Journal of Wood Science (2018) 64:209–219
https://doi.org/10.1007/s10086-017-1693-5

ORIGINAL ARTICLE

Influence of pretreated wood dowel with $CuCl_2$ on temperature distribution of wood dowel rotation welding

Jirong Zhang[1,2] · Ying Gao[1,2] · Jianan Zhang[1,2] · Xudong Zhu[1,2]

Received: 6 July 2017 / Accepted: 11 December 2017 / Published online: 29 January 2018

Abstract
This study examined the temperature distribution during rotation welding process using birch (*Betula* spp.) wood dowel and Chinese larch (*Larix gmelinii*) substrates. Wood dowels were divided into two categories including an untreated group and a group pretreated with cupric chloride. The mechanics test results indicated that the pullout resistance of the pretreated group with welded time 3 s showed the best performance. As a fitting analyses result, both the untreated group and pretreated group showed a significant nonlinear relationship among temperature, welded depth and welded time. In the untreated group case, a linear regression relationship was found between the highest temperature of the welding interface and the depth. However, two-stage fitting was used to fit the regression for the pretreated group. Compared with the untreated group, thermogravimetric (TG) analysis of the pretreated group welding interface presented two pyrolytic peaks, and it illustrated that the pretreatment promoted the depolymerization and pyrolysis of wood constituents.

Keywords Wood dowel welding · Pullout resistance · Temperature distribution · TG

Introduction

Wood is a natural polymer material, which could be used as a thermoplastic material in welding technology. The mechanism of the wood dowel rotation welding is that the lignin and hemicellulose are softened and melted by the heat, which is generated from friction between the modification and dowel. Then after cooling and curing, cross-linked grid structure occurred in the interface layer to obtain a non-adhesive glue [1]. The heat generated by friction between the dowels and the walls of the substrate was an important parameter. If the friction between the dowels and the substrate hole was insufficient, inadequate heat would not induce the wood components to fully melt and to be evenly distributed, while excessive friction could lead to excessive pyrolysis of the wood components. Therefore, the monitoring and detection of the temperature in the welding interface show great significance in wood dowel welding.

According to several studies, with the decrease in the insertion speed of the wood dowel, the welded time extended and then the friction increased between the wood dowel and the wall of the substrate hole, resulting in generating more black molten materials with the greater loss of the materials in the wood dowel surface. Belleville et al. found that different optimal insertion rates existed in different wood species. The best insertion rate of maple was 25 mm/s, while it was 16.7 mm/s for birch. However, it was not possible to successfully manufacture a specimen with speed 1000 rpm and insertion speed 25 mm/s. On the other hand, it produced a lot of carbonization and soot, which resulted in a poor welding joint with a speed of 2500 rpm and insertion speed of 12.5 mm/s for birch [2]. The results indicated that the variation in welded time had a greater impact on the pullout resistance of the welding joints. Belleville et al. found that the optimal rotational speed was 1400–1500 rpm for

✉ Ying Gao
gaoying@bjfu.edu.cn

Jirong Zhang
zhangjirong@bjfu.edu.cn

Jianan Zhang
zjn7160024@bjfu.edu.cn

Xudong Zhu
zhuxudong5008@bjfu.edu.cn

1 Beijing Key Laboratory of Wood Science and Engineering, Beijing Forestry University, Beijing 100083, People's Republic of China

2 MOE Key Laboratory of Wooden Material Science and Application, Beijing Forestry University, Beijing 100083, People's Republic of China

eucalyptus species with density range from 700 to 900 kg/m^3 at 12% moisture content (MC) [3]. Ganne-Chedeville et al. found that the rotational speed of 1515 rpm was better than 1165 rpm for commercial beech [4].

The relationship among temperature, friction time and thermal flux of wood dowel welding had been established through a heat-transfer model by Zoulalian et al.. The results indicated that the conversion efficiency of mechanical energy to thermal energy was 0.080 ± 0.01 and the optimal temperature was 180 °C for birch [5]. Rodriguez et al. found that the temperatures for softening and degradation of wood components had been achieved during the welding process. The welding temperatures reached around 263 and 274 °C in less than 1 s for birch and maple, respectively. The highest temperature appeared to be stabilized between 0.7 and 2 s; meanwhile thermal softening and decomposition of wood components occurred [6]. The highest temperatures with optimal parameters were 244 and 282 °C for sugar maple and yellow birch, respectively [2]. The highest temperature at the welding interface increased progressively with the increase of the rotational speed for both species. For sugar maple, an average temperature of 244.1 °C was measured at 1000 rpm, 281.1 °C at 1500 rpm, and 328.6 °C at 2500 rpm. For yellow birch, the average temperatures were 282.6 °C at 1000 rpm, 297.4 °C at 1500 rpm, and 327.3 °C at 2500 rpm. The above studies showed that temperature was of great significance to the welding properties of the dowels, which contained two important factors, namely, the temperature distribution at each depth and the temperature change during the welding process.

To improve the welding properties, several researches on the enhancement process have been studied. According to the study of Rodriguez et al., the welding properties could be significantly improved using smaller pre-drilled holes [6]. The use of dry dowels inserted hot into the substrate after preheating them at high temperature yielded consistently better results [7]. Natural additives, lignin and rosin, could significantly improve the welding properties [8]. Lignin, mono-oligosaccharides, acetic acid, vanillin, furfural, 5-hydroxymethylfurfural (5-HMF), and syringaldehyde in water extracts were quantified [9]. Application of rosin to the wood faces to be joined by both linear vibration welding and rotational dowel welding has shown to greatly enhance the water resistance of the welded wood joints [10].

In this paper, birch (*Betula* spp.) wood dowel and Chinese larch (*Larix gmelinii*) substrate were used as welding materials to study the effect of welding interface temperature on the welded joints properties. In China, larch is a kind of promising timber species for building material, and birch dowel is a common material used in the furniture industry. They are both excellent in performance and easy to obtain. In this study, we tried to explore applying the birch dowel as a building material in this new type of connection. The influence of the pullout resistance on the welded specimen was analyzed by setting different welding times.

