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Dependence of Dowel Joint Strength on Welding Temperature in Rotary Welding

Ovisnost čvrstoće spoja s moždanikom o temperaturi pri rotacijskom zavarivanju

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ABSTRACT • *The system for measuring the welding temperature with measuring probes has been developed for the requirements of this but also of future research (at the Faculty of Forestry and Wood Technology, University of Zagreb). The research is based on determining the welding temperature and its impact on the joint strength or the embedded force of the dowel. Based on research results, the impact of the dowel rotation frequency and temperature on the joint strength has been determined. The measured welding temperature increased as the rotation frequency increased (the rotation frequencies of 865 min^{-1} and 1520 min^{-1} were used in the research). The maximum welding temperature in pine samples welded at the rotation frequency of 1520 min^{-1} amounts to 217 °C, while in samples welded at the rotation frequency of 865 min^{-1} it amounts to 179 °C (weld penetration of 20 mm). The maximum welding temperature in beech samples welded at the rotation frequency of 865 min^{-1} amounts to 181 °C, and 213 °C at the rotation frequency of 1520 min^{-1} (weld penetration of 20 mm). The impact of the wood type on the welding temperature has not been proven. In order to avoid difficulties encountered in contact measurement of the welding temperature, a heat transfer model was developed for a more precise determination of the welding temperature.*

Keywords: *welding of wood; embedded force; temperature in rotary welding; dowel joints*

SAŽETAK • *Za potrebe ovoga, ali i budućih istraživanja na Fakultetu šumarstva i drvne tehnologije Sveučilišta u Zagrebu razvijen je sustav za mjerenje temperature zavarivanja uz pomoć mjernih sondi. Istraživanje se temelji na određivanju temperature zavarivanja te na njezin utjecaj na čvrstoću spoja odnosno na izvlačnu silu moždanika. Na temelju rezultata istraživanja utvrđen je utjecaj frekvencije vrtnje moždanika i temperature na čvrstoću spoja. S povećanjem frekvencije vrtnje povećava se i izmjerena temperatura zavarivanja (u istraživanju su primijenjene frekvencije vrtnje od 865 min^{-1} i 1520 min^{-1}). Najveća temperatura zavarivanja uzoraka borovine frekvencijom vrtnje od 1520 min^{-1} iznosila je 217 °C, dok je za uzorke zavarene frekvencijom vrtnje od 865 min^{-1} najviša temperatura zavarivanja iznosila 179 °C (dubina zavarivanja bila je 20 mm). Za uzorke bukovine zavarene frekvencijom vrtnje od 865 min^{-1} najviša temperatura iznosila je 181 °C, dok je za uzorke zavarene frekvencijom vrtnje od 1520 min^{-1} najviša temperatura zavarivanja bila 213 °C (dubina zavarivanja iznosila je 20 mm). Utjecaj vrste drva na temperaturu zavarivanja nije dokazan. Kako bi se izbjegle poteškoće pri kontaktnom mjerenju temperature zavarivanja, radi preciznijeg određivanja temperature zavarivanja razvijen je model prijenosa topline.*

Ključne riječi: *zavarivanje drva; izvlačna sila; temperatura pri rotacijskom zavarivanju; spoj s moždanikom*

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1 INTRODUCTION
1. UVOD

Wood welding is a more recent method of connecting wood or several wood elements or wood-based boards without the use of glue or other binders. Due to friction (rotation or vibration) between wood surfaces in contact, heat is generated, which either softens or melts lignin causing cellulose fibres to interlock in the resulting melt. As the melt hardens, the welded joint is created. There are many factors influencing the strength of the rotary welded joint such as welding duration (dowel displacement in the direction of the vertical axis per rotation), tightness (the difference between the dowel and hole diameters), weld penetration, rotation frequency, wood type, welding direction (parallel to the fibre direction or perpendicular to it), ring width (Pizzi *et al*., 2004; Župčić, 2010). The strength of the welded dowel may be compared to the strength of the glued dowel. Rotary welded joints have statistically slightly greater strength than glued dowels (Gutowski and Dodiuk, 2013; Župčić, 2010).

It is not easy and simple to measure the temperature in the welded joint. There are many attempts to measure the temperature in the joint during dowel rotation and the most common are those by thermovision. This requires the opening of the joint, which influences measured values by all means. Kanazawa *et al*. (2005) studied parameters that affect the dowel during rotational welding. The welding frequency was set at 1200 min^{-1} and the dowel longitudinal displacement rate amounted from 100 mm/min to 400 mm/min. The welding temperature measured by the thermal camera was somewhat over 180 °C. Rodrieguez *et al*. (2010) carried out a study using birch wood (*Betula Alleghaniensis)* and maple wood (*Acer Saccharum* L.) with three rotation frequencies (1000 min^{-1}, 1500 min^{-1} and 2500 min^{-1}). The welding temperature is directly correlated with the rotation frequency, that is, the higher the rotation frequency, the higher the welding temperature in the joint. The average temperature for maple wood at 1000 min^{-1} is between 269 °C and 273 °C, at 1500 min^{-1} between 279 °C and 281 °C, and at 2500 min^{-1} between 311 °C and 323 °C. The average temperature for birch wood at 1000 min^{-1} is between 243 °C and 252 °C, at 1500 min^{-1} between 263 °C and 277 °C, and at 2500 min^{-1} between 306 °C and 308 °C. The authors found that results obtained by the thermal camera are unreliable. Belleville *et al*. (2012) obtained almost identical temperature results with the same parameters, procedures and wood types. Contact measurement of the temperature in the joint welded at the rotation frequency of 1520 min^{-1} (Žulj *et al*., 2017) showed that the measured temperature value depends on the position where it is measured. The highest temperatures were recorded 8 mm from the position where the dowel enters the receiver hole and then the temperature decreases. In vibration welding on the welding line, the average of the maximum temperatures measured was approximately 165 °C, while in the centre it was approximately 200 °C (Ganne-Chedeville *et al*., 2006). It appears that already at 38 mm from the ends of the specimens, the maximum temperature has stabilised around 200 °C.

