Mehmet Karamanoğlu[1], Önder Tor[2]

Effects of Exposure Time and Temperature on Screw Driving Torques in Heat-Treated Anatolian Black Pine and Sessile Oak Wood

Učinci vremena izlaganja i temperature na zakretne momente uvrtanja vijaka u toplinski obrađeno drvo anadolskoga crnog bora i hrasta kitnjaka

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ABSTRACT • *This study aimed to investigate the characteristics of screw driving torques in heat-treated Anatolian black pine and sessile oak wood. The wood samples were subjected to heat under atmospheric pressure at three different temperatures (130, 180, and 230 °C) and two different exposure time levels (2 and 8 h). Screw driving torques of seating and stripping torque (SET and STT) was performed on all samples. The process of screw driving had two main torques, one of which was the seating torque defined as the torque required to clamp parts and the other one was the stripping torque defined as the maximum torque right before the screw strips in the material and the torque drops suddenly because of the formed screw threads being stripped in wood material. Results show that, in both wood species, the SET and STT values decreased due to the increase in heat treatment temperature and exposure time compared to the control groups.*

KEYWORDS: *screw; pilot hole; seating torque; heat-treated wood*

SAŽETAK • *Cilj ovog istraživanja bilo je ispitivanje svojstava zakretnih momenata zavrtanja vijaka u toplinski obrađeno drvo anadolskoga crnog bora i hrasta kitnjaka. Uzorci drva izloženi su toplini u atmosferskom tlaku pri trima različitim temperaturama (130, 180 i 230 °C) i tijekom dva različita vremena izlaganja (2 i 8 h). Na svim su uzorcima određeni zakretni momenti uvrtanja i odvrtanja vijaka (SET i STT). Riječ je o dvama glavnim zakretnim momentima u procesu spajanja vijcima, od kojih je jedan zakretni moment zatezanja, a drugi je zakretni moment odvrtanja, definiran kao maksimalni zakretni moment neposredno prije nego što se vijak izvuče iz materijala i*

[1] Author is researcher at Kastamonu University, Tosya Vocational School, Department of Materials and Materials Processing Technologies, Kastamonu, Turkey. ORCID ID: 0000-0002-2519-4425
[2] Author is researcher at Kastamonu University, Forestry Faculty, Department of Forest Industry Engineering, Kastamonu, Turkey. ORCID ID: 0000-0002-9405-1081

moment se naglo smanji zbog guljenja navoja formiranih u drvnome materijalu. Rezultati pokazuju da se vrijednosti SET i STT za obje vrste drva smanjuju s povećanjem temperature toplinske obrade i produljenjem vremena izlaganja u usporedbi s kontrolnim skupinama.

KLJUČNE RIJEČI: *vijak; pilot-rupa; zakretni moment zatezanja; toplinski obrađeno drvo*

1 INTRODUCTION
1. UVOD

Thermal modification (heat treatment) is one of the environmentally friendly methods used to improve the properties of wood materials. The heat treatment of wood is defined as the application of heat to the wood to bring about the desired improvement in the performance of the material without using any type of chemicals. The method has shown that, by exposing the wood material to temperatures between 170 °C and 220 °C in an oxygen-free environment, it is possible to modify wood components that are sensitive to moisture absorption and biodegradation. After thermal modification, if it does not directly contact the ground in use, dimensional stability and durability of the wood material increase substantially. Heat treatment serves to improve the natural quality properties of the wood, such as dimensional stability and resistance to bio-corrosion and resistance to outdoor weather conditions, biological resistance against fungi and insects, decorative color variation, and equip the wood material with new properties (Hill, 2006; Gündüz *et al*., 2007; Korkut and Kocaefe, 2009; Dagbro *et al*., 2010; Karamanoğlu and Akyıldız, 2013; Demirel and Temiz, 2015; Dagbro, 2016; Perçin *et al*., 2017; Karamanoğlu, 2020; Holy *et al*., 2020). Increasing environmental pressure has appeared in recent years in many countries, leading to important changes in the field of wood preservation. Heat treatment of wood is an eco-friendly method to modify wood without the use of any toxic chemicals (Kol, 2010; Todorović *et al*., 2020). Heat-treated timber is used in the construction of building cladding, interior paneling, parquet, and plank flooring, park and garden furniture, garden fencing, children’s playground equipment, window and window shutters, interior and exterior doors, sauna and sauna elements, interior furniture, and musical instruments. Heat-treated timber surfaces naturally tend to age by the effect of sunlight, rain, and wind. This condition does not affect the durability of the heat-treated timber but the wood surface turns grey after a certain period of time (Korkut and Kocaefe, 2009).