The temperature distribution and the highest temperature of the welding interface were also studied. At the same time, because of the softening and corrosion of the wood dowel surface, the effect of surface temperature on the welding interface pretreated with cupric chloride ($CuCl_2$) was analyzed, which provided a theoretical basis for improving the mechanism of the pullout resistance of welded joints.

Materials and methods

Materials

Birch (*Betula* spp.) wood dowels were 10 mm in diameter and 100 mm in length. The air-dried density at 12% MC of the birch dowel was 557 kg/m^3. The MC of wood dowels was 2%. Wood dowels were treated in the drying oven whose temperature was set to 63 °C, until 2% MC was achieved. The wood dowels were divided into two categories including an untreated group and a pretreated group. The wood dowels of pretreated group were immersed in 0.1 mol/L $CuCl_2$ solution for 30 min and then dried to 2% MC. The temperature of the $CuCl_2$ solution during immersion was around 20–25 °C, which is the indoor temperature in the laboratory. The study tried six different treatment times, 10, 20, 30 min, and 1, 2, and 4 h. After the preliminary experiment, it was found that 30 min was the best choice.

Larch (*Larix gmelinii*) blocks that were 40 mm (tangential, T) × 50 mm (radial, R) × 50 mm (longitudinal, L) were used as the substrate. The air-dried density at 12% MC of larch was 680 kg/m^3. Slats were pre-conditioned at 20 °C and 60% relative humidity (RH) until equilibrium MC was achieved.

Manufacture of specimen

Holes were pre-drilled on the tangential section of the wood substrates with a diameter of 8 mm and a depth in 30 mm using a drilling machine (Proxxon, TBH Typ 28 124, Germany). The drill machine had three rotation speed levels, 1080, 2400, and 4500 rpm, respectively. Since the study of other scholars and the pre-experimental results showed that 1080 and 4500 rpm were ineffective, a rotation speed of 2400 rpm was selected [3, 4]. Next, the wood dowels were welded into the pre-drilled holes in the substrates to create bonded joints. The welded times were 3, 5, and 7 s, respectively. Six specimens were used for the temperature test. After welding, the specimens were conditioned at 20 °C and 60% RH for 7 days before the pullout tests. Each test group included 30 repeated pieces for the pullout test.

Temperature test

The temperature was tested using six thermocouple sensors with the data collecting device (Bejing heshixingye Technology Co.,Ltd., XSL-A16XS1V0, China). Six sensors were set in six different depths along 5, 10, 15, 20, 23, and 28 mm (Fig. 1). The response speed of the K-type thermocouple sensor was 0.34 ms [11]. Origin 10 software was used to analyze the statistics.

Pullout test

The pullout resistance of the specimens was tested using universal testing equipment (WDW-300E, Jinan popwil Instrument co., China) that pulled the welding wood dowels out of the substrate at a speed of 2 mm/min [12]. The specimens were fixed by clamping the dowel into the jaw of the fixed beam and the substrate block was fixed to the mobile beam with a metal framework.

Thermogravimetric (TG) analyses

After the welding was completed, the interface layer produced black material. The black material on the welding interface layer of the welded specimen in each test group was collected, ground into a powder, and mixed evenly. The TG analyses were performed using 10 mg powders for each test. The samples for TG analyses were scrapped from the welding interface layer. The programmed heating pyrolysis of wood dowel and welding interface was carried out in a simultaneous thermal analyzer (NETZSCH, STA 449F3, Germany). The samples in the crucible of TG were heated from 323 to 973 K at a heating rate of 10 K/min [13]. Purified nitrogen was used as carrier gas to provide an inert atmosphere. Based on the TG analysis result, the derivative thermogravimetric analysis (DTG) curves were plotted [14].

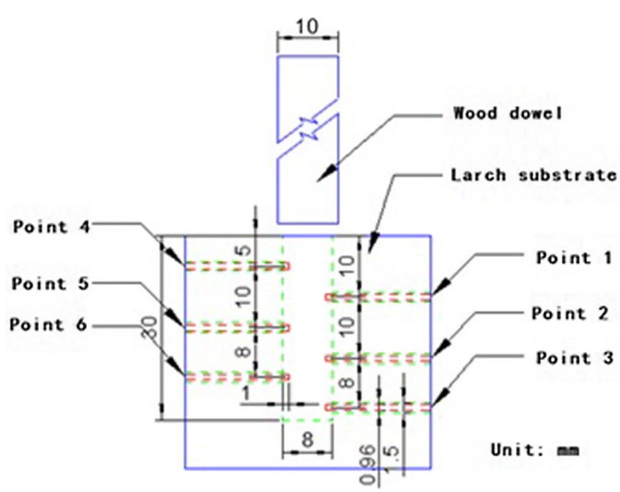

Fig. 1 Temperature test method

Results and discussion

Test results of pullout resistance

The results of pullout resistance are summarized in Table 1. The analysis of the pullout resistance with different welded times showed that pullout resistance was affected by the different welded times. For the untreated group, pullout resistance for welded time 3 s was 28.33 and 87.12% higher than the welded time of 5 and 7 s, respectively. For the pretreated group, pullout resistance for welded time 3 s was 37.91 and 56.61% higher than the welded time 5 and 7 s, respectively. In both the untreated group and pretreated group, with the extension of welded time, the pullout resistance decreased. The pullout resistance of welded time 3 s samples showed the smallest variability and the best reliability. According to the experimental results, welded time 3 s was the best choice for welding in this study.

The different welded times had a certain effect on the pullout resistance. According to the results of one-way analysis of variance, at the 5% significance level, the analysis showed a significant interaction between welded time and pullout resistance [$F = 34.46671$(untreated group), $F = 94.9855$(pretreatment group)].

