Temperatures in Rotary Welding of Dowels in the Beech Wood

Ivica Župčić, Karlo Povrženić, Krešimir Balaško, and Kristijan Radmanović *

Welding temperature is an important factor of rotary welding and affects the strength of the joint or the embedded force. This research focused on the parameters that affect the welding temperature and the effect of welding temperature on the embedded force of the dowel. Welding temperature was measured using measuring probes that were moved away from the dowel being welded. The results indicate that the speed of the dowel feed (duration of the welding process) influenced the welding temperature; the embedded force was then determined. With increased rotation frequency with the same duration of the welding process, there was a slight increase in the welding temperature. The influence of the rotational frequency on the extraction force was not unambiguously determined, because the rotational frequency is related to the duration of the welding process. As the welding temperature increased, the embedded force decreased. To avoid difficulties in contact measurement of welding temperature, it is necessary to develop a mathematical model of heat transfer to more accurately determine the welding temperature.

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Keywords: Welding solid wood; Embedded force; Rotary welding temperature; Dowel joints; Temperature transfer model

*Contact information: University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska cesta 23, 10 000 Zagreb, Croatia; *Corresponding author: kradmanovic@sumfak.hr*

INTRODUCTION

Wood is a natural polymer material that has long served man in everyday life. Because wood is a thermoplastic material, rotary, vibration, and ultrasonic welding techniques can be applied to it. In rotary welding, the dowel rotates and shifts in the direction of the longitudinal axis. Rotation results in friction between the rotating surface and the stationary surface, creating heat. The heat softens both the melted lignin and the hemicellulose, and with cooling, the melt thus forms a solid compound (cross-linked structure). During welding, a melt appears whose analysis provides insight into events in the welding process. Carbohydrates are the main component of the melt, and lignin modification occurs (Pizzi *et al.* 2006). In addition to the modification of lignin in the welding zone, there is also a migration of lignin from the cell wall to adjacent lumens (Župčić 2010). Welded joints are environmentally friendly, and the short time required for the joint to harden favors the welded joint over conventional wood bonding (Gedara *et al.* 2021). Approximately 2 s after welding, the rotary welded joint reaches a steady state (Yin *et al.* 2021).

Belleville *et al.* (2013) investigated the optimal parameters in rotary welding of dowels for yellow birch (*Betula alleghaniensis* Britt.) and sugar maple (*Acer saccharum* Marshall). The type of wood, the frequency of welding, and the displacement of the dowels along the longitudinal axis (insertion speed) had a significant influence on the strength of the joint. The optimal insertion speed for maple was 12.5 mm/s, and for birch 16.7 mm/s. Temperature profile measurements at the interface during rotational wood-dowel welding were also carried out. The maximum welding temperatures were 244 °C for sugar maple and 282 °C for yellow birch. Welding temperature is not easy to measure; thus there are different ways to measure welding temperature. Kanazawa *et al.* (2005) measured the welding temperature with a thermal chamber with the joint open. The measured temperature was higher than 180 °C, so it is to be assumed that if the joint was closed, the welding temperature would be higher. The unreliability of thermal chamber welding temperature measurements is also confirmed by Rodriguez *et al.* (2010). Gfeller *et al.* (2003) measured the welding temperature by inserting a sample into the joint in linear vibration welding. The measured temperature was over 170 °C. With such a method of measuring the welding temperature, friction could occur between the measuring probe and the wood to be welded (Gfeller *et al*. 2003). Welding depth affects the welding temperature. At a welding depth of 5 mm, the welding temperature was 350 °C and it decreases linearly, so at a depth of 23 mm, the welding temperature was 150 °C (Zhang *et al.* 2018). The temperature was measured using six thermocouple sensors with the data collecting device. Six sensors were set in six different depths along 5, 10, 15, 20, 23, and 28 mm. This shows that pyrolysis is most pronounced at the beginning of welding.

Rodriguez *et al.* (2010) conducted research on birch (*Betula alleghaniensis*) and maple (*Acer saccharum*) using the three rotational frequencies of 1000, 1500, and 2500 min^{-1}. The welding temperature is directly related to the rotational frequency; as the rotational frequency increases, the welding temperature in the joint increases. During the welding process, temperature was monitored with fast response thermo-couples placed in thin predrilled holes placed at 1 mm and 2 mm distance from the inserted dowel. For maple evaluated at 1000 min^{-1} the average welding temperature ranged from 269 and 273 °C, for 1500 min^{-1} the average welding temperature was between 279 and 281 °C, and for 2500 min^{-1} the average temperature was between 311 and 323 °C. The average temperature for birch at 1000 min^{-1} was between 243 and 252 °C, at 1500 min^{-1} the average temperature was between 263 and 277 °C, and at 2500 min^{-1} the average temperature was between 306 and 308 °C.