The rigidity and durability of the furniture and other wooden furniture accessories depended on the type and thickness of the wood, as well as on how these pieces were joined together (Aytekin, 2008; Perçin *et al*., 2017). To connect wood and wood-based composites to any wooden material or any other materials such as metal or plastics, fasteners such as nails, bolts, dowels, screws, and nail plates are used (Tor *et al*., 2016; Akrami and Laleicke, 2017; Yorur *et al*., 2017; Brandner, 2019). The screws are commonly used as joint components of the wood construction in engineered wood structures, furniture construction for the attachment of corner blocks to rails in chairs and tables, fastening tops to tables, cabinets, and bases, attachment of shelves to end members frames, and trims to cabinets, and installing hardware and since each wood species has its properties, they also have different direct screw withdrawal (DSW) resistance (Perçin *et al*., 2017; Uysal and Haviarova, 2019; Yorur *et al*., 2020).

There are some studies about the factors affecting DSW resistance in the literature. Perçin *et al*. (2017) reported that screw-withdrawal resistance in heat-treated wood decreased with increasing temperature in Hornbeam (*Carpinus betulu*s L.), black pine (*Pinus nigra* Arnold), and Uludağ fir (*Abies bornmuellerinana* Mattf.) wood species. Kariz *et al*. (2013) reported that the heat treatment reduces the withdrawal capacity of screws in Spruce (*Picea abies* Karst.) wood lamellas. The withdrawal capacity of screws from spruce wood that was heat-treated at temperatures of 210 °C and 230 °C decreased significantly compared to the control wood. Gašparík *et al*. (2015) reported that a significant decreasing effect of thermal modification on screw direct withdrawal load resistance was observed in European spruce trees (*Picea abies* L.).

In addition to these studies, a recent study on driving torques in wood and wood-based composites defined the driving torques as the torque required to drive the screw into a pilot hole. In the study, maximum drive torque (MDT) was defined as the torque at the first turning point on the torque curve where the clamping starts. The term of seating torque (SET) was the torque necessary to clamp parts. Stripping torque (STT) was the torque sufficient to cause the screw to fail in shear. Destruction torque is the torque that causes failure of the screw fastening system, and the term is more general than STT, covering other modes of failure, such as screw torsional failure and material splitting problem (Tor *et al*., 2015).

Therefore, the specific objectives of this study on heat-treated wood were to 1) determine seating and stripping torques in the heat-treated Anatolian black pine and sessile oak wood; 2) investigate the effects of heat treatment and exposure time on the screw driving torques.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wood material
2.1. Drvo

The Anatolian black pine (*Pinus nigra* J.F. Arnold subsp. *nigra* var. *caramenica* (Loudon) Rehder) and sessile oak (*Quercus petraea* Lieb.) were randomly selected and 3 stems at 5 meters, with a breast height diameter (DBH) of 30 – 40 cm, were obtained from forestlands in Kastamonu, Turkey. The lumber was cut from the logs in the sawmill, in parallel to the grain direction according to the Turkish standard, TS 4176. Experimental materials were selected randomly from mixed core and sapwood, with smooth fibers, no knots, no cracks, no difference in color and density, and annual rings perpendicular to the surfaces according to ASTM D7787 / D7787M (2013). Afterward, the lumbers were air-dried until they reached approximately 12 % MC. Then, the lumber was planed and cut into small clear specimens for heat treatment in the dimensions of 50 mm × 50 mm × 10 mm.

