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Article

Characterization of Arctic Driftwood as Naturally Modified Material. Part 1: Machinability

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Abstract: Arctic driftwood has reached the coast of Iceland for centuries. This material was used by the inhabitants of the island as a building material for houses, boats, churches and pasture fences. Nowadays, the driftwood is used in the furniture industry, for the finishing of internal and external walls of buildings and also by artists. The properties of driftwood differ to that of original resource due the long-term effects of exposure to Arctic Sea water and ice. This process can be considered as a natural modification, even if its effect on various wood properties and the potential use of driftwood are not yet fully understand. This research is focused on the comparison of cutting forces measured for Siberian larch (*Larix sibirica* L.) from Siberia provenance and driftwood found on the coast of Iceland. The cutting forces were determined directly from the cutting power signal that was recorded during the frame sawing process. A new procedure for compensation of the late/early wood ratio variation within annual rings is proposed to homogenize mechanical properties of wood. It allows a direct comparison of machinability for both types of larch wood investigated (driftwood and natural). Noticeable differences of normalized cutting force values were noticed for both wood types, which were statistically significant for two set values of feed per tooth. These results provide a new understanding of the effect of the drifting process in the Arctic Sea (natural modification) on mechanical and physical properties of wood. Such a natural modification may influence transformation processes of driftwood as well as performance of the coating systems applied on its surface.

Keywords: Arctic driftwood; natural modification; cutting forces; larch wood; sawing process

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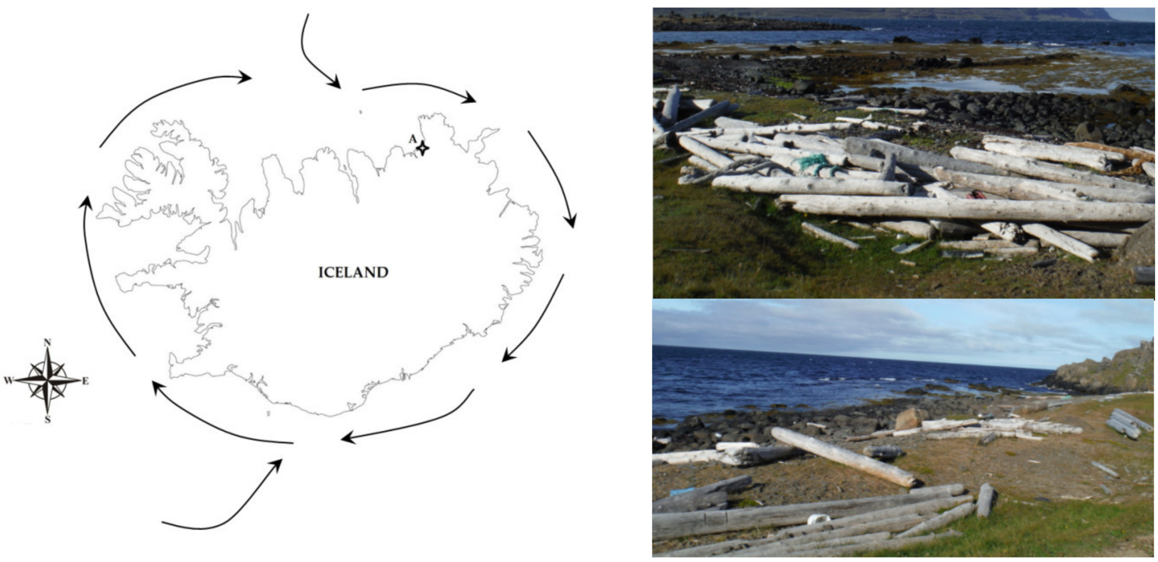
1. Introduction