Zoulalian and Pizzi (2007) made a heath transfer model by establishing a connection between temperatures, welding duration and thermal flows in the rotational welding of the dowel. According to research results, the optimum rotational welding temperature is 183 °C. The temperature of contact surfaces may be determined as the function of time and friction duration according to Eq 1:

$$T_0 = T_i + \frac{2 \cdot \beta \cdot \mu \cdot \tau \cdot \sqrt{\alpha}}{h^* \sqrt{\pi}} \cdot \sqrt{t} \quad (1)$$

Where:

T_0 – welding temperature
T_i – initial wood temperature
t – welding time
τ – friction under pressure
μ – rotation or vibration frequency
β – mechanical energy of friction transformed into heat energy (amounts to 0.080 ± 0.01for rotational and linear welding)
h – thermal conductivity
α – wood diffusivity

Vaziri *et al*. (2014) was to develop a computational model to explain the thermal behaviour of welded wood material rather than experimental methods, which are usually expensive and time consuming. This model serves as a prediction tool for welding parameters, leading to optimal thermo-mechanical performance of welded joints. The energy is produced by the friction welding of small wood specimens of Scots pine (*Pinus sylvestris* L.)

Župčić *et al*. (2011) studied the impact of welding time, as an important factor when welding beech wood, on embedded force values. The rotation frequency was 1520 min^{-1}, and dowels were welded at a depth of 20 mm with a 2 mm tightness. Samples welded between 0.56 s and 0.9 s exhibited the best results (the average embedded force amounted to 4994 N). As the welding time increased, the embedded force values decreased. With the welding duration in the interval between 1.81 s and 2.61 s, the average embedded force amounted to 2869bN. Auchet *et al*. (2010) studied a comparison between a constant welding speed and a changing (increasing) welding speed. The welding frequency amounted to 1600 min^{-1}. The highest embedded force (4.7 MPa) was generated at a constant welding speed of 20 mm/s, whereas the changing welding speed generated an embedded force of 3 MPa.

The research results (Župčić *et al*., 2014) reveal that beech wood is the best wood species for welding dowels, regardless of the fibre orientation - parallel or vertical. Also, research results indicate that the dowel welded to the beech base retains the largest strength, whereas the dowel welded to the spruce base reveals the weakest results. The type of wood affects the embedded force or strength of the joint.

Presumably, the temperature in the joint during welding is an important factor of the joint strength. It should also be mentioned that besides rotation frequency, the welding temperature is also influenced by welding duration, so that the optimum welding duration obtained in previous studies was used in this paper. Measuring a joint temperature during welding is very demanding as shown by previous studies. Namely, the opening of the joint that is welded is certainly not the best method as the melt cools down suddenly in the surrounding atmosphere so that measured values are of no relevance. Also, in case of contact temperature measurement, the probe is expected to be very sensitive and not to be in contact with the rotating dowel, and yet close enough to enable the measurement of the relative value. The research results in this paper are different from previous research. It is, therefore, necessary to connect measured temperature values with a mathematic model of theoretical heat transfer. For that purpose, an equation has been developed, which describes the heat source and its transfer to the point where the temperature is measured. The created model is an upgrade of previous heat transfer models as it also includes the influence of the z-axis on the measuring point.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Sample preparation
2.1. Priprema uzoraka

Materials required for the testing were taken from the commercial stack of unknown origin, while dowels were bought from a distributor of an unknown origin as well. Scots pine (*Pinus sylvestris* L.) and beech (*Fagus Sylvatica* L.) were used for the research with the water content of 10 % to 12 %. When making and preparing samples, techniques were used, such as sawing, planing, cutting down to final dimensions, drilling receiver holes on samples for dowel welding and drilling receiver holes for probes measuring the welding temperature. The samples of 30 mm × 200 mm × 30 mm for pine and of 30 mm × 300 mm × 30 mm for beech were used for the research. On pine elements, three 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 (Figure 1). Four receiver holes were drilled on beech elements, which is the only difference. Accordingly, four dowels were welded into beech elements and three into pine elements, while all other parameters remained the same. 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. Probes were put in the lateral receiver holes for measuring the welding temperature. All samples had approximately similar radial-tangential texture.

The dowels used for welding 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 1mm at the angle of 45˚ to enable an easier welding start. Prepared in this way, the dowels and elements (without cracks or visible damage) were conditioned under laboratory conditions for 45 days at (23 ± 2) °C and (55 ± 5) % relative air humidity.

After conditioning, the samples were welded by 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 min^{-1} or 1520 min^{-1} (depending on the sample type) (Table 1). The time required to weld the dowel into the sample amounted to 4 s (regardless of the weld penetration), and the pressure on the dowel after welding (after the rotation stopped) lasted 3 s to 5 s. The tightness in all sample types was 2 mm. The weld penetration amounted to 20 mm or 25 mm (Table 1). 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.

During the welding, the temperature was measured in the rotation zone by measuring probes, and software was developed and created at the Faculty of Forestry and Wood Technology (Figure 2a). The temperature was measured by four probes placed into the receiver hols perpendicular to the dowel welding direction (Figure 1). The distance between probes was 4 mm; the first probe measured the temperature at 4 mm, the fourth at 16 mm from the upper edge of the receiver hole into which the dowel was welded. The software recorded the current temperature and wrote it down in the form of a graph in real time. Due to the

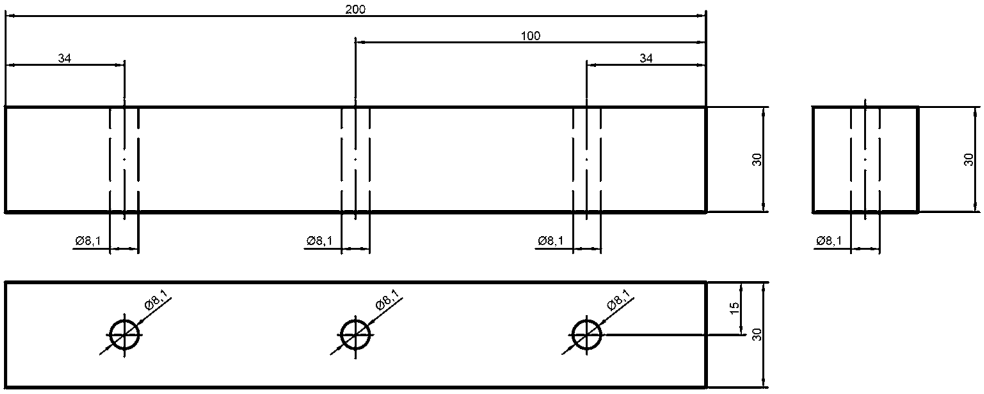


Figure 1 Orthogonal projection of pine elements with measuring probes positions
Slika 1. Ortogonalna projekcija elemenata borovine s pozicijama mjernih sondi