The mean values of the 3 s welded time samples with untreated wood dowels were 2790 N, and in the pretreatment groups 4695 N. It was 59% higher than the untreated welded time 3 s samples. In other words, the welded time 3 s

Table 1 Results of the pullout resistance for untreated and pretreatment group

Test group	Welding time (s)	Mean value (N)	Max value (N)	Min value (N)	Variable coefficient (%)
Untreated group	3	2790	3602	2072	15.92
	5	2174	3024	1056	25.45
	7	1491	2434	722	34.15
Pretreatment group	3	4695	6094	3006	15.21
	5	2915	3836	1584	24.34
	7	2037	2614	1208	21.01

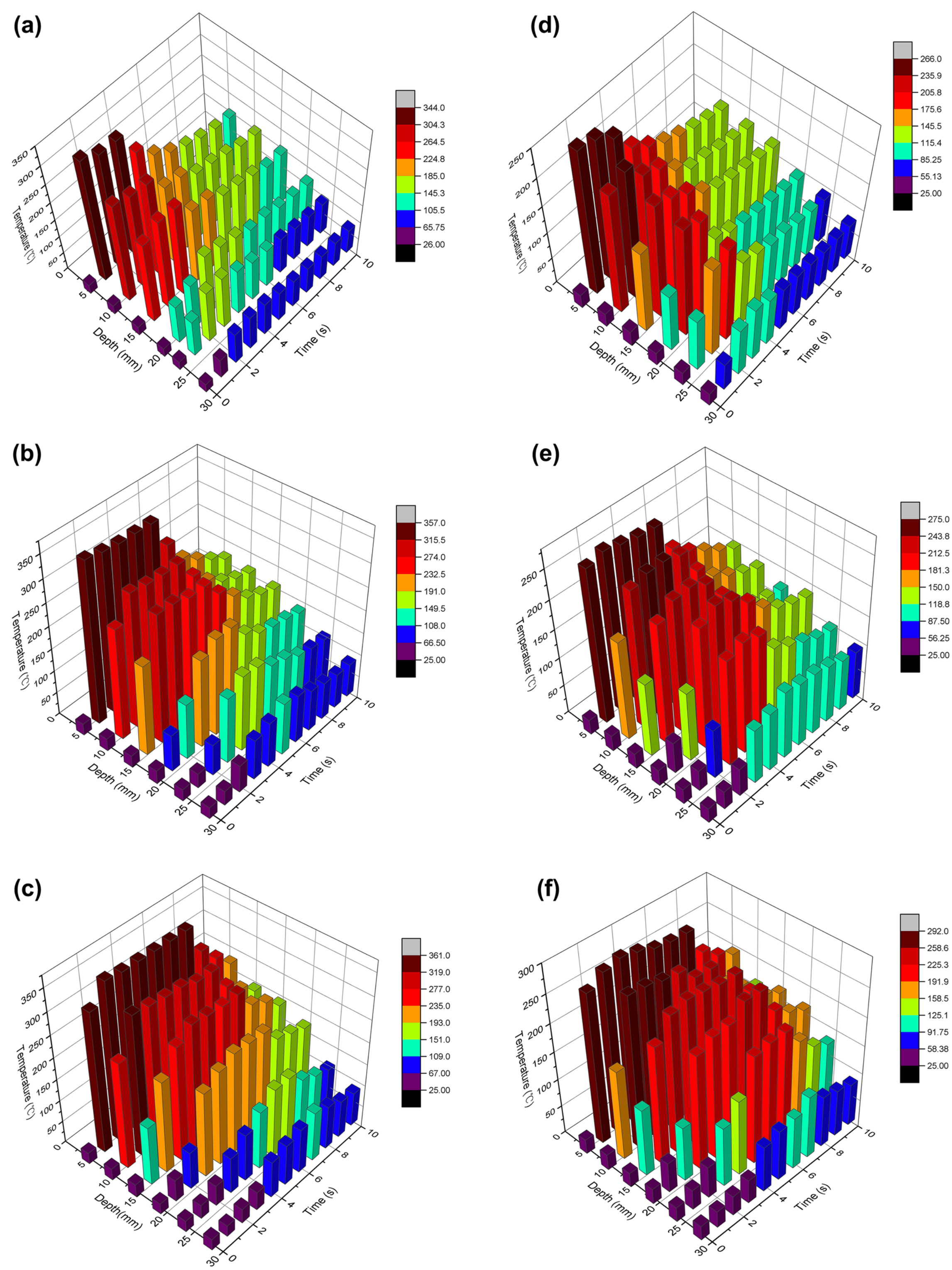

Fig. 2 Temperature distribution at different times for the untreated and pretreatment group. **a**–**c** Untreated group with welded times 3, 5, and 7 s. **d**–**f** Pretreated group with welded times 3, 5, and 7 s

samples pretreated with $CuCl_2$ showed better pullout resistance. It almost reached 5000 N, which is the tensile strength of wood dowel itself. On the other hand, the coefficient of variation of the pretreatment group was 15.2% and the untreated group was 15.9%, indicating that pullout resistance of welded time 3 s with pretreated wood dowels showed the smallest variability and better concentration. Welded time 5 s groups and welded time 7 s groups also showed that pretreatment with $CuCl_2$ could improve the pullout resistance. Therefore, pretreatment with $CuCl_2$ could significantly improve the welding properties.

The influence of pretreatment with $CuCl_2$ on welding temperature distribution

The temperature distribution of untreated samples and pretreated $CuCl_2$ samples with different welded times are shown in Fig. 2. The first three figures a, b, and c show the untreated group with welded times 3, 5, and 7 s, and the latter three d, e, and f are the pretreatment group with welded times 3, 5, and 7 s. It can be seen from Fig. 2 that in both the untreated groups and pretreated groups, the welding interface maintained a relatively high temperature in the rotation welding progress. The results indicated that the temperature decreased with the increase in the depth and the extension of time. Figure 2a, d shows that the temperature began to decline rapidly at 4 s for each depth. It indicated that the rotating friction provided a large amount of heat to the interface, and once the rotational friction stopped, the temperature decreased immediately. The same phenomenon also occurred in Fig. 2b, e at 6 s and Fig. 2b, f at 8 s.

According to the analyses of pullout resistance, the difference in temperature between 6 points during the welding process should be tested to explain the reason for the improvement in pullout resistance. Wood dowels of the pretreated group were immersed in $CuCl_2$ solution for 30 min; the wood dowel was acid corroded and softened. Because of the low friction coefficient and low welding temperature, wood dowels were not excessively charred in the early stage of the welding progress. The friction coefficient increased with the increase of the welding depth, which could provide sufficient heat to produce more molten material and a part of them flow to point 6. Based on the phenomena and results, pretreatment with $CuCl_2$ could significantly improve the pullout resistance.