Arctic driftwood has reached the coast of Iceland for centuries. In the early Middle Ages, 40% of the island area was covered by birch forests [1]. However, the low durability of birch combined with weak mechanical properties and small sizes of trees limited its use in construction. For that reason, driftwood was the main resource used by locals to build houses, boats, churches or bridges [1–4]. The majority of wood types reaching the coast of Iceland are softwood species, especially pine (*Pinus* sp.), spruce (*Picea* sp.) and larch (*Larix* sp.) [5]. These species possess weaker mechanical properties than birch wood from inland Europe [6,7] but are still widely used for construction elsewhere. Historical sources reveal that driftwood was an appreciated building material due to its high suitability for use as structural members as well as superior durability [1,3]. Eggertsson [5] discovered that driftwood arrives to the coasts of Iceland with sea ice and surface currents from the north. By applying the method of dendrochronology on the driftwood, the main origin was revealed to be mostly from the boreal forests of northern Europe and from the Russian part of Asia (Figure 1a). Alternatively, some logs originate from Alaska and Northern Canada [8]. Hellmann et al. [8–11] reported that in the majority of cases, pine, spruce and larch logs were identified on the northern coast of Iceland. The same studies revealed that larch wood found on the northern beaches in Iceland originates from Central and Eastern Siberia. The majority of logs harvested in Siberian forests are transported using rivers to ports located on the coast of the Arctic Sea [10]. Some of these logs are not captured at the final location and cruise farther to the open seas. In addition, whole trees felled due to natural forest processes are taken by rivers each year, especially during intensive snow melting periods and ice breakup on rivers in spring. Similar events occur in North American forests, supplying logs identified as a second major source of Arctic driftwood [12].



(**a**) (**b**)

Figure 1. The arctic driftwood on the Icelandic coasts: (**a**) general view of surface water currents around Iceland [5] and sampling location (A) of the investigated driftwood log collection; (**b**) the Arctic driftwood on the North Icelandic coast (photo by Chuchala).

Driftwood is defined here as remains of trees that flow into the ocean as a consequence of river bank erosion and flooding, storms, winds or other natural occurrences as well as a side effect of logging. These trees are carried by rivers and sea currents for distances of hundreds or thousands of kilometers. Drifting logs can repeatedly be covered by Arctic ice along the drift, which may result in a substantial extension of the exposure time to sea water. Observations of the drifted wood have been used to analyze the dynamics of Arctic Sea ice cover [13]. Dalaiden et al. [14] have created a model that predicts trails of runoff wood from different locations. Arctic driftwood is exposed to sea water and Arctic ice for a few months to several years before it reaches the coasts of Iceland, Greenland or other drylands. It is estimated that the average distance the driftwood travels following sea currents corresponds to 400–1000 km (250–620 miles) per year [15]. Therefore, it is estimated that it takes at least 4 to 5 years for a log from Siberia to reach the coast of Iceland. Such harsh conditions have a major impact on the properties of the wood. A study carried out by Komorowicz et al. [16] showed differences in the physical and mechanical properties of pine driftwood compared to the reference material. A reduced compressive strength along the grain, lower calorific value and increased equilibrium moisture content were observed for driftwood. Reported lower compressive strength along the fibers of Arctic driftwood may be caused by the presence of fungi on the drifting logs, which develop during the wood's journey in the sea [17–20].

Differences in thermal degradation of driftwood during combustion, gasification and pyrolysis processes were also reported [21,22]. Endeavors [21–24] proposed using driftwood as a low-cost thermal energy source and demonstrated that the calorific values are slightly lower than those of natural wood. Furthermore, the same studies have shown that driftwood, when compared to the reference wood species from land, contains much larger amounts of chlorine, sodium, calcium and magnesium. More slags are generated during the burning of driftwood, compared to reference wood directly delivered from the forest [21–24].