Table 1 Type of samples with designations
Tablica 1. Vrste uzoraka s oznakama

Sample designation *Oznaka uzorka*	**Wood type** *Vrsta drva*	**Rotation frequency, min^{-1}** *Frekvencija vrtnje,* min^{-1}	**Weld penetration, mm** *Dubina zavarivanja,* mm
BO_865_20_x	Pine	865	20
BO_1520_20_x	Pine	1520	20
BO_865_25_x	Pine	865	25
BO_1520_25_x	Pine	1520	25
BU_865_20_x	Beech	865	20
BU_1520_20_x	Beech	1520	20
BU_865_25_x	Beech	865	25
BU_1520_25_x	Beech	1520	25

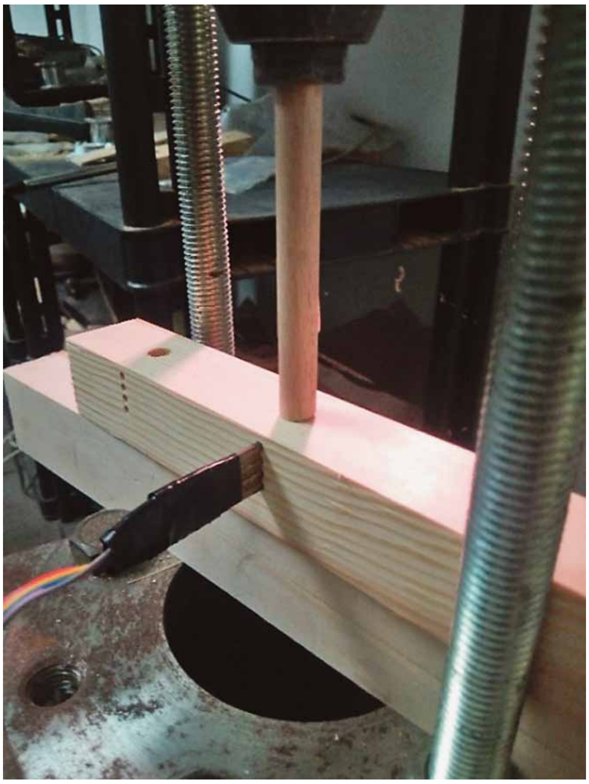
x – indicates the ordinal number of welded dowel (1-30) / *x – označava broj zavarenog moždanika (1-30)*

software deficiency, maximum temperature values were red by Acrobat Reader DC with the possible reading error of ±1.5 °C. PT1000 temperature probes were used for the testing with the temperature range between -70 °C and +550 °C. The probes were of class B with a possible error of 0.3 %. Welded samples were conditioned for seven days under laboratory conditions.

The average water content (HRN ISO 13061-1:2015) of beech samples amounted to 9.33 % (the minimum water content amounted to 8.89 %, and the maximum water content to 11.11 %), the average density (HRN ISO 13061-2:2015) amounted to 0.547 g/cm³ (the minimum density amounted to 0.544 g/cm³, and the maximum 0.556 g/cm³). The average water content (HRN ISO 13061-1:2015) of pine samples amounted to 11.37 % (the minimum water content amounted to 9.67 %, and the maximum water content to 11.48 %), the average density (HRN ISO 13061-2:2015) amounted to 0.503 g/cm³ (the minimum density amounted to 0.496 g/cm³, and the maximum 0.504 g/cm³).

2.2 Testing method
2.2. Metoda ispitivanja

The welded samples were conditioned for seven days and then tested on the universal testing machine. The sample testing was carried out on a computer-controlled Shimadzu AG-X universal testing machine. The testing speed was 5 mm/min. The samples were tested by *articulation* gripping jaws, which enabled their precise positioning (Figure 2b). Embedded force and displacement measurements were done by computer, so that all values were measured exactly and precisely. A total of 239 samples were used for the testing, all of them properly welded, so that there were no visible er-



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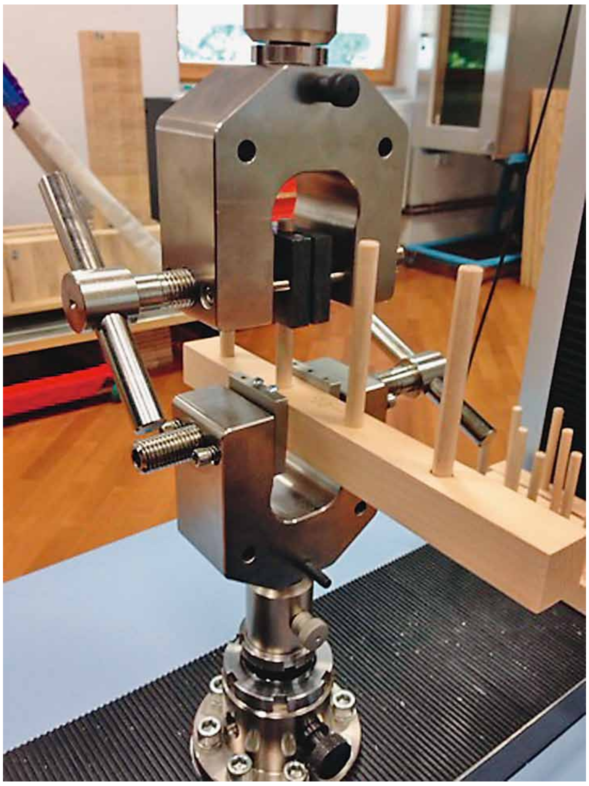

b

Figure 2 Positioning of a) device with probes during welding temperature measurement, b) samples during embedded force testing
Slika 2. Pozicioniranje a) sondi za mjerenje temperature zavarivanja, b) uzorka tijekom ispitivanja izvlačne sile

rors or damages on the samples. The dowel welding temperature and embedded force were measured for all welded samples.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Contact measurement of welding temperature
3.1. Kontaktno mjerenje temperature zavarivanja