2.2 Heat treatment
2.2. Toplinska obrada

Heat treatment was applied in a small heating unit, temperature-controlled to ±1 °C. The temperature of the oven was increased to the temperature at which the actual heat treatment occurs. Heating time was taken as 1 hour in all groups. Then, the samples at ambient temperature were placed in the oven and heat treated at 3 different temperatures (130, 180, and 230 °C) and for 2 different durations (2 and 8h) under atmospheric pressure and in the presence of an inert (nitrogen) environment (Figure 1). After heat treatment, treated and untreated samples were kept in the conditioning room with a temperature of (20 ±2) °C and relative humidity of (65±5) % until they reached a constant rate (TS 642 ISO 554, 1997).

2.3 Measurement of screw driving torques
2.3. Mjerenje zakretnog momenta uvrtanja

All control and heat-treated test samples were cut to 50 mm in width × 50 mm in length × 10 mm in thickness and conditioned at (20 ±2) °C and (65 ± 5) % relative humidity (RH) (ASTM D 618-13, 2013). Before driving a screw into the samples, pilot holes of 3.2 mm were drilled through the thickness of the samples at the center of each sample face. The torque measurements were carried out by the Kraftform torque screwdriver set that included two different screwdrivers based on the torque range (Figure 2). The torque of the first screwdriver ranged from 0.3 to 1.2 N·m and the second one ranged from 1.2 to 3.0 N·m. The measurement accuracy was ± 6 %, which complies with the requirements of ISO 6789-2 (2017). A 10 mm metal plate was used to be consistent with the screw penetration depths in the testing block. The test setup for evaluating SET and STT is shown in Figure 2.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Comparisons of mean screw driving torques
3.1. Usporedbe srednjih zakretnih momenata uvrtanja i odvrtanja vijaka

Table 1 summarizes mean SET and STT values in heat-treated pine and oak wood. In general, the mean

Heat treatment temperatures, °C and time levels, h
Temperature toplinske obrade, °C i vremenski intervali, h

Wood / *drvo*	C	130-2	130-8	180-2	180-8	230-2	230-8
Pine *borovina*							
Oak *hrastovina*							

Figure 1 Control samples of pine and oak (C) and heat treated samples
Slika 1. Kontrolni uzorci borovine i hrastovine (C) te toplinski obrađeni uzorci

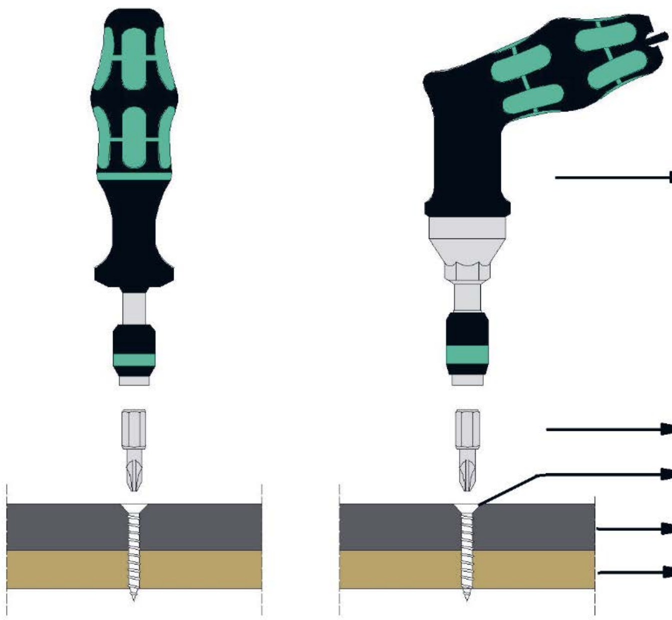

Figure 2 Test setup for evaluating SET and STT of driving screw
Slika 2. Postavi ispitivanja za određivanje SET-a i STT-a pri uvrtanju vijka

SETs ranged from 0.306 to 0.375 N·m and the mean STT ranged from 0.481 to 1.156 N·m for heat-treated pine samples, while the mean SETs ranged from 0.719 to 0.881 N·m and the mean STT ranged from 1.513 to 2.860 N·m as shown in Figure 3.