Arctic driftwood is relatively well researched when considering silviculture, dendrology and dendrochronology [5,8–11]. However, this material was not systematically studied regarding its mechanical and physical properties. These are highly relevant when considering its use in the modern sustainable construction sector and/or furniture industry. For these particular sectors, the quality of the wood surface obtained after machining is very important, as these surfaces are often covered with protective and decorative coatings. Wood surface quality is affected by several wood–machine–tool interaction factors. Especially, wood species, its density and moisture content, as well as cutting parameters including feed speed, cutting speed, cutting depth, processing direction and cutting forces, influence the resulting surface quality [25]. The roughness of the wood surface affects the adhesion strength of coatings. The contact area for the mechanical interlocking between coating and wood substrate increases following the roughness of the surface, which results in an increase in adhesion [25,26]. The early/late wood ratio is another important factor affecting the adhesion of coating. In the majority of wood species, early wood is more porous than late wood. Consequently, the coating penetration depth within the early wood zone is higher due to simplified impregnation of the finishing product into capillaries of the wood [27]. Arctic driftwood is gaining popularity for use in architecture, furniture design and art [28]. Archeological investigations in the territory of Iceland reveal that driftwood was a very common and important construction resource several centuries ago [1–4]. It is not proved, however, if its popularity was related to the superior performance of drifted (naturally modified) wood or simply easy access to such resources.

The aim of this study was to investigate an effect of the long-term travel of larch wood in the Arctic Sea on its machinability properties. For that reason, an experimental testing was performed to measure cutting forces while sawing wood on a frame sawing machine and then the measured values of the forces were subjected to double normalization (by the wood density and by the ratio of late to early wood). The double normalization was carried out in order to eliminate the effect of morphological differences of the tested wood on the values of the cutting forces. The new knowledge regarding mechanical properties may lead to optimization of the surface treatment methodologies adopted for driftwood as well as proper selection of cutting process conditions used for generating quality products.

2. Materials and Methods

2.1. Material

Arctic driftwood was used for the preparation of experimental samples. The driftwood was collected in Kópasker, the north coast of Iceland (latitude: 66.167418° N, longitude: −16.647679° W) by a local farmer, who was the owner of that land (Figure 1a). Collected logs were cut into boards, which were stored in outdoor conditions for a period of two years (Figure 2a). A single, randomly selected board was used for the preparation of six rectangular blocks (Figure 2b) of dimensions 50 × 50 × 600 mm^3 (width (W) × height (H) × length (L), respectively). This operation was performed in the carpentry workshop Trésmiðja H Ben ehf in Akureyri (Iceland). All experimental samples after transportation to Poland were conditioned in laboratory conditions for 12 months, assuring a constant air temperature (T_a) of 20 °C and relative humidity (RH) of 65%.

(**a**) (**b**)

Figure 2. The investigated driftwood: (**a**) driftwood boards stored in outdoor conditions on North Icelandic farm; (**b**) derived experimental samples (only "WOOD 1" samples were used for determination of the driftwood fracture properties).

The biological species of experimental samples was verified as Siberian larch (*Larix sibirica* L.) by microscopic observation on Leica DM2500 light microscope (Leica Microsystems, Wetzlar, Germany) with magnification of 1000×. Ultrathin (10–20 µm) samples of transverse, tangential and radial sections were cut-out by the microtome and mounted on the microscope slide. The origin of drifted logs was estimated by combining microscopic observations and literature references as Central or Eastern Siberia [5,8–11]. More detailed identification of the origin based on dendrological analysis was not possible due to lack of access to the full radial section of log. Non-treated reference wood samples were prepared from a log of Siberian larch imported by the sawmill Sylva Sp. z o. o. from Wiele (Poland) from Eastern Siberia. A material matching (as much as possible) the driftwood samples dimensions, annual ring orientation as well as late/early wood ratio was prepared by the sawmill for comparative analysis. The reference wood samples were not exposed to any treatment.

The wood density ρ, defined here as a ratio of the wood mass to its volume at the air-dry state (moisture content MC = 12%), was measured separately on each block of both driftwood and reference sample groups. All results are summarized in Table 1 together with the average width of annual ring (WAR), the average width of late (LW) and early (EW) wood in annual rings and ratio of late and early wood (*L*/*E*).