The features of the welded joint were determined by measuring the welding temperature and embedded force of the dowel welded into pine or beech. The probe closest to the surface (probe 1) recorded an average temperature of 184 °C in pine samples and 180 ° in beech samples. Slightly higher temperature values were recorded at probe 2 for pine and beech samples. A decrease in the welding temperature was measured at probe 3, although not significant statistically. Probe 4, 16 mm from the surface, exhibited the lowest temperatures because the dowel diameter decreased due to friction so that the tightness was smaller as well, which had a direct impact on the friction between the rotating dowel and the static base. The average temperature of probe 4 was 68 °C for pine and 69.4 °C for beech (Figures 3 and 4). Such welding temperature distribution was expected. The friction is the highest at the beginning of welding because of the maximum tightness, so that the highest welding temperatures are reached. As the weld penetration or welding duration increase (by dowel displacement along the longitudinal axis), the tightness decreases, as well as the welding temperature. Therefore, the dowel top is not welded, but the accumulation of the melt (lignin) appears between fibres in very small quantities. The melt did not form the weld that would achieve certain strength (Figure 5). The optimum weld penetration for a 2 mm tightness is 20 mm. By increasing weld penetration by 5 mm, embedded force increases slightly, but the joint strength decreases (Župčić, 2010).

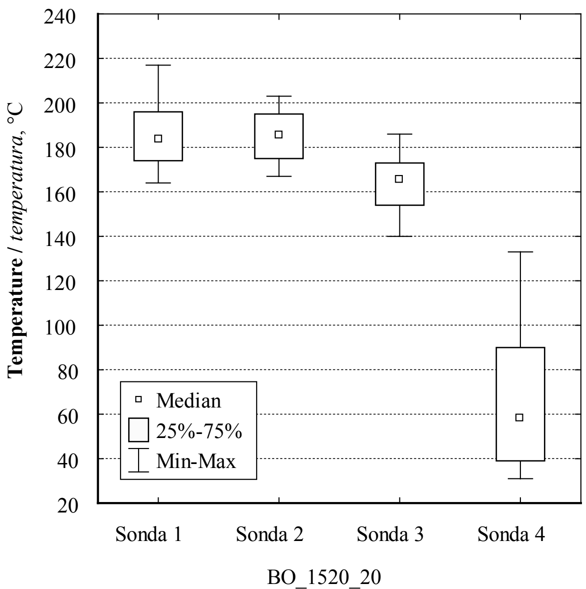

Figure 3 Distribution temperatures by probes in pine wood sample (BO_1520_20)
Slika 3. Raspodjela temperature po sondama u uzorku borovine (BO_1520_20)

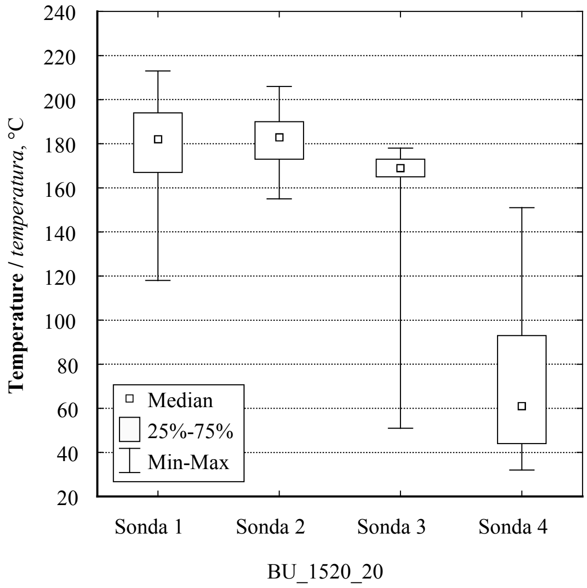

Figure 4 Distribution temperatures by probes in beech wood sample (BU_1520_20)
Slika 4. Raspodjela temperature po sondama u uzorku borovine (BU_1520_20)

The analysis of research results showed that the welding temperature in pine and beech samples depends on rotation frequency (Table 2 and 3, and Figure 6 and 7). Samples welded at a frequency of 1520 min^{-1} exhibited higher temperature values (significant statistically, Scheffe test p<0.050) with the rotation frequency of 865 min^{-1} in pine and beech. In percentages, there is a 21 % increase in the welding temperature at the weld penetration of 20 mm for pine, and an 18 % increase for beech. At the weld penetration of 25 mm, there is a 24 % increase in the welding temperature for pine and 22 % for beech. The welding temperature slightly increases (statistically not significantly, Scheffe test p<0.050) as weld penetration increases for beech, indicating that the observed weld penetration has no impact on the welding temperature.

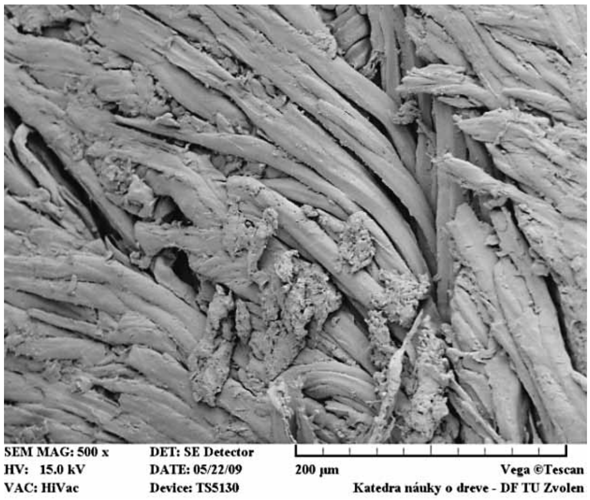

Figure 5 Wear of dowel tip (Župčić, 2010)
Slika 5. Prikaz istrošenosti vrha moždanika (Župčić, 2010.)