To avoid shortcomings, welding temperature measurements (Zoulalian and Pizzi 2007) determined the relationship between welding temperature, the duration of the welding process, and the heat flux in rotary welding. Fast response thermocouples capable of measuring temperature at 0.3 s intervals were inserted in thin pre-drilled holes placed at 1 and 2 mm distances from the walls of the hole in which the dowel was to be inserted. The temperature of the contact surfaces can be determined using the time function. According to the authors, the optimal welding temperature would be 183 °C. Vaziri *et al.* (2014) developed a computational model to explain the thermal behaviour of welded wood material. This model serves as a prediction tool for welding parameters. This three-dimensional heat transfer model can simulate the thermal behaviour of welded wood (Vaziri *et al.* 2014). With regard to difficulties arising from contact measurement of temperature, the heath transfer model was created to obtain more exact welding temperature results to account for the effects of time, heat source intensity, and the ability of material when transferring heat energy from the source to the measuring point (Župčić *et al.* 2021).

Ganne-Chedeville *et al.* (2005) found that a key rotation frequency of 1515 min^{-1} achieved a higher joint strength compared to a welded joint with a rotation frequency of

1165 min^{-1} for beech (*Fagus sylvatica* L.) and pine (*Pinus sylvestris* L.). Beech dowels with a diameter of 12 mm welded at a rotation frequency of 1500 min^{-1} achieved the highest strength of the welded joint. Through increasing the rotational frequency from 4000 to 6500 min^{-1} and reducing the welding duration, the joint strength decreased (Leban *et al.* 2008). The highest values of the embedded force (average 4994 N) were achieved by beech dowels welded with a rotational frequency of 1520 min^{-1} with the duration of the welding process in the interval from 0.56 to 0.9 s (Župčić *et al.* 2011). Increasing the welding time to 2.6 s reduces the embedded force, so in the last interval from 1.81 s to 2.61 s, the average value of the embedded force was 2869 N. Increasing of the rotational frequency from 865 to 1520 min^{-1} increased the pulling force in pine (*Pinus sylvestris* L.) and in beech specimens (*Fagus sylvatica* L.) (Župčić *et al.* 2021). Increasing the rotational frequency of the dowel also affected a slight increase in temperature during welding and embedded force. Samples that were treated with $CuCl_2$ with a welding process duration of 3 s achieved 68% higher embedded force than untreated samples with the same welding time (Zhang *et al.* 2018). With extension of the welding time, the embedded force was reduced.

The welding temperature depends on the friction that occurs between the surfaces in contact (one surface rotates and the other rests). Therefore, the welding temperature depends on the rotational frequency of the dowel, the difference between the diameter of the dowel and the hole, the type of wood, and the duration of the welding process. Measuring the temperature in the joint during the welding process is demanding, which is evident from previous research. Additionally, during contact temperature measurement, the measuring probe is expected to be highly sensitive, not in contact with the rotating dowel, and yet close enough to be able to measure the required data. Therefore, it is necessary to connect the measured values of temperature with the mathematical model of theoretical heat transfer (which is not the focus of this paper).

The aim of this paper was not to determine the maximum temperature during welding, but the distribution and movement of temperature in the joint in rotary welding depending on the duration of the welding process and the rotation frequency. It can be assumed that the welding temperature impacts the maximum embedded force or strength of the joint, and its determination and measurement is not easy. During welding, the wearing away of the surface of the dowel and the substrate in which the dowel is welded is not uniform, so the measuring probe (made in the form of a comb on top of which is a platinum temperature sensor) (Fig. 2) was moved away from the joint to be welded and could not come into contact with the dowel.

EXPERIMENTAL

Sample Preparation

Materials required for the testing were taken from a commercial stack of unknown origin. Beech (*Fagus sylvatica* L.) (Croatian origin) were used for the research with the water content of 10 to 12%, after air drying. When making and preparing samples with beech, the following techniques were used: sawing, planing, cutting down to final dimensions, drilling receiver holes on samples for dowel welding, and drilling receiver holes for probes measuring of the welding temperature. All holes were drilled on a CNC machine to be as accurate as possible and to allow proper positioning of the temperature measuring probes (Fig. 1a, 1b). Samples of (30 x 300 x 30) mm were used for the research. On beech elements, four receiver holes were drilled for dowel welding with four perpendicular receiver holes of 3 mm in diameter and a mutual distance of 4 mm for each receiver hole (Fig. 1a). The receiver holes into which the dowel was welded were drilled by a spiral drilling bit of 8.1 mm in diameter and HSS mark (Hight Speed Steal) (Schachermayer d.o.o., Zagreb, Croatia). Measuring probes were put in the lateral receiver holes for measuring the welding temperature. All samples had approximately similar radial-tangential texture. The samples thus prepared (Fig. 1a) were kept for 30 days in laboratory conditions (temperature of 23 ± 2 °C, relative air humidity of 55 ± 5%).