Table 1. Physical properties of examined wood samples (average values with standard deviations).

Sample Code	Sample Name	ρ	WAR	LW	EW	*L*/*E*
		kg m^{-3}	mm	mm	mm	–
DL	Driftwood Larch	554.7 ± 15.5	0.72 ± 0.23	0.15 ± 0.04	0.57 ± 0.20	0.28 ± 0.09
L	Larch	694.9 ± 31.5	0.52 ± 0.09	0.15 ± 0.04	0.37 ± 0.07	0.41 ± 0.10

Legend: ρ—density of air-dry wood at MC = 12%; WAR—width of annual rings; LW—width of the late wood; EW—width of the early wood; ratio E/L—ratio of the late to early wood.

2.2. Machinability Tests Methodology

Sawing tests were performed on the PRW15M sash-gang saw with a hybrid dynamically balanced driving system and elliptical teeth trajectory movement [29]. The concept of the machine was developed at the Gdańsk University of Technology (Gdańsk, Poland) [29] and a prototype manufactured by REMA S.A. (Reszel, Poland). Detailed technical parameters of the sash-gang saw and saw blades used in experimental cutting tests are presented in Table 2.

Table 2. Technical parameters of sash-gang saw and its saw blade used in the experimental cuttings.

Parameter		Symbol	Value	Unit
Machine Parameters				
number of strokes of saw frame per min		n_F	685	spm
saw frame stroke		H_F	162	mm
number of saws in the gang		m	5	–
average cutting speed		v_c	3.69	$m \cdot s^{-1}$
feed speed	slow	v_{f1}	0.99	$m \cdot min^{-1}$
	fast	v_{f2}	1.45	$m \cdot min^{-1}$
feed per tooth	slow	f_{z1}	0.116	mm
	fast	f_{z2}	0.171	mm
Tool Parameters				
the sharp saw blades with stellite tipped teeth		–	–	–
overall set (kerf width)		S_t	2	mm
saw blade thickness		s	0.9	mm
free length of the saw blade		L_0	318	mm
blade width		b	30	mm
tooth pitch		t_p	13	mm
tool side rake angle		γ_f	9	°
tool side clearance		α_f	14	°
tension stresses of saws in the gang		σ_N	300	MPa

The use of electric power (active and passive) during idling and working cycles was continuously monitored with the power converter PP54 (LUMEL S.A., Zielona Góra, Poland). The data was collected with the acquisition converter µDAQ USB30 A/D (Eagle Technology, Zonnebloem, Cape Town, South Africa) and further processed to determine energetic effects of cutting. The mean value of feed per tooth f_z (mm) for a sash-gang saw was calculated as in Equations (1) and (2) [30–32]:

$$f_z = \frac{1000 \times v_f \times t_p}{n_F \times H_F} \tag{1}$$

$$v_f = \frac{L}{t_c} \tag{2}$$

where: v_f—feed speed ($m \cdot min^{-1}$), t_p—tooth pitch (mm), L—length of the sample (m), H_F—saw frame stroke (mm), n_F—number of strokes of saw frame per min (spm) and t_c—cutting time (min) necessary to process sample of the length L.

The average cutting power Pc (W) was calculated as the difference of the mean total power PT and the average idle power Pi [28], as expressed in Equation (3):

$$P_c = P_T - P_i \tag{3}$$

The average idle power P_i (W) of the frame saw PRW15-M was determined each time before beginning the proper cutting cycle. It allowed the minimization of the effect of the varying temperature of the machine components (such as hydraulic oil, gear boxes, etc.) on the energetic effects corresponding directly to the cutting process. The average cutting power in a working stroke P_{cw} (W) was calculated as in Equation (4), following the proceeding works of authors [31,32]:

$$P_{cw} = 2 \times P_c \tag{4}$$

The corresponding cutting forces F_c (N) (as related to one tooth of the saw blade) were calculated as a ratio of the obtained average cutting power in a working stroke P_{cw} at the average cutting speed v_c, and the average number of teeth in contact with the kerf z_a (Equation (5)) [33].