Relationship among temperature, welded depth, and time

A fitting analyses showed that a significant nonlinear relationship existed among temperature, welded depth, and welded time. Based on the analysis of nonlinear fit performed using the Origin 10 software, the nonlinear relationship could be inferred. Temperature was set as the Z coordinate axis, the welding depth as the X coordinate axis, and the welded time as the Y coordinate axis. The regression fitting curves are shown in Fig. 3, in which the first three figures a, b, and c show the untreated groups with welded times 3, 5, and 7 s, and the latter three d, e, and f are the pretreatment groups with welded times 3, 5 and 7 s; the corresponding nonlinear fitting formulas are shown in formulas (1)–(8).

Untreated group—3 s

$$Z = \frac{-1141.49 + 394.94X + 70785.2Y - 11595.9Y^2 + 568.624Y^3}{10^{-7} + 11.7576X - 1.17828X^2 + 0.07225X^3 + 153.446Y - 8.05726Y^2}. \quad (1)$$

Untreated group—5 s

$$Z = \frac{9675.302 + 3211.689X + 640539.934Y - 48113.503Y^2 + 646.233Y^3}{1 + 247.623X - 22.395X^2 + 1.20891X^3 + 1032.501Y + 37.01452Y^2}. \quad (2)$$

Untreated group—7 s

$$Z = \frac{-874.70052 + 252.263X + 29995.411Y + 4058.075Y^2 - 464.652Y^3}{1 + 5.44714X - 1.0865X^2 + 0.10717X^3 + 91.19061Y + 2.98207Y^2}. \quad (3)$$

The correlation coefficients of the nonlinear fitting formulas of the three welded time experimental groups were 97.51, 96.62, and 97.63%, respectively, which indicated that the fitting precision of the nonlinear fitting surface was high. The regression relationship among temperature depth, and time was in accordance with the general formula (4):

$$Z = \frac{Z_0 + A_{01}X + B_{01}Y + B_{02}Y^2 + B_{03}Y^3}{1 + A_1X + A_2X^2 + A_3X^3 + B_1Y + B_2Y^2}. \quad (4)$$

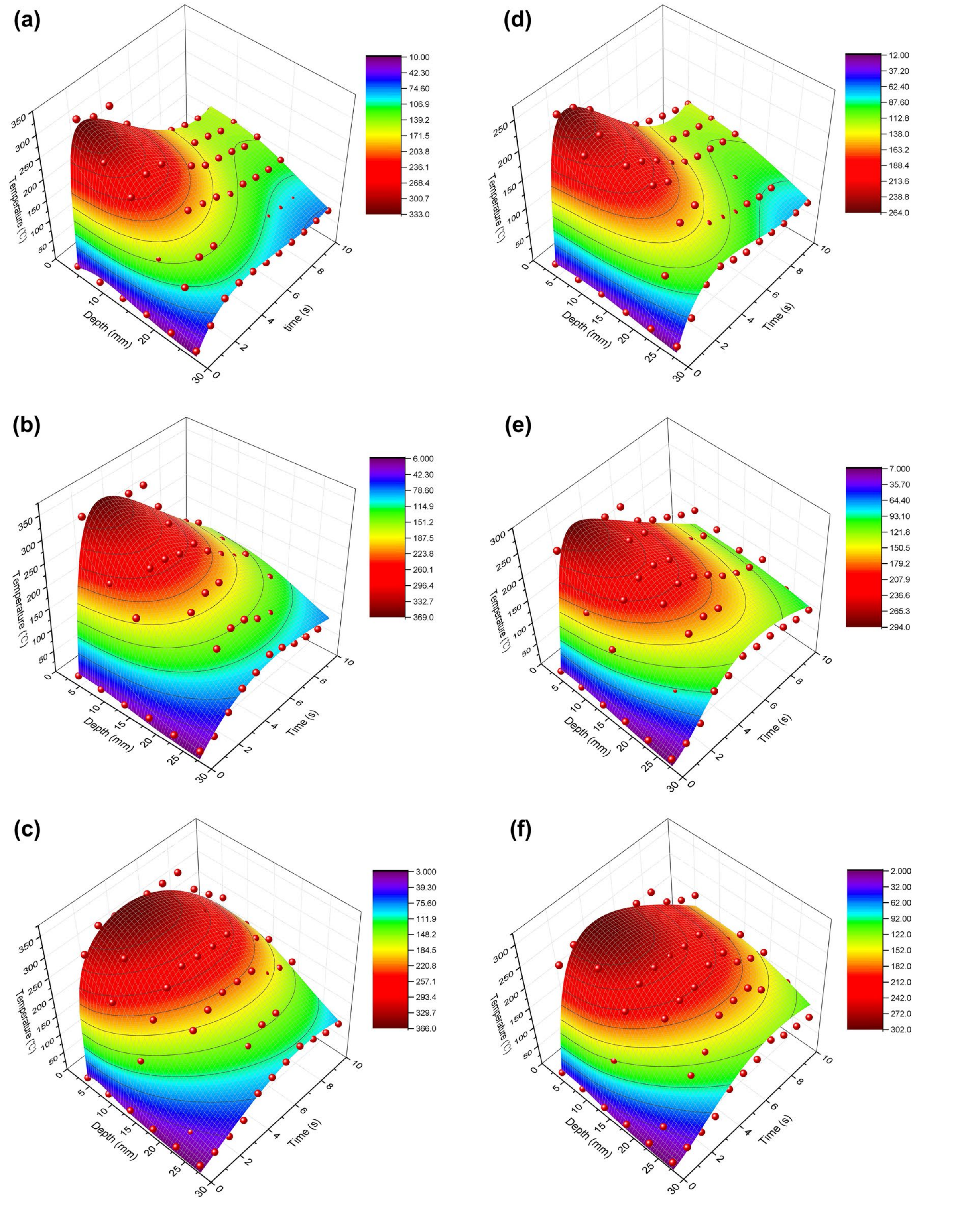

Fig. 3 Temperature regression analyses of different times for the untreated and pretreatment group. **a**–**c** Untreated group with welded times 3, 5, 7 s. **d**–**f** Pretreated group with welded time 3, 5, and 7 s