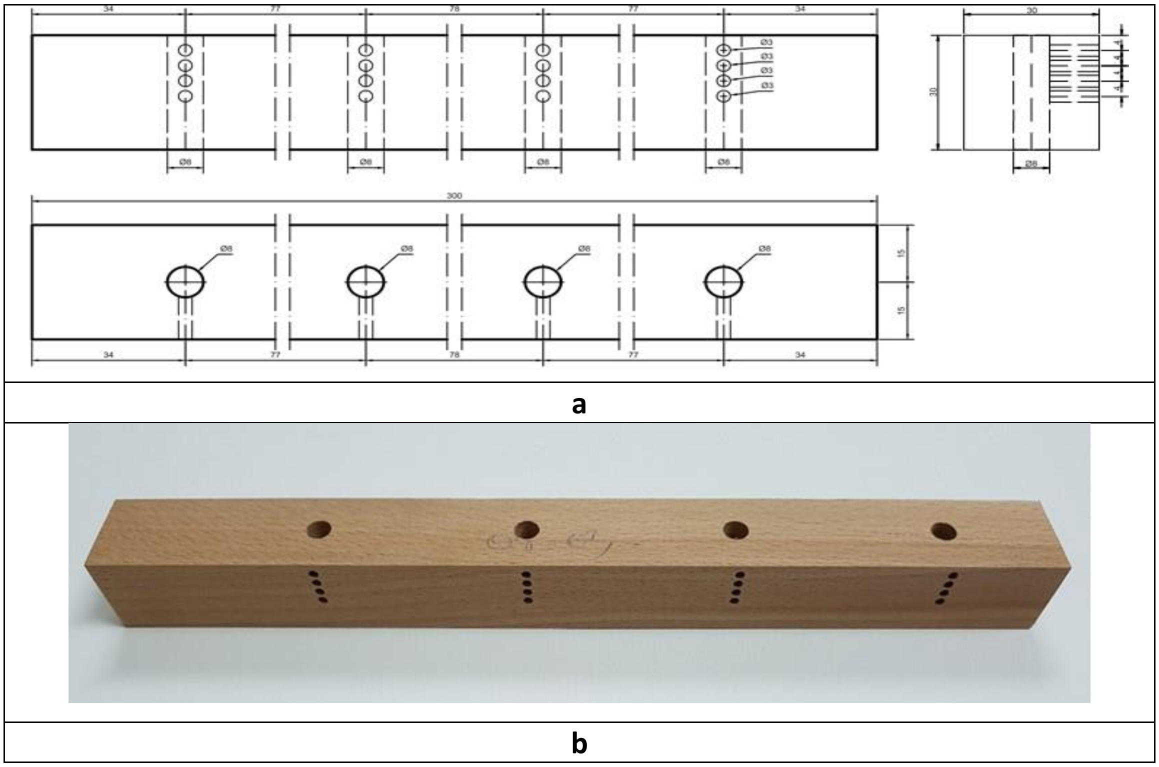

Fig. 1. a) Octagonal projection of elements with the measuring probes position, b) element prepared for welding and temperature measurement

The dowels used for welding (bought from a distributor of an unknown origin Schachermayer d.o.o., Zagreb, Croatia) were obtained from smooth beech sticks of 1000 mm in length and 10 mm in diameter. As required by the testing, the sticks were cut down to the length of 120 mm and, subsequently, their ends were bevelled by 1 mm at the angle of 45° to enable an easier welding start. Prepared in this way, the dowels were equilibrated under laboratory conditions for 30 days (temperature of 23 ± 2 °C, relative air humidity of 55 ± 5%).

Determination of Water Content and Sample Density

After production, the samples were equilibrated under laboratory conditions for 30 days (temperature of 23 ± 2 °C, relative air humidity of 55 ± 5%). After this time in the climate chamber, the water content and density were determined. The average water content (as per HRN ISO 13061-1 (2015)) of beech samples amounted to (approximately) 9.34% (the minimum water content amounted to 8.97%, and the maximum water content to 10.31%), the average density (HRN ISO 13061-2 (2015)) amounted to 0.693 g/cm³ (the minimum density amounted to 0.682 g/cm³, and the maximum was 0.699 g/cm³).

Welding of Dowels and Temperature Measurement

After 30 days of conditioning (temperature of 23 ± 2 °C, relative air humidity of 55 ± 5%), the samples were welded using a welding machine with the possibility of dowel rotation and automatic displacement along its longitudinal axis. The welding was carried out as the dowel rotated at the set constant rotation frequency with dowel displacement along the longitudinal axis. The rotation frequency during the welding amounted to 865, 1070, 1520, and 1720 min^{-1} (depending on the sample type) (Table 1). The time required to weld the dowel into the sample amounted to 2.6, 3.0, 4.2, and 5.2 s (Table 1), while the pressure on the dowel after welding (after the rotation stopped) lasted 5 to 10 s. The tightness in all sample types was 2 mm. The weld penetration amounted to 20 mm. The element into which the dowel was welded was static, and the welding direction of the rotating dowel was perpendicular to the direction of wood fibres. A total of 280 samples were welded. Some had a crack or fracture of the dowel and were not used in the research.