$$z_a = \frac{H}{t_p} \tag{5}$$

2.3. Normalization and Statistical Analysis

The obtained cutting force values were subjected to a single normalization (by density), followed by a novel two-level normalization (by density and by the late to early wood ratio). The normalization processes consisted of dividing values of derived cutting forces by the density of machined wood, that was followed by addition division by the corresponding late to early wood ratio assessed on the machined wood samples. The two-level normalization was intended to compensate for the effect of the tested wood morphology on the cutting forces.

The differences between the morphological parameters of the tested wood, as well as differences between the obtained values of cutting forces, were statistically analyzed using one-way and multi-factor analysis of variance (ANOVA).

3. Results and Discussion

The values of cutting forces per cutting tooth obtained from the experimental series of sawing samples of larch wood, both drifting in the Arctic Sea and not subjected to any modification and thermal treatment processes, are summarized in Figure 3. Two test point groups for each type of sawn wood are presented in the chart. These groups correspond to values of cutting forces obtained while sawing wood at two levels of feed speed v_f. The variation of feed speed is represented as a basic geometrical parameter of the cutting process, i.e., uncut chip thickness h. Two values of uncut chip thicknesses h presented in Figure 3 are h_1 = 0.116 mm and h_2 = 0.171 mm, which correspond to v_{f1} = 0.99 m·min^{-1} and v_{f2} = 1.45 m·min^{-1}. Linear regressions were created for each group of points representing both types of wood. Relatively high values of determination coefficients r^2 were noticed as a result of regression with r^2 = 0.98 for natural (reference) larch wood and r^2 = 0.95 for driftwood larch.

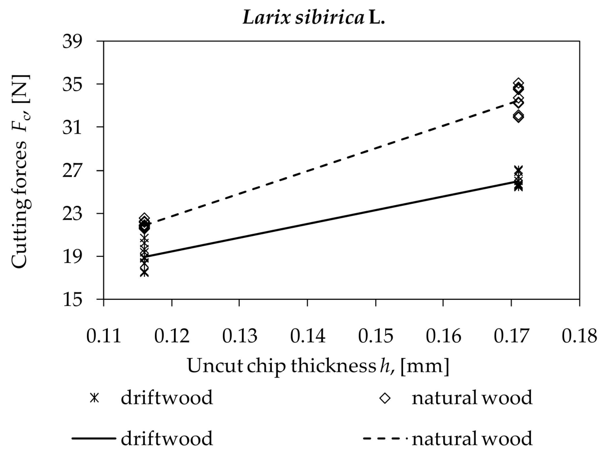


Figure 3. Relation between cutting forces per cutting tooth and uncut chip thickness when sawing drifted larch wood and natural larch wood.

Analyses of the results presented in Figure 3 allow the formulation of a statement that differences in cutting force values of drift and natural woods are noticeable. However, even if all the efforts were directed to assure homogenous and comparable experimental materials representing drift and natural woods, the differences between the average density (Table 1) may affect measured cutting forces [33]. Therefore, following protocols proposed in previous studies [30–32,34], the cutting forces were normalized to eliminate the effect of differences in the density of the tested wood samples on the values of these forces. Results obtained after data normalization are presented in Figure 4. It becomes evident that differences noted in the original cutting force values (Figure 3) are associated with the density differences within tested wood samples. Cutting forces normalized by the density are not noticeably different between driftwood and reference larch samples, even if slopes of the regression curves vary. This indicates different fracture properties of both types of wood, particularly shear yield strength [35,36]. It should be noticed, however, that the density variation is not the lone source of variation within experimental samples. The annual ring morphology, including its average width as well as the ratio of late and early woods, is also varied (Table 1).