Pretreated group—3 s

$$Z = \frac{53.1297 + 110.584X + 21941.3Y - 3760.5Y^2 + 189.386Y^3}{10^{-5} + 5.91414X - 0.36763X^2 + 0.01678X^3 + 54.5401Y - 3.10624Y^2}. \tag{5}$$

Pretreated group—5 s

$$Z = \frac{16020.3 + 4414.35X + 211304Y + 241935Y^2 - 17051.4Y^3}{10^{-14} + 355.566X - 30.4784X^2 + 1.51296X^3 - 28.9277Y + 815.262Y^2}. \tag{6}$$

Pretreated group—7 s

$$Z = \frac{7275.13 + 545.237X + 90006.1Y + 49525.2Y^2 - 3563.72Y^3}{10^{-15} + 106.1X - 13.2893X^2 + 0.687208X^3 + 270.961Y + 110.209Y^2}. \tag{7}$$

The correlation coefficients of the nonlinear fitting formula of the three welded time the pretreated experimental groups were 94.77, 93.93, and 94.52%, respectively, which indicated that the fitting precision of the nonlinear fitting surface was high. The regression relationship among temperature and depth, time is also in accordance with the general formula (4).

The relationship between the highest temperature and welded depth

Because the welding process time is shorter, the pyrolysis of wood components occurred in the short term. So the highest temperature of the welding interface at different depths had significant influence on the molten material. Figure 4 shows the linear regression relationship between the highest temperature and the depth of untreated group. The corresponding linear fitting formula is shown in formulas (8)–(10).

Untreated group—3 s

$$Y = -10.51144X + 397.84254. \tag{8}$$

Untreated group—5 s

$$Y = -10.26982X + 408.24198. \tag{9}$$

Untreated group—7 s

$$Y = -11.02664X + 425.68181. \tag{10}$$

The correlation coefficients of the linear fitting formulas of the three welded time experimental groups were 98.79, 98.90, and 98.73%, respectively, which indicated that the fitting precision of the linear fitting surface was high. The regression relationship between the highest temperature and depth was in accordance with the general formula 11:

$$Y = kX + b. \tag{11}$$

From Fig. 4, the temperature trend of each measuring point at different welded times was similar. But in welded time 7 s experimental group, the temperatures at depth of 23 and 28 mm were significantly different from the other two groups of welded time 3 and 5 s. The highest temperature of each depth of the welded time 3 s group was lower than that of the other two groups, indicating that relatively smaller amount of heat generated by shorter friction time. In the welding interface, welded time 5 s experimental group had much more black melt material than the welded time of 3 s experimental group, and the black melt material overflowed from the wall of the hole between the wood dowel and the larch substrate (Fig. 5). This phenomenon showed that due to the extension of the friction time, the heat generated by friction was relatively large, which resulted in more molten material. However, in the welded time 7 s experimental group, the friction time was further increased with more molten material overflow, resulting in the welding interface layer not having enough molten material to fill. So it caused cracking phenomenon and also made the 23 and 28 mm temperature less than the welded time 5 s experimental group. But there was still a small amount of molten material flow into these two points; so the temperature was still higher than that of the welded time 3 s experimental group.

The above analysis showed that with the extension of the welded time, the high temperature of the welding interface was maintained longer and more heat was generated during the welding progress.

Figure 6 shows the regression relationship between the highest temperature and the depth of the pretreated group. According to the distribution characteristics of the highest

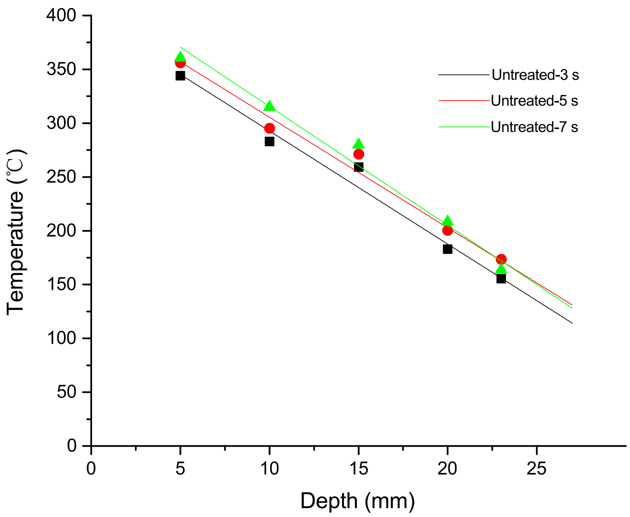

Fig. 4 Linear regression analyses of the highest temperature with each test point of the untreated group

temperature, two-stage fitting was used to fit the regression. It was found that the linear regression relationship was at the depth of 5–15 mm, and the depth of 15–28 mm was for the nonlinear regression relationship. The corresponding linear fitting formula iss shown in formulas (12)–(14).

Pretreated group—3 s

$$\begin{cases} Y = -5.37X + 291.47 \\ Y = 216.73208 - 0.08934 \times e^{\frac{X}{3.91909}} \end{cases}. \tag{12}$$

Pretreated group—5 s

$$\begin{cases} Y = -4.47X + 295.1 \\ Y = 236.35068 - 0.09284 \times e^{\frac{X}{3.91711}} \end{cases}. \tag{13}$$

Pretreated group—7 s

$$\begin{cases} Y = -3.93X + 310.6 \\ Y = 266.02188 - 0.59921 \times e^{\frac{X}{5.04288}} \end{cases}. \tag{14}$$

The correlation coefficients of the three sets of fitting formulas were higher than 95%, indicating that the three formulas had high fitting precision between the highest temperature and the depth of the different welded time for the pretreated group. The general formula is as follows:

$$\begin{cases} Y = kX + b \\ Y = Y_0 - a \times e^{\frac{X}{t}} \end{cases}. \tag{15}$$