Table 1. List of Designations Used

Sample Designation	Welding Duration (s)	Rotation Frequency (min^{-1})	Feed According to Rotation (mm)
BU_865_f90_x	2.6	865	0.534
BU_1070_f90_x	2.6	1070	0.431
BU_1520_f90_x	2.6	1520	0.304
BU_1720_f90_x	2.6	1720	0.268
BU_865_f52_x	4.2	865	0.330
BU_1070_f52_x	4.2	1070	0.267
BU_1520_f52_x	4.2	1520	0.188
BU_1720_f52_x	4.2	1720	0.166
BU_865_f40_x	5.2	865	0.266
BU_1520_f70_x	3.0	1520	0.263
x- indicates the ordinal number of the welded dowel (1 through 28)			

During the welding, the temperature was measured in the rotation zone by measuring probes and software developed and created at the University of Zagreb, Faculty of Forestry and Wood Technology. The temperature was measured by three measuring probes placed into the receiver holes perpendicular to the dowel welding direction (Fig. 1). Although the sample was prepared for temperature measurement using four probes, temperature measurements in this study were performed with three measuring probes. The distance between measuring probes was 4 mm. The first probe measured the temperature at 4 mm, the second at 8 mm from the upper edge, and third at 12 mm from the upper edge of the receiver hole into which the dowel was welded. The first measuring probe was 1.9 mm away, the second 2.3 mm, and the third 2.7 mm from the rotating dowel. Wearing away of the dowel and the substrate in which the dowel is welded is not always symmetrical. For this reason, a greater distance is a guarantee that the dowel will not come into contact with the measuring probe. The software recorded the current temperature and displayed the data in the form of a graph in real time. PT1000 (M – el GmbH, Geithain, Deutschland) platinum temperature sensors were used for the testing with the temperature range between -70 and +550 °C. The temperature sensor was of class B with a possible error of 0.3%, temperature coefficient 3850 ppm/°C, and dimensions (2.3 x 2.1 x 0.9) mm. The platinum temperature sensor was made by sensing the resistance of metal platinum (Pt) as a function of temperature. It was used because of its high measurement accuracy, large measurement range, reproducibility, and stability. The software measured 188 temperature data in one second and recorded them in Microsoft Excel 2007.

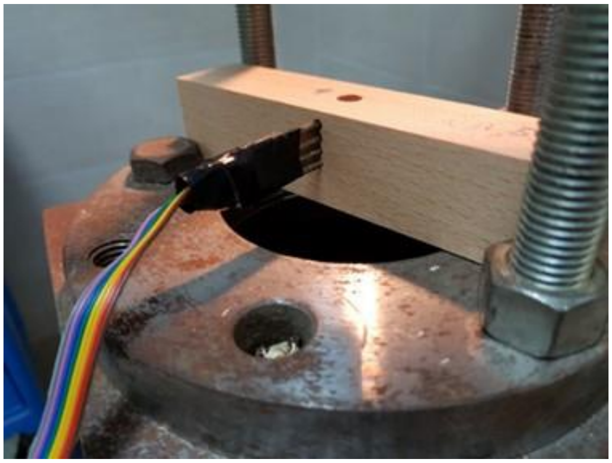

Fig. 2. Positioning of the device with probes during the welding temperature measurement

Testing Method of Embedded Force

The welded samples were conditioned for eight days and tested on the universal testing machine after that. The sample testing was conducted on a computer-controlled Shimadzu AG-X universal testing machine. The flow and procedures were programmed with the corresponding software (Trapezium X, Shimatzu, Kyoto, Japan). The testing speed was 5 mm/min. The samples were tested by *articulation* gripping jaws that enabled their precise positioning (Fig. 3). A total of 275 samples were used for the testing, all of them properly welded, so that there were no visible errors or other damage on the samples. The dowel welding temperature (Fig. 2) and embedded force (Fig. 3) were measured for all welded samples.

Fig. 3. Positioning of samples during the embedded force testing

RESULTS AND DISCUSSION

To achieve rotational welding, friction and displacement of the dowel in the direction of the longitudinal axis is required. The result of friction is the heat that occurs between the surfaces in contact. The heat generated melts the structure of the wood, the melt is formed, and cooling leads to welding. The heat responsible for the formation of the joint depends on a number of factors, such as the rotation frequency, the duration of the welding process, the difference between the diameter of the dowel and the diameter of the hole into which it is welded, the type of wood, and the speed feed of the dowel, *e.g.* displacement speeds, by increasing the displacement of the dowel per revolution. In all graphs, a slight increase in the embedded force is visible with an increase in the speed feed of the dowel (Fig. 4). This is an expected trend given the research conducted so far. Namely, at the same rotation frequency of the dowel, and by shortening the duration of the welding process, it is to be expected that the welding temperature will decrease. At a rotational frequency of 865 min^{-1} with a welding duration of 2.6 s, the displacement of the dowel per revolution was 0.534 mm. Under these conditions, the dowel is on the verge of endurance due to the high torsional force that tends to break it. Therefore, in such welding conditions there were dowel fractures, but a large embedded force was achieved that will be apparent later and visible from the graphs. Therefore, it follows that these are the optimal welding conditions for achieving the optimal embedded force, but not the quality of the joint due to possible dowel fractures. Through an increased duration of welding, the embedded force is slightly reduced, but the possibility of dowel fracture is also reduced.