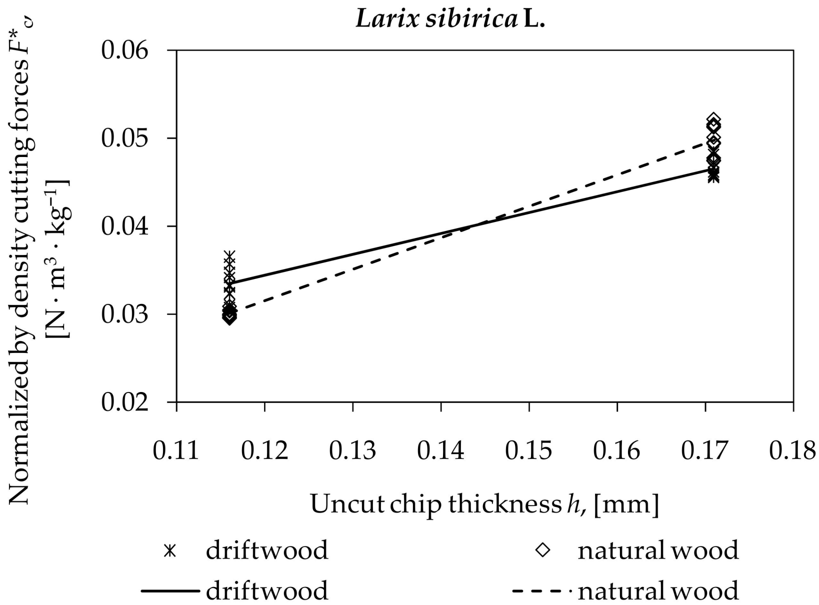


Figure 4. Relation between values normalized by density cutting forces per cutting tooth and uncut chip thickness when sawing drifted larch wood and natural larch wood.

The wood morphological features, such as width of annual rings, have a significant effect on the cutting resistance during the drilling process [37]. These observations were evidenced for pine, beech and oak wood species, other than the Siberian larch investigated here. Nevertheless, Koizumi et al. [38], Zhu et al. [39] and Luostarinen and Heräjärvi [40,41] reported that the width of annual rings of the larch wood strongly affects its mechanical properties. Likewise, the share of late wood within an annual ring has a substantial effect on the density value among other wood properties. Mikkola and Korhonen [42] reported a similar observation noticed for pine wood trees growing in cold weather climate zones. Several studies [43–47] revealed that properties of Siberian larch may vary significantly within diverse regions of Siberia. This was confirmed in the case of the experimental samples researched in this study. Even if the late wood width was similar in both investigated Siberian larch samples, the average ring width varied noticeably. Consequently, the late/early wood ratio *L/E* was different in the case of the studied drift and natural woods (Table 1). The results of the ANOVA summarized in Table 3 confirmed the statistical significance of differences within yearly ring anatomical structures.

Table 3. Significance of differences between annual ring characteristics noticed for drifting and natural larch samples (ANOVA, α = 0.05), where: DL—driftwood larch, L—natural larch.

Larch Wood (*Larix siberica* L.)							
Sample Code	**Source**	**DF**	**Adj SS**	**Adj MS**	**F—Value**	**P—Value**	**F—Critical**
Density, ρ (kg m^{-3})							
DL	between groups	1	59,009	59,009	99.09	1.66×10^{-6}	4.96
L	within groups	10	5955	595	-	-	-
total		11	64,964	-	-	-	-
Width annual rings, WAR (mm)							
DL	between groups	1	0.566	0.566	19.75	4.21×10^{-5}	4.01
L	within groups	56	1.604	0.029	-	-	-
total		57	2.170	-	-	-	-
Width late wood in annual rings, LW (mm)							
DL	between groups	1	9.22×10^{-5}	9.22×10^{-5}	0.058	0.81	4.01
L	within groups	56	0.088	0.002	-	-	-
total		57	0.088	-	-	-	-
Width early wood in annual rings, EW (mm)							
DL	between groups	1	0.580	0.580	26.98	2.98×10^{-6}	4.01
L	within groups	56	1.205	0.021	-	-	-
total		57	1.785	-	-	-	-
Ratio late wood to early wood in annual rings, Ratio L/E $(-)$							
DL	between groups	1	0.272	0.272	32.72	4.32×10^{-7}	4.01
L	within groups	56	0.465	0.008	-	-	-
total		57	0.737	-	-	-	-