The ratios of STT/SET for each combination were calculated as shown in Table 1. In general, the ratios decreased when the heat treatment temperature was increased from 130 to 210 °C for both wood species. In a study about screw driving torques obtained in plywood face, the ratios of STT/SET ranged from 2 to 7 with seven layers and 4 to 7 with nine layers (Tor *et al*., 2020). This ratio is important to keep the torque applied under control when screw driving. Robert (2010) suggested that the ratio should be greater than 3 for high-volume production with power tools. Therefore, the operators should be more careful when driving screws into the pine and oak wood with and without the heat treatment because of the sensitivity level between the SETs and STTs.

A three-factor ANOVA was performed using the GLM procedure for each data set of SET and STT separately at the 5 % significance level to analyze the interaction and the main effects in pine and oak wood. The ANOVA results indicated that three-way interaction was statistically significant with the p-value < 0.0001.

Table 1 Summary of mean SET and STT values and their ratios
Tablica 1. Srednje vrijednosti SET-a i STT-a i njihovih omjera

Wood species *Vrsta drva*	**Heat treatment temperature, °C** *Temperatura toplinske obrade*, °C	**Exposure time, h** *Vrijeme izlaganja*, h	**Mean** *Srednja vrijednost*		**Ratio STT/SET** *Omjer* STT/SET
			SET	**STT**	
Pine *borovina*	Control / *kontrolni uzorak*	-	0.444 (7)	1.213 (13)	2.7
	130	2	0.375 (12)	1.156 (16)	3.1
		8	0.375 (7)	1.056 (13)	2.8
	180	2	0.369 (7)	1.069 (11)	2.9
		8	0.325 (8)	0.894 (9)	2.8
	210	2	0.306 (5)	0.769 (13)	2.5
		8	0.319 (8)	0.481 (5)	1.5
Oak *hrastovina*	Control / *kontrolni uzorak*	-	0.906 (4)	2.863 (5)	3.2
	130	2	0.869 (5)	2.869 (6)	3.3
		8	0.881 (4)	2.775 (5)	3.1
	180	2	0.856 (4)	3.106 (15)	3.6
		8	0.806 (2)	2.813 (5)	3.5
	210	2	0.725 (7)	1.863 (11)	2.6
		8	0.719 (8)	1.563 (11)	2.2