Table 2 Descriptive statistics of welding temperature results depending on weld penetration and rotation frequency in pine wood
Tablica 2. Deskriptivna statistika rezultata temperature zavarivanja borovine ovisno o dubini zavarivanja i frekvenciji vrtnje

Code *Oznaka*	**Breakdown table of descriptive statistics** / *Pregledna tablica deskriptivne statistike* *N* = 118							
	Mean, °C *Srednja vrijednost,* °C	**Sample number** *Broj uzoraka*	**Std. Dev, °C**	**Min, °C**	**Max, °C**	**Q25, °C**	**Median, °C**	**Q75, °C**
BO_865_20	144	29	26,59	83	179	128	156	165
BO_865_25	148.93	29	22,65	91	178	136	157	165
BO_1520_20	190.07	30	10,96	167	217	181	191	199
BO_1520_25	187.27	30	17,16	158	222	174	187	201
All groups / *Sve grupe*	167.92	118	29,12	83	222	157	170	190

Table 3 Descriptive statistics of welding temperature results depending on weld penetration and rotation frequency in beech wood
Tablica 3. Deskriptivna statistika rezultata temperature zavarivanja bukovine ovisno o dubini zavarivanja i frekvenciji vrtnje

Code *Oznaka*	**Breakdown table of descriptive statistics** / *Pregledna tablica deskriptivne statistike* *N* = 120							
	Mean, °C *Srednja vrijednost,* °C	**Sample number** *Broj uzoraka*	**Std. Dev, °C**	**Min, °C**	**Max, °C**	**Q25, °C**	**Median, °C**	**Q75, °C**
BU_865_20	174.13	30	3,59	167	181	171	175	177
BU_865_25	176.77	30	4,25	171	192	173	177	179
BU_1520_20	186.97	30	13,42	165	213	175	187	198
BU_1520_25	194.67	30	8,76	171	212	190	195	200
All groups / *Sve grupe*	183.13	120	11,75	165	213	175	179	194

Weld penetration is an important factor influencing the embedded force and strength of the welded joint. The strength of the welded joint increases, as weld penetration increases up to 20 mm and then decreases to the weld penetration of 30 mm (Župčić 2010). Due to dowel wear, friction decreases so that there is no welding. To mitigate the wear problem concerning the dowel tip, the receiver hole should be drilled with different diameter (smaller than the inlet diameter) or the conus hole (Župčić *et al*., 2008; Župčić, 2010).

Figures 8 and 9 show the impact of temperature on embedded force depending on rotation frequency and weld penetration for pine and beech samples. In pine samples, the embedded force of the welded dowel increases as the welding temperature increases. The welding temperature increases as rotation frequency increases. In beech samples, an increase in the welding temperature leads to a slight increase in the embedded force of the welded dowel. An increase in rotation frequency does not result in a significant welding temperature increase. The reason for this is the melt emerging around the measuring probe and influencing the process of temperature measurement. Besides that, the portion of the late growth ring of the wood may also influence the welding temperature so that it should be further looked into. According to results, embedded

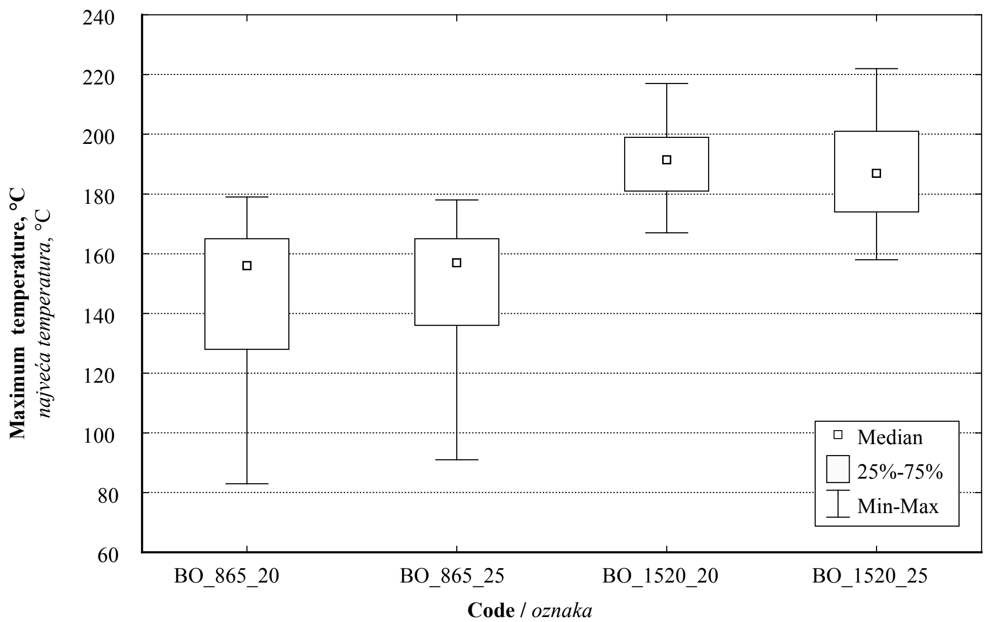

Figure 6 Comparison of welding temperature in pine wood
Slika 6. Usporedba temperatura zavarivanja borovine