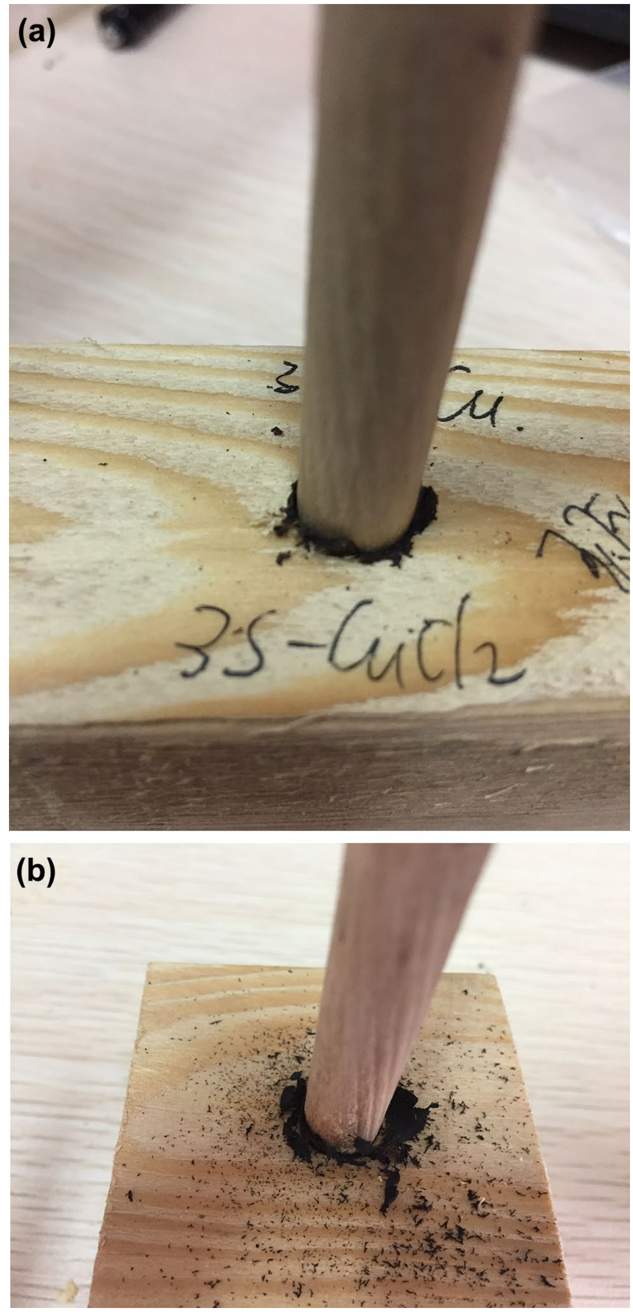

Fig. 5 Black molten materials out of the welding interface. **a** Welding time 3 s, **b** welding time 5 s

For the analysis of the fitting formula in Fig. 6 and fitting formulas (12)–(14), compared with the untreated test group, the highest temperature of the welding interface in the pretreated group was significantly lower than that in the untreated group, indicating that pretreatment with $CuCl_2$ significantly reduced the friction between the birch wood dowel and the inner wall of the larch substrate. And the slope of linear fitting curve of 5–15 mm was significantly smaller than that of untreated group, which indicated that

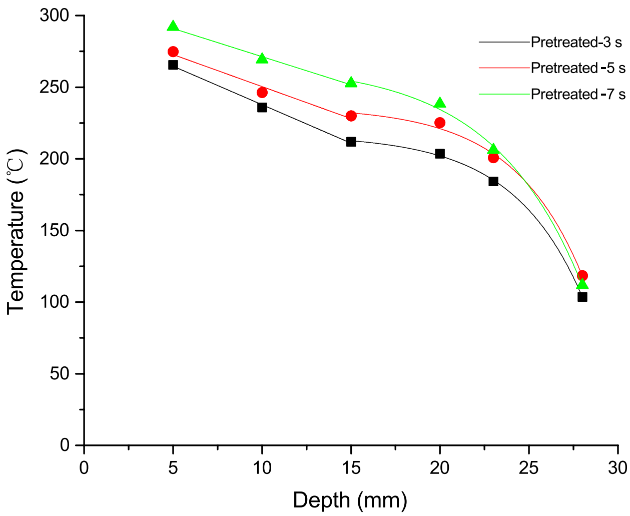

Fig. 6 Regression analyses of the highest temperature with test points for the pretreated samples

the highest temperature of the pretreated group decreased less than that of untreated group. The degree of loss before the depth of 15 mm was lower than that of the untreated group. Although the initial frictional force was insufficient, the heat generated by the continuous friction reduced the temperature difference between the depths. However, at the depth of 15–23 mm, the highest temperature of the welding interface decreased obviously, but decreased rapidly at the depth of 28 mm.

TG analyses

From the TG curves in Fig. 7, the weightlessness process of the samples was divided into three stages: in the first stage, before 225 °C, the weightlessness was gentle, probably because of water evaporation and partial wood extract caused by pyrolysis; in the second stage, 225–390 °C, the weightlessness was very intense, probably caused by the cellulose and hemicellulose pyrolysis; in the third stage, 390–600 °C, the weightlessness continued, but slowly. The weightlessness behavior of the wood dowel and welding interface material of the untreated and pretreated group were similar, but the weight loss percent and the final residual ratio during weight loss were slightly different, as shown in Table 2.

The residual ratio of the wood dowel in the pretreated group was higher than that in the untreated group. It indicated that the wood dowel after being immersed in $CuCl_2$ solution for 30 min had a relatively large amount of lignin, probably because acid hydrolysis occurred in hemicellulose and cellulose during the immersing process, causing a relative increase in lignin content. The lower weight loss percent of the wood dowel of the samples pretreated with $CuCl_2$ in the second stage could also indicate that the content of hemicellulose and cellulose was relatively small. With the extension of the welded time, the interface material of the samples pretreated with $CuCl_2$ showed a decreasing trend. It indicated that the extension of welded time promoted the