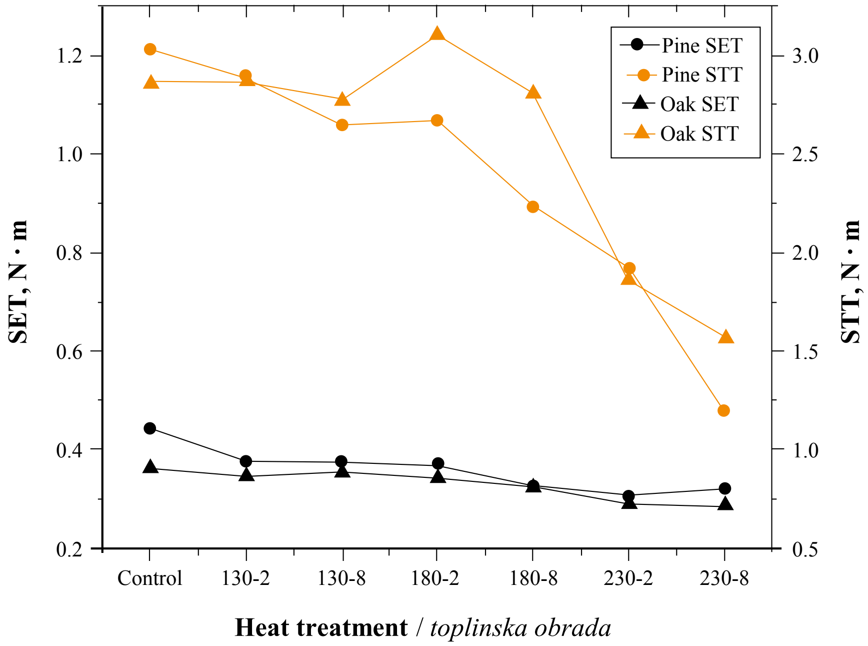

Figure 3 Trend of mean SET and STT for both wood species
Slika 3. Trend srednjh vrijednosti SET-a i STT-a za obje vrste drva

3.2 Treatment temperature effects
3.2. Utjecaj toplinske obrade

According to Table 2, in general, mean SET and STT values decreased due to the increasing heat treatment temperature in both pine and oak samples. The mean SET values in the temperature level of heat treatment were the highest in control samples of both pine and oak, while the mean STT values were the highest in control samples of pine while the values of oak samples did not indicate a proportional decreasing trend.

3.3 Exposure time effects
3.3. Utjecaj vremena izlaganja

Table 3 demonstrates that the mean SET and STT of the samples heat-treated in the long-term (8 hours) were mostly lower than the corresponding ones in the short-term (2 hours) compared to the control samples. There was no significant difference between the mean SETs in the exposure time for the heat treatment at the temperature of 130 and 230 °C in both wood samples. This can be explained by the structural changes in wood materials such as the chemical structure of lignin, cellulose, and hemicellulose, all of which prevent reabsorbing of water molecules. Correlatively, the mechanical resistance properties of wood materials decrease in the heat treatment of wood samples (Hill, 2006; Korkut and Kocaefe, 2009; Perçin and Ayan, 2012).

3.4 Wood species effects
3.4. Utjecaj vrste drva

Table 4 shows that the mean SET and STT values obtained in oak samples were significantly higher than the corresponding ones in pine samples in all treatment combinations. This may be due to the different anatomical properties of wood materials - oak wood is denser, its cell walls are thicker, its lumen is narrower than that in pine wood (need reference). Studies on wood-based composites such as oriented strandboard (OSB), medium-density fiberboard (MDF), particleboard (PB), and wood-plastic composites (WPC) re-

Table 2 Mean comparison of SET and STT values in terms of temperature within exposure time by wood species
Tablica 2. Usporedba srednjih vrijednosti SET-a i STT-a obiju vrsta drva s obzirom na temperaturu unutar vremena izlaganja

Wood species *Vrsta drva*	**Exposure time, h** *Vrijeme izlaganja,* h	**Treatment temperature** / *Temperatura obrade,* **°C**							
		SET, N·m				**STT, N·m**			
		Control *Kontrolni uzorak*	**130**	**180**	**230**	**Control** *Kontrolni uzorak*	**130**	**180**	**230**
Pine *borovina*	2	0.444 (A)	0.375 (B)	0.369 (B)	0.306 (C)	1.212 (A)	1.156 (A)	1.069 (A)	0.769 (B)
	8		0.375 (B)	0.325 (C)	0.319 (C)		1.056 (BA)	0.894 (B)	0.481 (C)
Oak *hrastovina*	2	0.906 (A)	0.869 (B)	0.856 (B)	0.725 (D)	2.862 (B)	2.869 (B)	3.106 (A)	1.862 (C)
	8		0.881 (BA)	0.806 (B)	0.719 (C)	2.862 (A)	2.775 (A)	2.812 (A)	1.562 (B)
		LSD±0.0374				LSD±0.1955			

Table 3 Mean comparison of SET and STT values in terms of exposure time within set temperature range by wood species
Tablica 3. Usporedba srednjih vrijednosti SET-a i STT-a obiju vrsta drva s obzirom na vrijeme izlaganja unutar temperature obrade