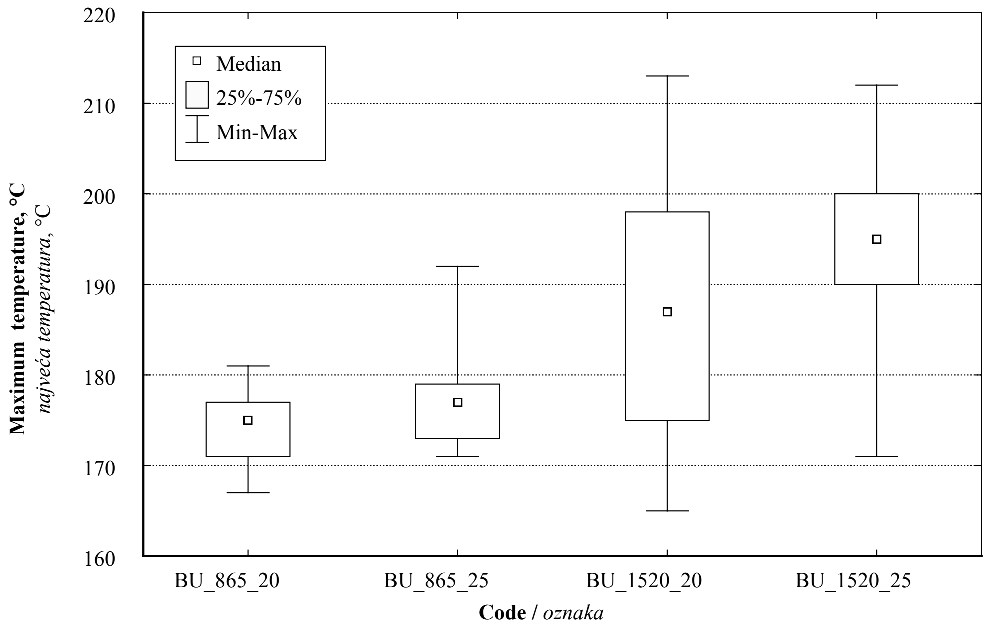

Figure 7 Comparison of welding temperature in beech wood
Slika 7. Usporedba temperatura zavarivanja bukovine

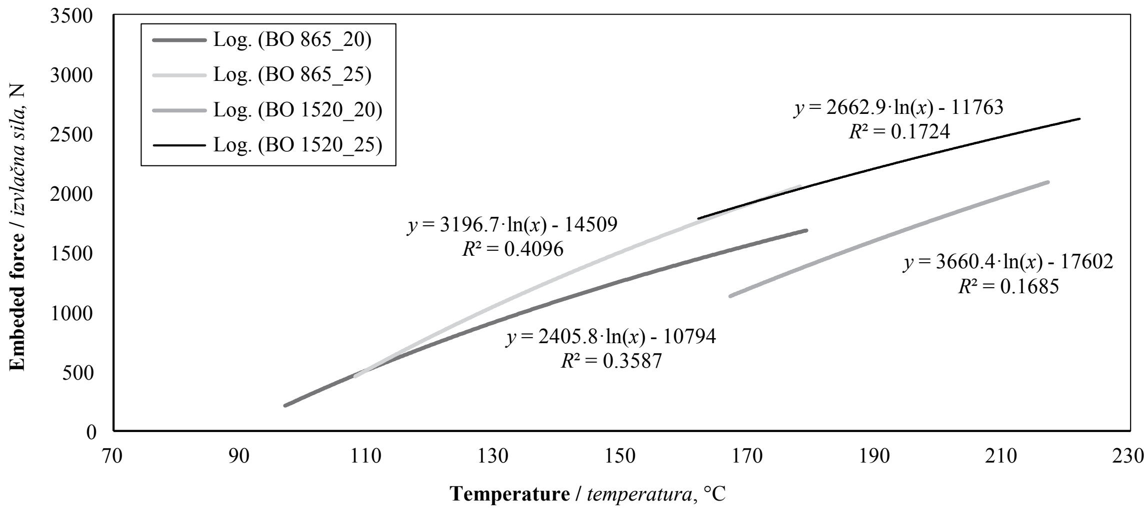

Figure 8 Impact of temperature on embedded force in pine wood samples depending on rotation frequency and weld penetration
Slika 8. Utjecaj temperature na izvlačnu silu na borovim uzorcima ovisno o frekvenciji vrtnje i dubini zavarivanja

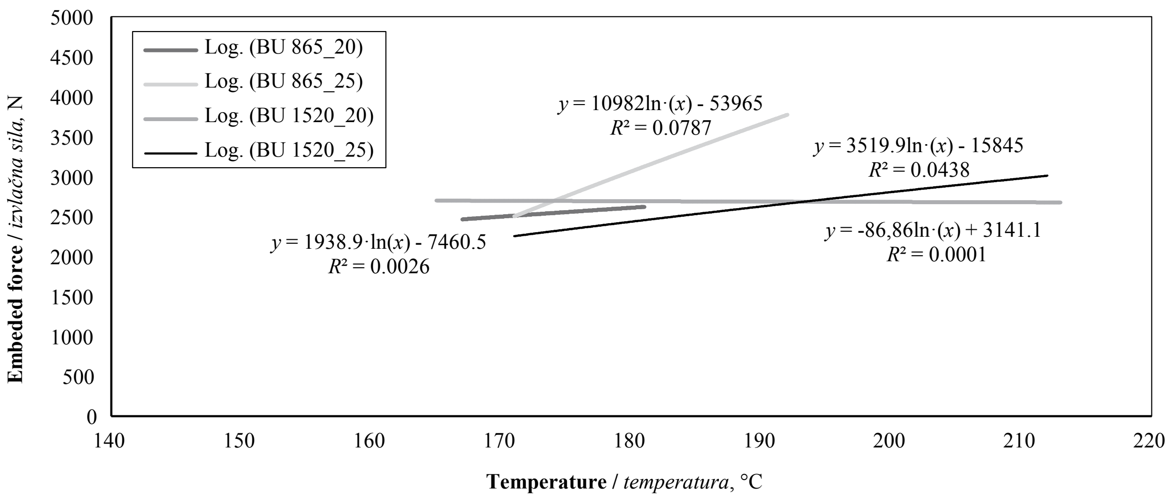

Figure 9 Impact of temperature on embedded force in beech wood samples depending on rotation frequency and weld penetration
Slika 9. Utjecaj temperature na izvlačnu silu na bukovim uzorcima ovisno o frekvenciji vrtnje i dubini zavarivanja