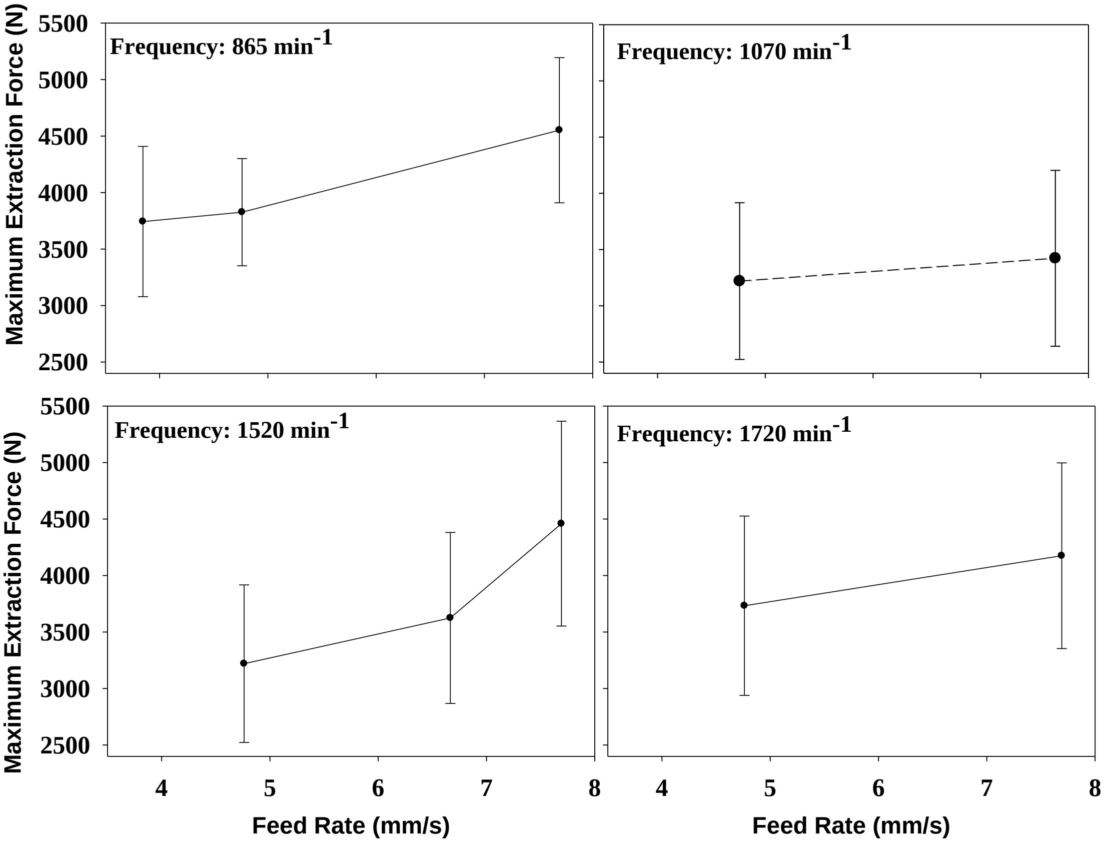

Fig. 4. Diagram of depending the maximum of the extraction force on feed rate for frequencies (865, 1070, 1520, and 1720) min^{-1}

When the welding temperature was compared with the speed of the dowel feed, it was observed that the situation was reversed in relation to the embedded force. Namely, by increasing the speed feed of the dowel movement, the welding temperature decreased (Fig. 5). This is also an important finding, namely to achieve the maximum embedded force at the joint, it is not enough just to study the rotational frequency, but rather it is important to also consider the speed feed of the dowel or the duration of the welding process. The highest welding temperature was measured by a second probe 8 mm from the top of the substrate and 2.3 mm from the rotating dowel (Fig. 5). The lowest temperature was measured by the third probe. The reason for this is the consumption of the top of the dowel due to wear, which results in a reduction in friction, and thus a reduction in temperature. The top of the dowel is worn intensively at the beginning of welding and at the end of the welding depth the diameter of the dowel is equal to the diameter of the hole and is usually not welded because the other wood fibers are melt-free (Fig. 6). Natural additives, such as lignin and rosin, can statistically significantly improve the water resistance of the welded joint (Placencia *et al.* 2015).