Koizumi et al. [38], Zhu et al. [39] and Luostarinen and Heräjärvi [40,41] evidenced a significant effect of the late wood ratio on diverse mechanical properties of wood. A second level of cutting force normalization was, therefore, proposed as a novelty in this research. The alternative approach aims to account for the effect of differences in the morphology of the tested wood on the cutting process energy requirements. The physical interpretation of such normalized values corresponds to the double-normalized cutting force that is required to cut wood of a unit density $\rho = 1$ kg·m^{-3} and a ratio of late to early wood $L/E = 1$. The values of such double-normalized specific cutting forces are presented for experimental samples in Figure 5. It becomes evident that the mutual position of both trends has reversed and become almost parallel to each other. An increase in the double-normalized cutting forces in relation to the uncut chip thickness is apparent. This corresponds to literature references [30–32,34,48], and confirms the versatility of the fracture toughness theory of the wood cutting process as proposed by Atkinks [35] and Orlowski et al. [36]. This theory, based on a linear regression describing the phenomenon of an increase in the cutting forces with an increase in the uncut chip thickness, allows determination of the values of fracture toughness and shear yield stress in the shear plane [35,36].

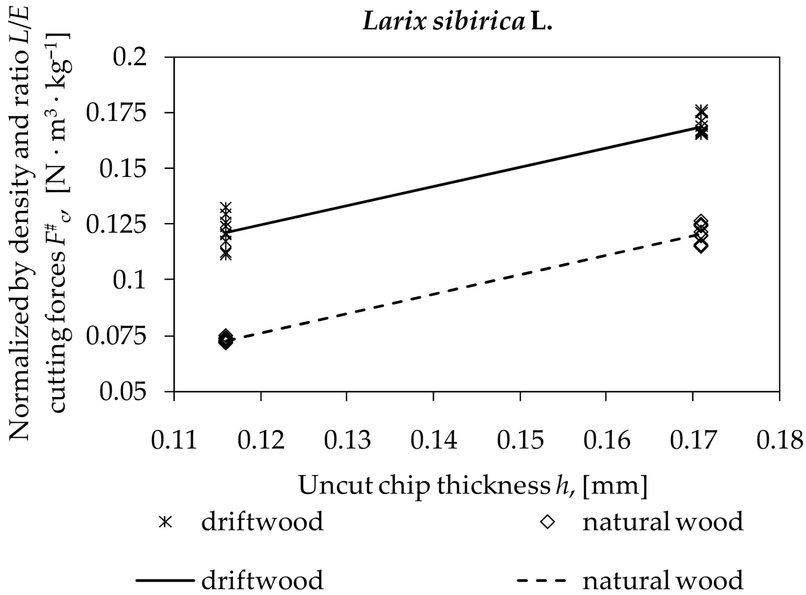


Figure 5. Relation between double normalized (by density and by ratio L/E) cutting forces per one cutting tooth and uncut chip thickness when sawing drifting and natural larch woods.

The level of difference between cutting force values obtained for driftwood and natural wood is evident and amounts to approximately 0.05 N·m^3·kg^{-1} for both smaller and larger uncut chip thicknesses. These differences are statistically significant, as tested by the multi-factor ANOVA (Table 4). It can be stated, therefore, that the double normalization removes the effect of density and of late to early wood ratio from the cutting force quantifiers.

Table 4. Significance of differences between values of double normalized cutting forces obtained for two levels of uncut chip thickness while sawing process of drifting and natural larch samples (ANOVA) (α = 0.05). DL—driftwood larch, L—natural larch.