Fig. 7 TG/DTG curves of wood dowel and welding interface

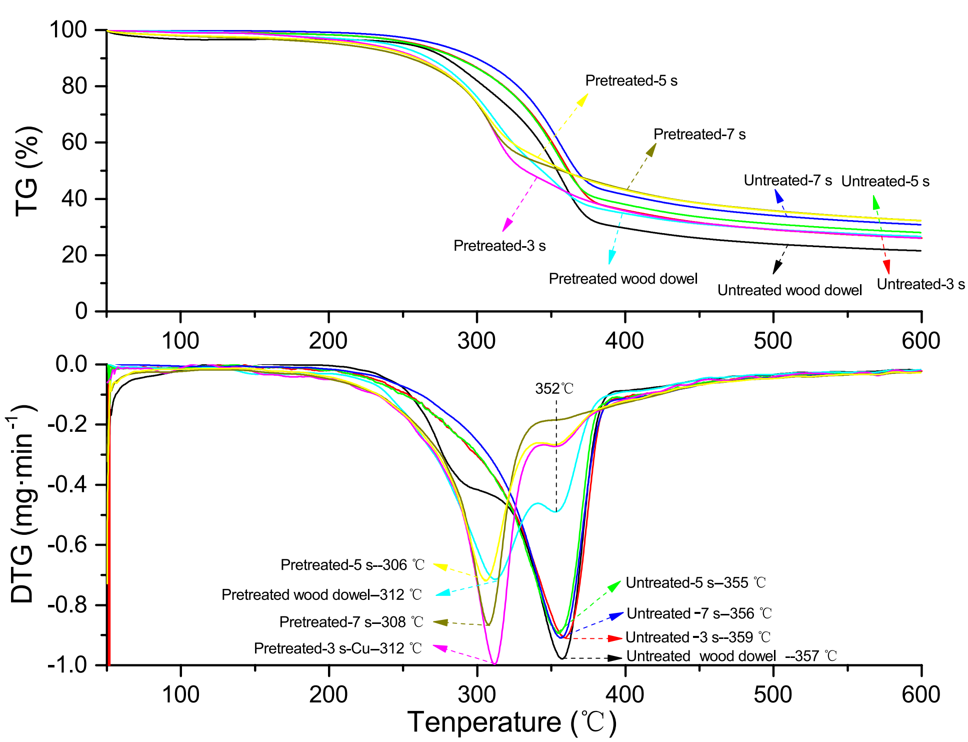

Table 2 TG weight loss percent and residual ratios for wood dowel and welding interface

Test group	Weight loss percent (%)			Residual ratio (%)
	First stage	Second stage	Third stage	
Untreated wood dowel	3.7	66.7	8.0	21.5
Untreated—3 s	3.1	63.5	8.1	25.3
Untreated—5 s	2.4	59.5	10.0	28.0
Untreated—7 s	1.4	57.1	10.6	30.8
Pretreated wood dowel	3.9	59.3	10.2	26.7
Pretreated—3 s	4.9	56.7	12.3	26.1
Pretreated—5 s	5.4	48.8	13.5	32.2
Pretreated—7 s	6.3	47.6	13.9	32.3

The first stage: before 225 °C, the second stage: 225–390 °C, the third stage: 390–600 °C

pyrolysis of hemicellulose and cellulose, causing a relative reduction in the content of hemicellulose and cellulose in the interface material. The increase in the weight loss percent at the third stage may be caused by a small amount of lignin pyrolysis. Compared with the interface material of the untreated group and the pretreatment group at the same welded time, the residual ratio and the third stage weight loss percent were lower in the untreated group than in the pretreatment group. The weight loss percent of the untreated interface material was higher than that of the pretreated interface material at the second stage. The results indicated that the relative content of lignin in pretreated interface materials may be higher than that of untreated interface materials.

From the DTG curves, unlike the untreated group, the wood dowel and welding interface materials of the pretreated group showed two peaks at 310 and 352 °C, respectively. The results indicated that the acid hydrolysis of hemicellulose and cellulose was caused by the pretreatment with $CuCl_2$, and the pyrolysis temperature of the relevant components was early. The peak temperature around 352 °C showed a decreasing trend with the extension of the welded time, and it even disappeared for the pretreated specimens with welded time 7 s. The extension of the welded time led to a greater degree of pyrolysis of hemicellulose and cellulose, as well as the breakage of the long cellulose chain. The peak near 310 °C of $CuCl_2$ pretreated samples with welded time 3 s was the strongest, the samples with welded time 7 s slightly weaker, and the samples with welded time 5 s the weakest. The peak strength near 310 °C of the samples of welded time 7 s pretreated with $CuCl_2$ was lower than that of the welded time 3 s group. It showed that the higher degree of hemicellulose and cellulose components pyrolysis during welding for welded time 7 s group. The peak strength near 310 °C of the samples with welded time 7 s pretreated with $CuCl_2$ was higher than that of welded time 5 s group. Beacuse the interface material components of welded time 7 s group were pyrolysis basically in the vicinity of 310 °C, but part of the interface material component of welded time 5 s group were pyrolysis in the vicinity of 352 °C. After 390 °C, the pyrolysis rate of pretreated interface material was significantly higher than that of the untreated interface material. This was probably because of the greater degree of hemicellulose and cellulose pyrolysis in the interface material pretreated with $CuCl_2$ during the welding process, resulting in a relative increase in lignin content and then the pyrolysis rate increase. It may also result from the role of acid hydrolysis in the impregnation process and the effect of friction tearing during the welding process, which made the lignin more exposed to the pretreated interface material, causing the pyrolysis rate to increase during the TG analysis.

From the TG curves, it could be found that the shoulder of the pyrolysis weight loss appeared in advance. This phenomenon was consistent with the phenomenon where the pyrolysis velocity peak appeared early at approximately 310 °C on the DTG curve. This proved that the pyrolysis rate during the early stage of the welding progress was increased. It was generally believed that the thermogravimetric platform prior to 250 °C was a process in which the cellulose was depolymerized and formed the glassy state transition, thereby forming a reactive cellulose. In this study, the $CuCl_2$ on the wood dowel may have a catalytic effect on the pyrolysis process of cellulose, causing the TG curve shoulder of wood dowel pretreated with $CuCl_2$ to appear in advance and to increase the reaction speed [15]. However, with the increase in reaction temperature, the pyrolysis rate of wood dowel pretreated with $CuCl_2$ was lower than that of the untreated group. The addition of copper ions caused the cellulose pyrolysis weight loss to decrease significantly and slowly into the carbonization stage, which resulted in the total weight loss rate of wood dowel pretreated with $CuCl_2$ to be lower than that of the untreated group. It was also one of the reasons why the final residual ratio of the welding interface material of the pretreated group was higher than that of the untreated group. As the temperature of the welding interface reached about 250 °C during the welding process, the cellulose underwent a faster pyrolysis reaction under the catalysis of $CuCl_2$. Finally, the relative crystallinity of the interface material in the pretreated group was lower than that of the untreated group, which was consistent with the previous X-ray diffraction (XRD) analysis [16, 17]. The DTG curve showed that with the extension of welded time, the amount of cellulose pyrolysis was greater during the welding process, which was also one of the reasons for the decrease in pullout resistance.