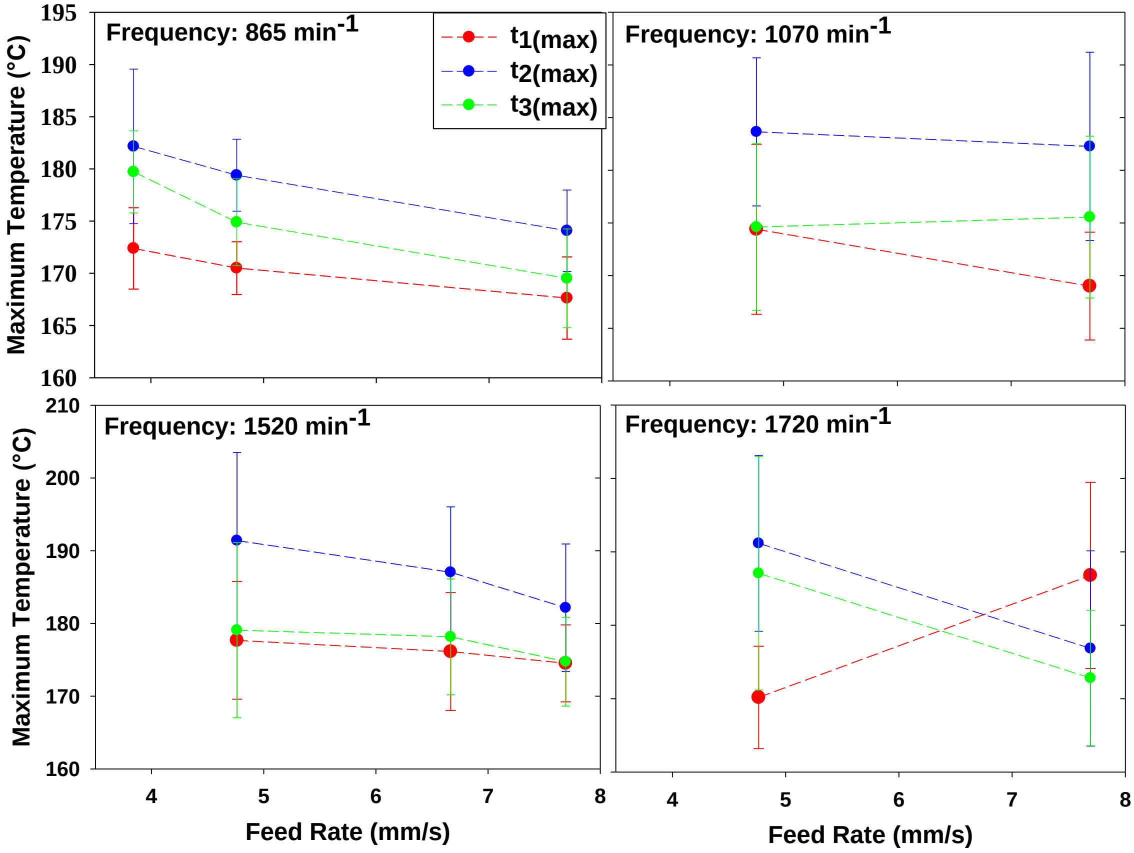

Fig. 5. Diagram of depending of the welding temperature measured at three measuring points (t_1, t_2, and t_3) on the feed rate for frequencies (865, 1070, 1520, and 1720 min^{-1})

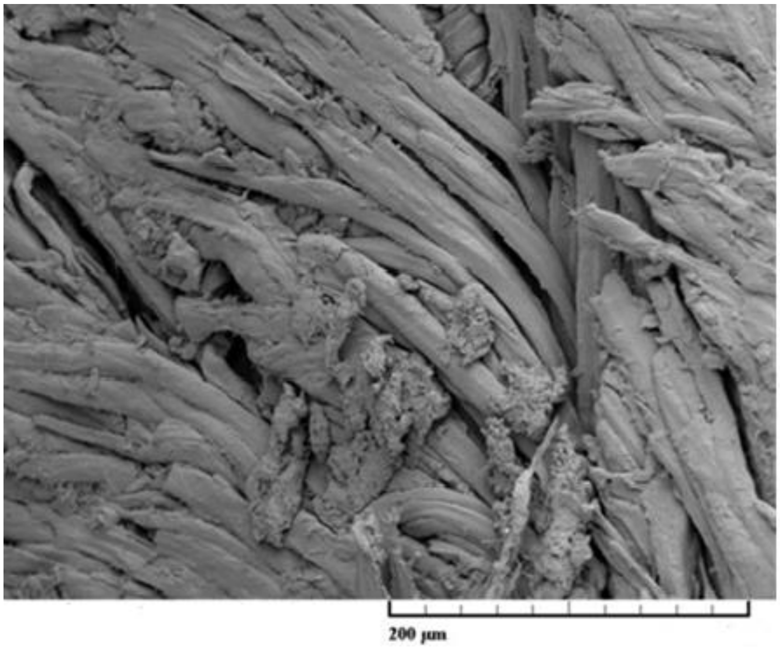

Fig. 6. The top of the dowel with fibers oriented in the direction of rotation, insufficient accumulation of melt between the fibers that would form a welded joint (Župčić 2010)

If the duration of the welding process was kept the same, and the rotation frequency of the dowel was increased, then there was a slight increase in the welding temperature (Fig. 7). When defining optimal welding conditions, in addition to the rotational frequency, the duration of the welding process is also important. If the duration of welding is longer, more black melt (which comes to the surface of the element and hardens by cooling) appears, which negatively affects the strength of the joint. Prolonging the duration of welding results in the appearance of a smooth black surface, and the strength of the welded joint is unsatisfactory.