Larch Wood (*Larix siberica* L.)							
Sample Code	**Source**	**DF**	**Adj SS**	**Adj MS**	**F—Value**	**P—Value**	**F—Critical**
Double normalized cutting forces, $F^{\#}{}_{c}(h_1)$ (N·m^3·kg $^{-1}$)							
DL	between groups	1	0.012	0.012	487.4	1.74×10^{-14}	4.414
L	within groups	18	0.0004	2.4×10^{-5}	-	-	-
total		19	0.012	-	-	-	-
Double normalized cutting forces, $F^{\#}{}_{c}(h_2)$ (N·m^3·kg $^{-1}$)							
DL	between groups	1	0.011	0.011	670.1	1.08×10^{-15}	4.414
L	within groups	18	0.0003	1.72×10^{-5}	-	-	-
total		19	0.012	-	-	-	-

Such significant differences in the double-normalized cutting force values as presented in Figure 5 indicate that the long period of wood contact with the Arctic Sea water, in combination with the effect of low temperatures of the freezing Arctic ice, significantly alter the machinability of larch wood. It is evident that the double-normalized cutting forces are higher in the case of driftwood. Based on previous research, this might be related to the higher mineral (or ash) content deposited in driftwood [23]. It was reported by Lhate et al. [49] that a high mineral content may be attributed to poor machining properties by increasing of the friction between the tool and the processed wood. This results in increased values of cutting forces, elevated heat release and intensive cutting edge dullness. The other explanation for higher values of double-normalized cutting forces noticed in the case of sawing driftwood may be analogous to those observed by Orłowski and Sandak [50] and Orlowski et al. [51] during cutting of frozen pine wood. An increase in cutting forces was associated with the effect of frozen water crystals deposited inside of wood fibers that provided additional strength and material stiffness. Likewise, the presence of sodium chloride, among other minerals, inside driftwood fibers was reported by Cotana et al. [22] and Bartocci et al. [21]. Such crystals may increase the strength of the cell wall structure, which results in higher cutting forces.

The statistically significant increase in double-normalized cutting forces while processing driftwood is a confirmation of the modification of the native wood properties induced during its journey in the Arctic sea. It remains an open question, however, to what extent such natural modification has an effect on other properties of the drifted wood. Further studies are also necessary to confirm if such modification remains beneficial for the use of drifted wood in diverse applications.

4. Conclusions

The presented research allows the derivation of the following conclusions:

- The long period of larch wood logs' exposure to the Arctic Sea water, combined with the effect of cyclic freezing conditions of Arctic ice, resulted in the natural modification of driftwood and the alteration of several material properties. Exploring the exact causes of this phenomenon requires more detailed research and a broad reference sample set covering the whole variance of altered material properties. The new knowledge reported here may result, however, in a better management of driftwood. The appropriate selection and optimization of manufacturing processes may lead to the superior quality of protective or decorative coatings on products made of drifted wood.
- The wood modification observed in driftwood affects the overall machinability properties of this material, revealed as changes of double-normalized cutting forces. It is known that elevated cutting forces result in a deterioration of the machined surface smoothness. As a consequence, the adhesion of coatings on these machined surfaces is altered.
- The ratio of late and early woods within the annual ring is an important factor affecting the values of cutting forces. A higher content of late wood increases the cutting power required for wood sawing. Special attention should be directed toward controlling the L/E ratio while researching the effect of wood modification on machinability.
- The double normalization of cutting forces by density and followed by *L/E* ratio allows the direct comparison of machinability properties not possible for wood samples with different properties of annual growth.

The obtained results showed that the drifting of larch wood across the Arctic Sea significantly increases the cutting force values during the frame sawing process. However, the details of the effect of this natural modification on other wood properties (chemical, mechanical and physical) are still unknown. Further research is therefore being conducted by authors to reveal the mechanisms of material changes due to the drifting of wood in the Arctic Sea.

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