Wood species *Vrsta drva*	**Heat treatment temperature, °C** *Temperatura toplinske obrade, °C*	**Exposure time, h / *Vrijeme izlaganja,* h**					
		SET, N·m			**STT, N·m**		
		Control *Kontrolni uzorak*	**2**	**8**	**Control** *Kontrolni uzorak*	**2**	**8**
Pine *borovina*	130	0.444 (A)	0.375 (B)	0.375 (B)	1.212 (A)	1.156 (A)	1.056 (A)
	180		0.369 (B)	0.325 (C)		1.069 (AB)	0.894 (B)
	230		0.306 (B)	0.319 (B)		0.769 (B)	0.481 (C)
Oak *hrastovina*	130	0.906 (A)	0.869 (A)	0.881 (A)	2.862 (A)	2.869 (A)	2.775 (A)
	180		0.856 (B)	0.806 (C)		3.106 (A)	2.812 (B)
	230		0.725 (B)	0.719 (B)		1.862 (B)	1.562 (C)
			LSD±0.0374			LSD±0.1955	

ported in the literature that the density directly affected the mean SET and STT values (Yu *et al*., 2015; Tor *et al*., 2015; Tor, 2019; Kuang, 2016).

4 CONCLUSIONS
4. ZAKLJUČAK

The effects of heat treatment on SET and STT were investigated in two different commonly used wood species. Results revealed that mean SETs ranged from 0.306 to 0.444 N·m for pine samples and from 0.719 to 0.906 N·m for oak wood samples whereas the mean STT ranged from 0.481 to 1.213 N·m for pine wood samples and from 1.513 to 3.106 N·m for oak samples. The ratio of STT/SET ranged from 1.5 to 3.1 N·m for pine samples, and from 2.2 to 3.6 N·m for oak samples. In the study, the highest mean SET and STT values were obtained for oak wood in all cases. In both wood species, the mean SET and STT values decreased because of the increase in the temperature and exposure time compared with the control samples. These results will be interesting for manufacturers of furniture and decoration equipment who use heat-treated wood. With this study, operators will understand the process of screw driving torques and know how much torque they will need to drive screws in the samples that were heat-treated at different exposure times. Therefore, knowing the limitations of screw driving torques will possibly reduce work accidents and material consumption and ease assembly in furniture construction.

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Table 4 Mean comparison of SET and STT values in terms of wood species within set temperature range
Tablica 4. Usporedba srednjih vrijednosti SET-a i STT-a s obzirom na vrstu drva pri jednakoj temperaturi obrade

Treatment temperature, °C *Temperatura toplinske obrade, °C*	**Exposure time, h** *Vrijeme izlaganja*, h	**Wood species** / *Vrsta drva*			
		SET, N·m		**STT, N·m**	
		Pine *borovina*	**Oak** *hrastovina*	**Pine** *borovina*	**Oak** *hrastovina*
Control / *kontrolni uzorak*	-	0.444 (B)	0.906 (A)	1.212 (B)	2.862 (A)
130	2	0.375 (B)	0.869 (A)	1.156 (B)	2.869 (A)
180		0.369 (B)	0.856 (A)	1.069 (B)	3.106 (A)
230		0.306 (B)	0.725 (A)	0.769 (B)	1.862 (A)
130	8	0.375 (B)	0.881 (A)	1.056 (B)	2.775 (A)
180		0.325 (B)	0.806 (A)	0.894 (B)	2.812 (A)
230		0.319 (B)	0.719 (A)	0.481 (B)	1.562 (A)
		LSD±0.0374		LSD±0.1955	

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Corresponding address:

Assoc. Prof. ÖNDER TOR, PhD

Kastamonu University, Forestry Faculty, Department of Forest Industry Engineering, Kuzeykent, 37150, Kastamonu, TURKEY, e-mail: ondertor@kastamonu.edu.tr