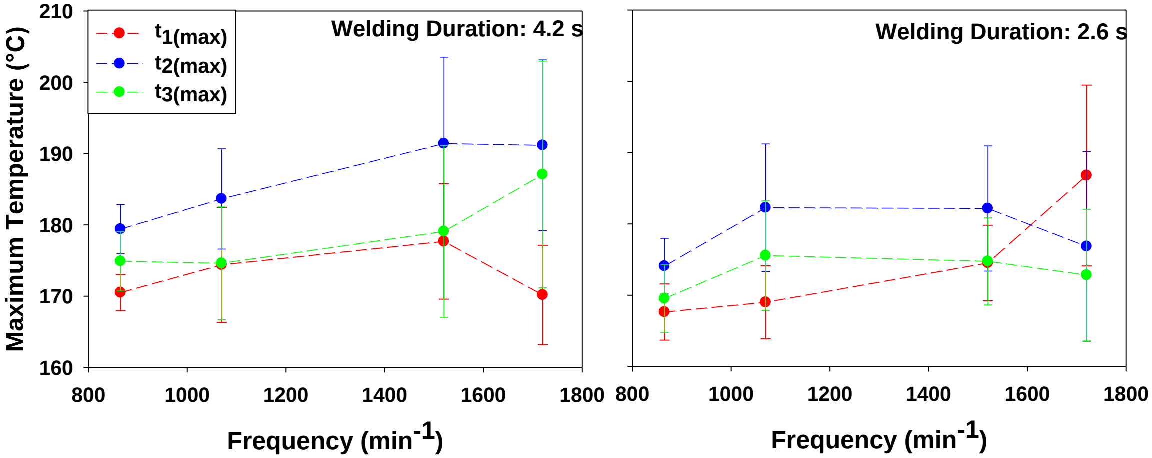

Fig. 7. Diagram of depending of the welding temperature measured at three measuring points (t_1, t_2, and t_3) on the frequencies for welding duration 4.2 s and 2.6 s

The speed of temperature change increases with increasing displacement rate of the dowel (Fig. 8) for all studied rotational frequencies. The highest rate of temperature change occurred on the middle measuring probe and the lowest on the last measuring probe. The lowest speed of temperature change was recorded at the lowest dowel displacement.

