughness. As can be shown from Fig. 3d, it is the trend of the influence of the interaction effect between laser power and water pressure on surface roughness. It can be observed that higher laser power and lower water pressure will increase the surface roughness. These results play an important role in revealing the variation law of surface roughness and guiding the selection of cutting parameters. According to the surface roughness, the established regression model equation was solved to estimate the optimal cutting parameters of NCAW part fabricated by WACL processing: cutting speed was 30 mm/s, laser power was 45 W, and water pressure was 1.55 MPa. Under the optimal conditions, the predicted value of Ra was 0.544  $\mu\text{m}$ .

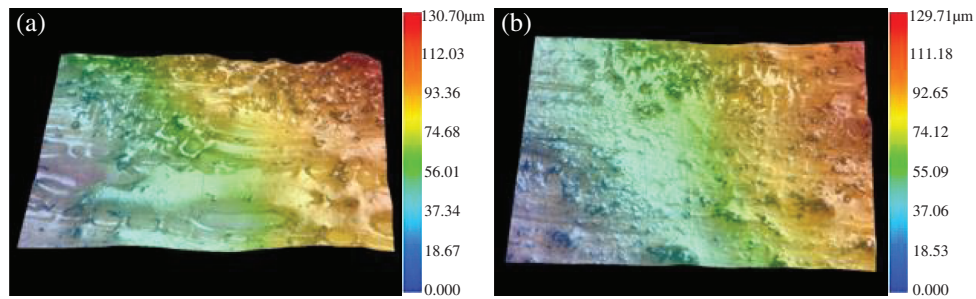
### 3.4 Experimental Validation

Validation tests were conducted under optimal conditions to verify the reliability of the test results of NCAW during WACL cutting. It was found that the Ra value was 0.5  $\mu\text{m}$  after tests, which was basically consistent with the predicted Ra value of 0.544  $\mu\text{m}$  under the optimal conditions, that is, the model fitted well with the actual situation.





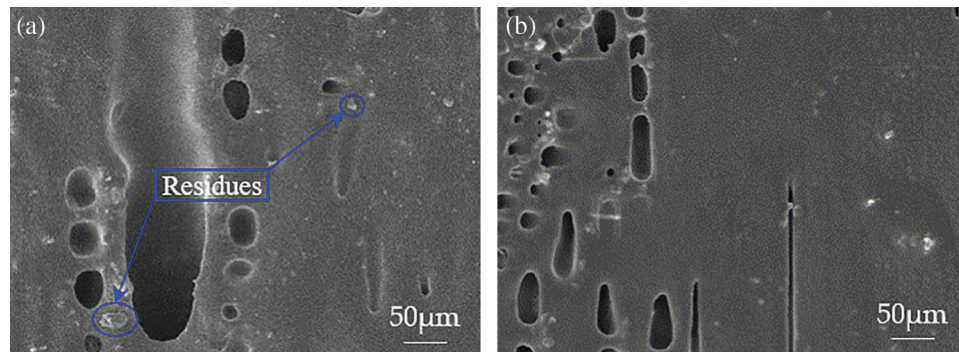
**Figure 3:** The interaction effect of cutting parameters on surface roughness