Conclusions

The pretreatment of wood dowel with $CuCl_2$ could effectively improve the pullout resistance of wood dowel welding. The samples with welded time 3 s pretreated with $CuCl_2$ showed the best pullout resistance, and it was 68.28% higher than untreated samples with welded time 3 s. In both the untreated group and pretreated group, pullout resistance was affected by the different welded times. With the extension of the welded time, pullout resistance decreased. The pullout resistance of welded time 3 s was 28.33% and 87.12% higher than that for welded times 5 and 7 s, respectively. The pullout resistance for welded time 3 s showed the smallest variability and the best reliability.

The welding interface had high temperature during the welding process, but the temperature decreased rapidly once the rotation stopped. There was nonlinear regression that could fit the temperature distribution of the welding interface. Moreover, a relationship also existed between the highest temperature of the welding interface and welding depth.

TG analysis showed that the enhancement mechanism of wood dowel pretreated with $CuCl_2$ was that acid hydrolysis of hemicellulose and cellulose of wood dowel occurred during the process of $CuCl_2$ immersion. This method promoted the formation of more molten materials by the depolymerization and pyrolysis of the wood constituents.

In this paper, $CuCl_2$ was found to effectively improve the pullout resistance of wood dowel welding [11]. But as a chemical substance, $CuCl_2$ is not the best choice considering its slight adverse effect on the environment. Instead of $CuCl_2$, an environment-friendly enhancement method should be further developed in future studies.

Acknowledgements This research work was jointly supported by the National Key R&D Program of China (2017YFC0703503), the National Natural Science Foundation of China (31770602), the Special Found for Beijing Common Construction Project (2015GJ-01), and the project for Follow-up Hot Issues of Beijing Forestry University (2016BLRD03).

Author contributions YG designed the experiment; XZ and JZ performed the experiment and analyzed data; JZ and JZ completed the pullout resistance test; JZ prepared and edited the manuscript; and YG reviewed and directed the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

References

1. Pizzi A, Despres A, Mansouri HR, Leban JM, Rigolet S (2006) Wood joints by through-dowel rotation welding: microstructure, 13c-nmr and water resistance. J Adhes Sci Technol 20(5):427–436
2. Belleville B, Stevanovic T, Pizzi A, Cloutier A, Blanchet P (2013) Determination of optimal wood-dowel welding parameters for two North American hardwood species. J Adhes Sci Technol 27(5–6):566–576
3. Belleville B, Ozarska B, Pizzi A (2016) Assessing the potential of wood welding for Australian eucalypts and tropical species. Eur J Wood Wood Prod 74(5):1–5
4. Ganne-Chedeville C, Pizzi A, Thomas A, Leban JM, Bocquet JF, Despres A, Mansouri H (2005) Parameter interactions in two-block welding and the wood nail concept in wood dowel welding. J Adhes Sci Technol 19(13–14):1157–1174
5. Zoulalian A, Pizzi A (2007) Wood-dowel rotation welding-a heat-transfer mode. J Adhes Sci Technol 21(2):97–108
6. Rodriguez G, Diouf P, Blanchet P, Stevanovic T (2010) Wood-dowel bonding by high-speed rotation welding—application to two canadian hardwood species. J Adhes Sci Technol 24(8–10):1423–1436
7. Pizzi A, Leban JM, Kanazawa F, Properzi M, Pichelin F (2004) Wood dowel bonding by high-speed rotation welding. J Adhes Sci Technol 18(11):1263–1278
8. Placencia PMI, Rheme M, Pizzi A (2015) Mechanical properties of welded wood joints with natural additives. Holztechnologie 56:5–9
9. Placencia PMI, Deutschle AL, Saake B, Pizzi A, Pichelin F (2016) Study of the solubility and composition of welded wood material at progressive welding times. Eur J Wood Wood Prod 74(2):191–201
10. Pizzi A, Mansouri HR, Leban JM, Delmotte L, Pichelin F (2011) Enhancing the exterior performance of wood linear and rotational welding. J Adhes Sci Technol 25(19):2717–2730
11. Zhu XD, Yi SL, Gao Y, Zhang JR, Ni C, Luo XY (2017) Influence of welded depth and $CuCl_2$ pretreated dowels on wood dowel welding. J Wood Sci. https://doi.org/10.1007/s10086-017-1644-1
12. Kanazawa F, Pizzi A, Properzi M, Delmotte L, Pichelin F (2012) Parameters influencing wood-dowel welding by high-speed rotation. I Adhes Sci Technol 19:1025–1038
13. Ren XY, Du HS, Wang WL, Gou JS, Chang JM (2012) Study on the law of thermal loss and pyrolysis of larch wood based on TG–FTIR. Spectrosc Spectr Anal 32(4):944–948
14. Tan H, Wang SR, Luo ZY, Cen KF (2006) Pyrolysis behavior of cellulose, xylan and lignin. J Fuel Chem Technol 34:61–65
15. Liao YF (2003) Mechanism study of cellulose pyrolysis. Dissertation, Zhejiang University, China
16. Zhu XD, Yi SL, Gao Y, Zhao YT, Qiu YQ (2017) Mechanical evaluation and XRD/TG investigation on the properties of wooden dowel welding. Bioresources 12(2):3396–3412
17. Zhu XD, Gao Y, Yi SL, Ni C, Zhang JR, Luo XY (2017) Mechanics and pyrolysis analyses of rotation welding with pretreated wood dowels. J Wood Sci 63:216–224