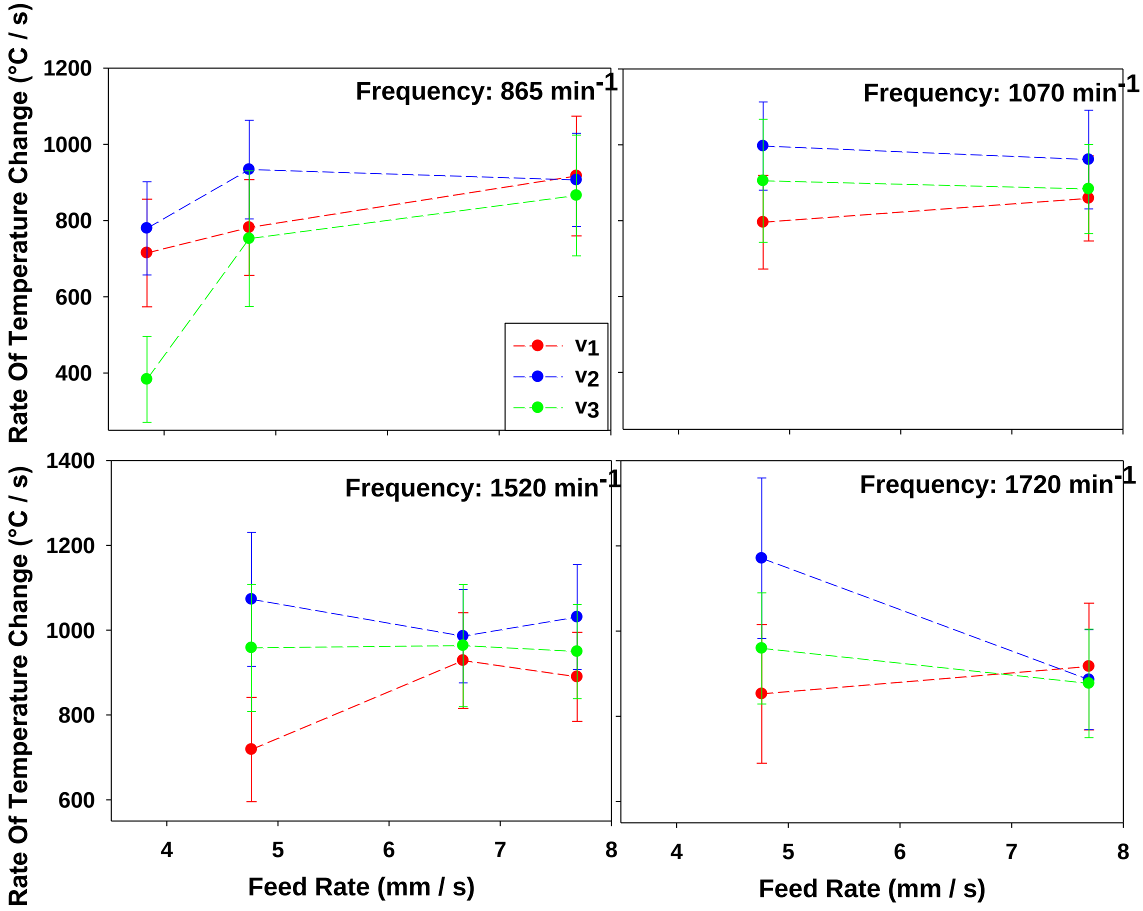

Fig. 8. Diagram of depending the rate of temperature change measured at three measuring points (v_1, v_2, and v_3) on the feed rate for frequencies (865, 1070, 1520, and 1720 min^{-1})

When defining optimal welding conditions, in addition to the rotational frequency, the duration of the welding process is also important. If the welding time is longer, then more black melt (it is visible on the surface of the element and exits laterally next to the dowel) will appear, which will affect the strength of the joint. With a welding duration of 2.6 s and a rotation frequency of 865 min^{-1}, during welding, the dowel or the substrate in which the dowel is welded will break. Namely, in such welding conditions there is a large torsional force on the dowel and its fracture. When the duration of the welding process was reduced from 4.2 s to 2.6 s, the embedded force increased at all four observed rotational frequencies (Fig. 9). When optimizing the welding process, in addition to the rotation frequency, it is necessary to correctly select the duration of the welding process. As is well known, shortening the duration of welding increases the pulling force or the possibility of fracture of the substrate or dowel.

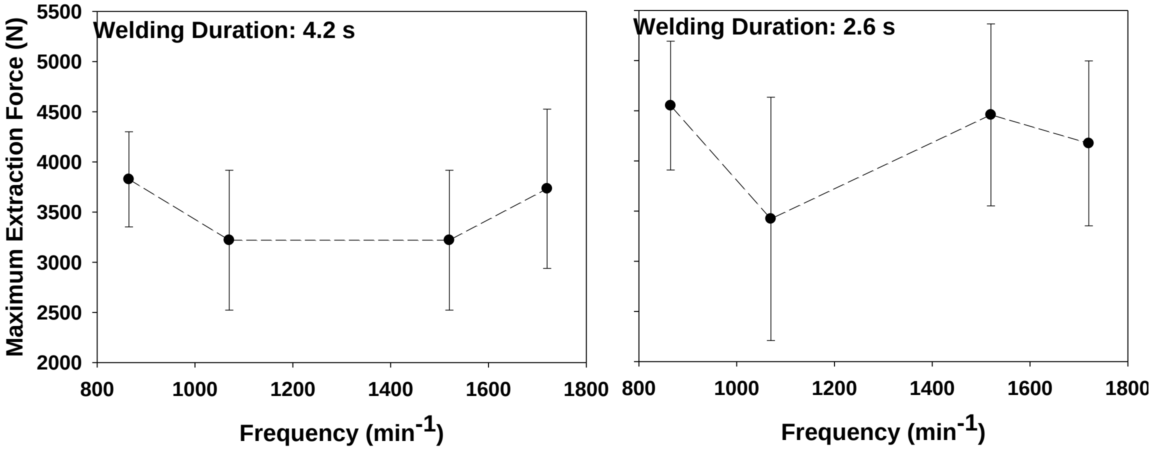

Fig. 9. Diagram of depending the maximum of the extraction force on the frequency for welding duration 4.2 s and 2.6 s

CONCLUSIONS

1. The welding temperature was found to have an impact on the quality of welding and on the welded joint. The investigated welding parameters that affected the welding temperatures were the speed feed of the dowel, the duration of the welding process, and the rotation frequency. At a rotation frequency of 865 min^{-1} with a welding duration of 2.6 s, the dowel broke due to torsion. Dowels that did not crack during welding achieved a high embedded force (over 4500 N on average).
2. The welding temperature decreased with increasing speed feed of the dowel. The drop in welding temperature depended on the duration of the welding process and the rotation frequency. The highest welding temperatures were recorded on the second probe (around the middle of the welded joint, 8 mm from the beginning of welding), and the lowest on the first probe (4 mm from the beginning of welding). There was a slight increase in welding temperature with increasing rotation frequency with unchanged duration of the welding process. With decreasing welding temperature, the extraction force increased, indicating the connection between the welding temperature and the embedded force. An increase in the embedded force for the same rotation frequency was recorded, provided that the duration of the welding process decreased.
3. The rotation frequency is related to the duration of welding, so when optimizing the welding process, care should be taken that at lower rotational frequencies (865 min^{-1} and 1070 min^{-1}), reducing the duration of welding led to fractures during the welding process.
4. The rate of change in the temperature of the welded joint increased with increasing velocity of the dowel displacement. This increase was more intense at lower speeds.

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