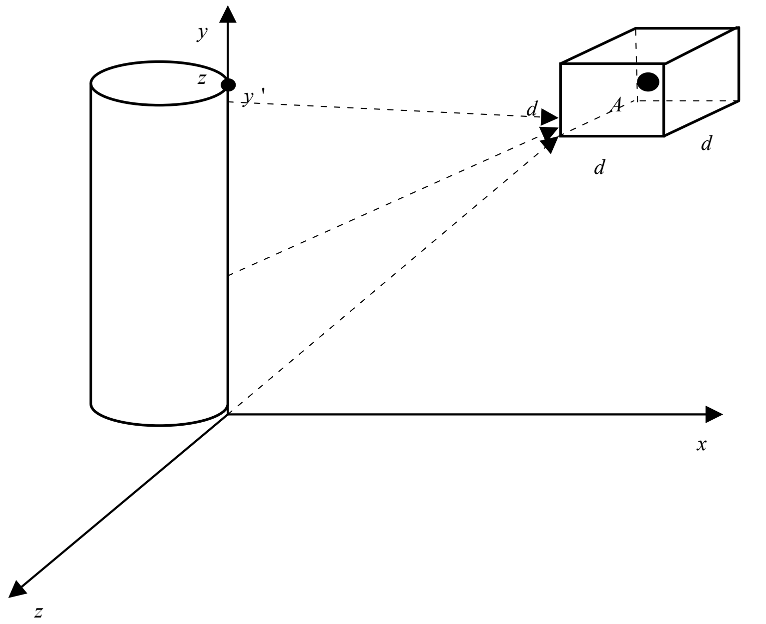

Figure 10 Wood welding in a three-dimensional rectangular coordination system (A – point at which temperature is measured)
Slika 10. Zavarivanje drva u trodimenzionalnom pravokutnom koordinatnom sustavu (A – točka u kojoj se mjeri temperatura)

force of the joints of pine wood is depending more on welding temperature than beech wood (need to be investigated in more detail). Between pine wood and beech wood, there is a difference in wood density, properties of wood and wood structure.

3.2 Theoretical research into heat transfer
3.2. Teorijsko istraživanje prijenosa topline

The wood welding process is shown in a three-dimensional rectangular coordinate system, where welding is done along the y-axis (Figure 10). During the process, the dowel is in dynamic contact with each point along the y-axis, represented by 0 ≤ y ≤ y'. For that reason, these points become heat sources. As the time intervals over which the dowel is in contact with every single point along the y-axis differ, so does the intensity of the heat sources.

Around point A, the infinitesimal volume $dV = dx \cdot dy \cdot dz$ is isolated, where *d*x, *d*y and *d*z are the dimensions of the sides of the infinitesimal volume. According to the first law of thermodynamics, the change in the internal energy (*d*U) of the marked volume is:

$$dU = \delta Q_u - \delta W, \tag{2}$$

Where:
δQ_u – total heat,
δW – work done.

Work may be done if the observed medium changes its volume, and since wood does not significantly change its volume in the given temperature range, the work done may be neglected. After neglecting the work done, there follows:

$$dU = \delta Q_u. \tag{3}$$

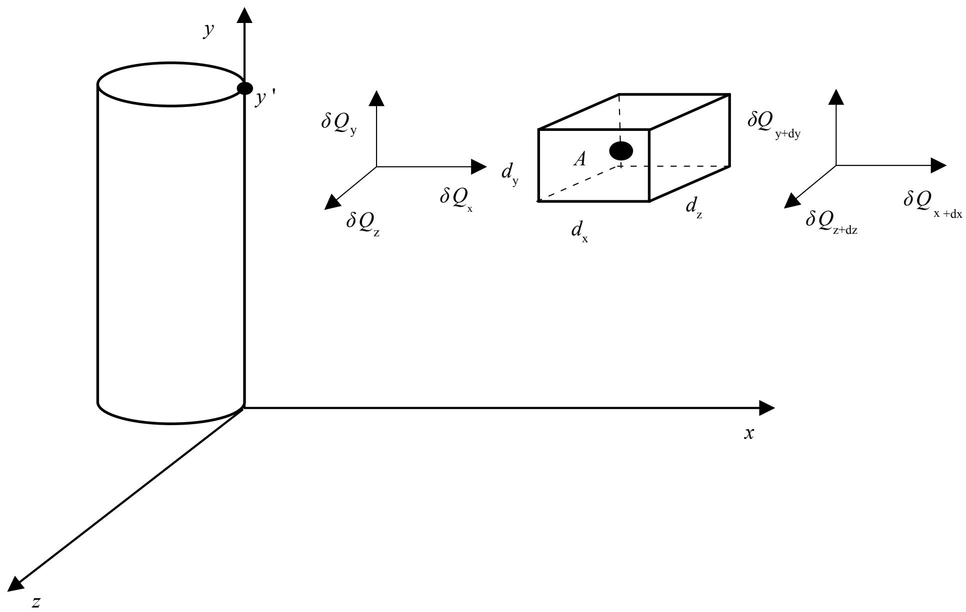

Figure 11 Change in internal energy during wood welding (A – point at which temperature is measured)
Slika 11. Promjena unutarnje energije tijekom procesa zavarivanja drva (A – točka u kojoj se mjeri temperatura)

According to Eq. 3, the change in the internal energy of the observed volume is equal to the total change in the heat of that volume, which may be recorded as a difference between supplied ($\delta Q_{dov.}$) and transferred ($\delta Q_{odv.}$) heat and source heat ($\delta Q_{izv.}$):

$$dQ_u = \delta Q_{dov.} - \delta Q_{odv.} + \delta Q_{izv} \quad (4)$$

$$\delta Q_{dov.} = \delta Q_x + \delta Q_y + \delta Q_z \quad (5)$$

$$\delta Q_{odv.} = \delta Q_{x+dx} + \delta Q_{y+dy} + \delta Q_{z+dz}. \quad (6)$$

In general, heat may be defined by way of heat flux density (Galović, 2002):

$$\delta Q = q \cdot dS \cdot dt. \quad (7)$$

Where:

q – heat flux density,

dS – surface through which heat flux is observed,

dt – time interval.