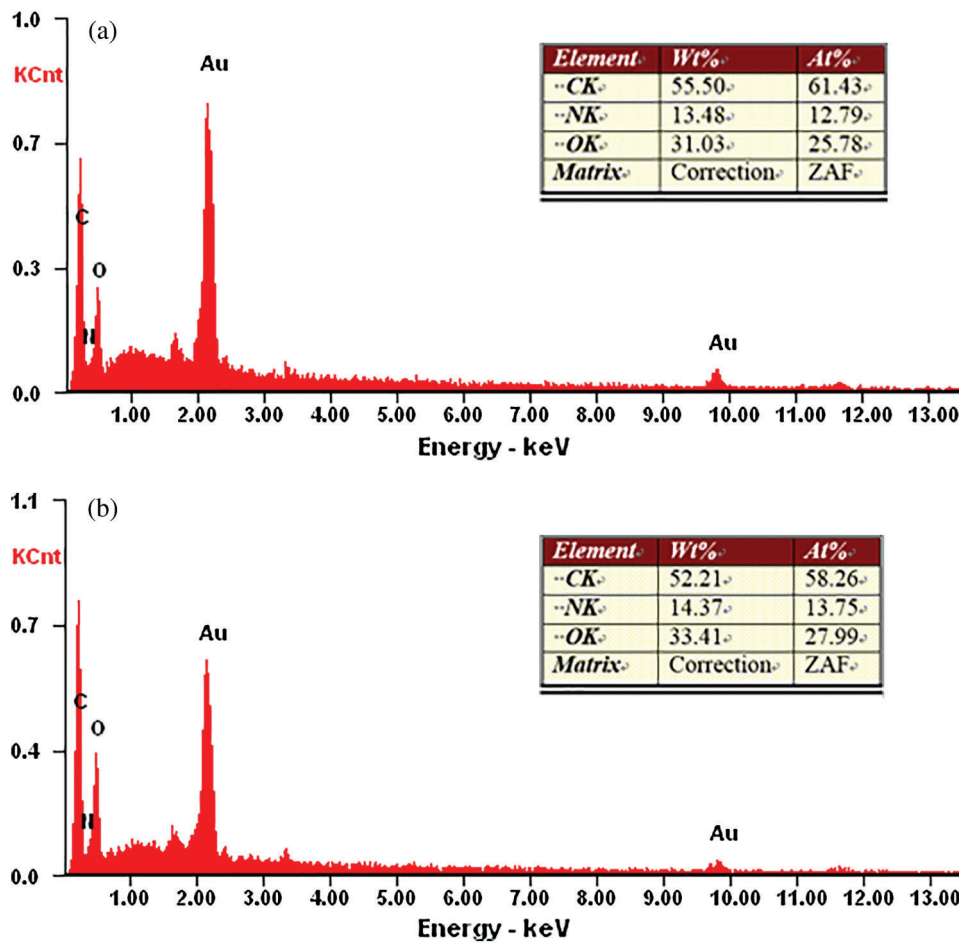
**Figure 4:** Three-dimensional (3D) shapes of machined surface. (a) No. 16 part, (b) Optimized part

### 3.5 Surface Quality of NCAW

The optimized cutting parameters were applied to conduct the NCAW cutting experiment by WACL, and the Ra value of optimized part is 0.5  $\mu\text{m}$ , and the three-dimensional (3D) shape was shown in Fig. 4b. In Tab. 2, the Ra value of No.16 part is minimum, 0.83  $\mu\text{m}$ , and its 3D shape is shown in Fig. 4a. Compared with the No.16 part in the test, the Ra value of the optimized NCAW parts decreased by 39.76%. Surface quality is an important index of NCAW cutting by WACL. The smaller the surface roughness is, the better the surface quality is.



**Figure 5:** Micromorphology of tangential section of machined surface. (a) No. 16 part, (b) Optimized part



**Figure 6:** Energy dispersive spectrometer (EDS) data of machined surface. (a) No. 16 part, (b) Optimized part

Fig. 5 shows the micromorphology of the tangential section of No. 16 part and optimized part. Compared with Figs. 5a and 5b shows that the surface of the kerf and the inner wall of the tracheids are clean, with almost no residue, presenting smooth surface and good surface quality. This is because the cooling actions of the water jet carry away the steam generated by the wood vaporization, and the solid particles generated by the vaporization are also reduced, while the washing impact of the water washes



away the carbon particles remaining on the kerf surface, resulting in a good surface quality of the machined NCAW part. Due to the content changes of chemical composition on the kerf surface of NCAW parts, the surface quality changes. Therefore, the EDS analysis is conducted. In Fig. 6, compared with Figs. 6a and 6b presents that the carbon element content on kerf surface of the optimized part decreased, because some carbides of cut section are effectively taken away under the interaction of cutting parameters. Cooling and impact effects of water jet reduce carbides and residues of machined surface. Therefore, the surface roughness decreases using the optimized combination of cutting parameters so that the surface quality of NCAW part is improved.

#### 4 Conclusions

WACL cutting of NCAW leads to the variation of surface quality of cut section. Carbon content variation of machined surface was following the changes of cutting parameters. The cutting speed, laser power and water pressure had significant effects on surface roughness of cut section. The surface roughness increased as an increasing in laser power, but it decreased with increasing of cutting speed and water pressure due to the amount of decreasing heat transferring as the increasing of cutting speed and water pressure. The established model indicated the relationship between surface roughness and cutting parameters, which is helpful for selecting appropriate cutting parameters to obtain desired surface quality. The optimal cutting parameters of NCAW part fabricated by WACL processing: cutting speed was 30 mm/s, laser power was 45 W, and water pressure was 1.55 MPa. The results of SEM and EDS revealed that the surface quality of NCAW part was improved using the optimized combination of cutting parameters.

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**Conflicts of Interest:** The authors declare that they have no conflicts of interest to report regarding the present study.

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