Supplied and transferred heat may be recorded with regard to the dependence on the axes of the three-dimensional coordinate system:

$$\delta Q_x = q_x \cdot dy \cdot dz \cdot dt \quad (8)$$

$$\delta Q_y = q_y \cdot dx \cdot dz \cdot dt \quad (9)$$

$$\delta Q_z = q_z \cdot dx \cdot dy \cdot dt \quad (10)$$

$$\delta Q_{x+dx} = q_{x+dx} \cdot dy \cdot dz \cdot dt \quad (11)$$

$$\delta Q_{y+dy} = q_{y+dy} \cdot dx \cdot dz \cdot dt \quad (12)$$

$$\delta Q_{z+dz} = q_{z+dz} \cdot dx \cdot dy \cdot dt \quad (13)$$

Heat flux densities of transferred heat (q_{x+dx}, q_{y+dy} i q_{z+dz}) may be developed in the Taylor series so that, while neglecting higher derivation orders, there follows:

$$q_{x+dx} = q_x + \frac{\delta q_x}{\delta x} dx \quad (14)$$

$$q_{y+dy} = q_y + \frac{\delta q_y}{\delta y} dy \quad (15)$$

$$q_{z+dz} = q_z + \frac{\delta q_z}{\delta y} dz \quad (16)$$

The combination of Eq. 8 – 16 determines the equation for the total heat depending on the coordinate axes:

$$dQ_u = \delta Q_{dov.} - \delta Q_{odv.} = -\frac{\delta q_x}{\delta x} dx \cdot dy \cdot dz \cdot dt - \frac{\delta q_y}{\delta y} dx \cdot dy \cdot dz \cdot dt - \frac{\delta q_z}{\delta z} dx \cdot dy \cdot dz \cdot dt = dx \cdot dy \cdot dz \cdot dt \cdot \left(-\frac{\delta q_x}{\delta x} - \frac{\delta q_y}{\delta y} - \frac{\delta q_z}{\delta z} \right) \quad (17)$$

Heat ($dQ_{izv.}$) generated by the source along y-axis may be defined by the heat flux of the source ($\varphi_{izv.}$)

$$dQ_{izv.} = \varphi_{izv.} \cdot dx \cdot dy \cdot dz \cdot dt \quad (18)$$

The change in the internal energy in Eq. 3 may be defined as follows:

$$dU = dm \cdot c \cdot d\theta = \rho \cdot c \cdot dx \cdot dy \cdot dz \cdot d\theta \quad (19)$$

Where:

dm – change in mass

c – specific heat capacity

ρ – density

$d\theta$ – temperature change

By inserting Eq. 17 and 18 in Eq. 4, and after abbreviations, there follows:

$$\rho \cdot c \cdot \frac{d\theta}{dt} = -\frac{\delta q_x}{\delta x} - \frac{\delta q_y}{\delta y} - \frac{\delta q_z}{\delta z} + \varphi_{izv.} \quad (20)$$

Heat flux density may be defined by the thermal conductivity coefficient (λ) in the following way (Galović, 2002):

$$q_x = \lambda_x \cdot \frac{\delta Q_x}{dx} \quad (21)$$

$$q_y = \lambda_y \cdot \frac{\delta Q_y}{dy} \quad (22)$$

$$q_z = \lambda_z \cdot \frac{\delta Q_z}{dz} \quad (23)$$

By inserting Eq. 21, 22 and 23 in Eq. 20, and while neglecting the change in the thermal conductivity coefficient along the coordinate axes ($\frac{\delta \lambda_x}{\delta x}, \frac{\delta \lambda_y}{\delta y} i \frac{\delta \lambda_z}{\delta z} = 0$), there follows:

$$\frac{d\theta}{dt} = -\frac{\lambda_x}{\rho \cdot c} \cdot \frac{\delta^2 Q_x}{dx^2} - \frac{\lambda_y}{\rho \cdot c} \cdot \frac{\delta^2 Q_y}{dy^2} - \frac{\lambda_z}{\rho \cdot c} \cdot \frac{\delta^2 Q_z}{dz^2} + \frac{\varphi_{izv.}}{\rho \cdot c} \quad (24)$$

According to Eq. 24, the temperature measured at point A depends on time ($\frac{d\theta}{dt}$), heat source intensity ($\frac{\varphi_{izv.}}{\rho \cdot c}$) and the ability of material to transfer heat energy from the source to the measuring point ($-\frac{\lambda_x}{\rho \cdot c} \cdot \frac{\delta^2 Q_x}{dx^2} - \frac{\lambda_y}{\rho \cdot c} \cdot \frac{\delta^2 Q_y}{dy^2} - \frac{\lambda_z}{\rho \cdot c} \cdot \frac{\delta^2 Q_z}{dz^2}$).

4 CONCLUSIONS
4. ZAKLJUČAK

Research results show that embedded force values (joint strength) depend on the welding temperature, which is confirmed by the research of Kanazawa *et al.* (2005) and Rodriguez *et al.* (2010).

It was found that pine samples are welded at a higher rotation frequency (1520 min^{-1}) and achieve higher embedded force values on average.

It was also found that the welding temperature depends on rotation frequency, or that samples welded at the frequency of 1520 min^{-1} reach higher temperature values as compared to samples welded at the rotation frequency of 865 min^{-1}. According to the results, there is no statistically significant temperature difference between samples of the same frequency regardless of weld penetration. However, there is a statistically significant difference between samples with different rotation frequencies.

The maximum temperature in pine samples welded at the rotation frequency of 1520 min^{-1} (BO_1520_20 and BO_1520_25) amounts to 220 °C, and in samples welded at the rotation frequency of 865 min^{-1} (BO_865_20 and BO_865_25) to 180 °C. The average welding temperature at 865 min^{-1} regardless of weld penetration amounts to around 143 °C, and at 1520 min^{-1} to 189 °C.

The maximum temperature in beech samples welded at the rotation frequency of 865 min^{-1} (BU_865_20 and BU_865_25) amounts to 210 °C, and in samples welded at the rotation frequency of 1520 min^{-1} (BU_1520_20 i BU_1520_25) to 187 °C. The average welding temperature at 865 min^{-1} is 175 °C, and at 1520 min^{-1} 190 °C.

With regard to difficulties arising from contact measurement of temperature, the heat transfer model was made to obtain more exact welding temperature results related to annul time, heat source intensity and the ability of material when transferring heat energy from the source to the measuring point.

$$\frac{d\theta}{dt} = -\frac{\lambda_x}{\rho \cdot c} \cdot \frac{\delta^2 Q_x}{dx^2} - \frac{\lambda_y}{\rho \cdot c} \cdot \frac{\delta^2 Q_y}{dy^2} - \frac{\lambda_z}{\rho \cdot c} \cdot \frac{\delta^2 Q_z}{dz^2} + \frac{\varphi_{izv.}}{\rho \cdot c} \quad (25)$$

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