Power Consumption during Edge Milling of Medium-Density Fiberboard and Edge-Glued Panel

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This paper presents the energy consumption differences during the edge milling of various board materials (medium-density fiberboard (MDF), medium-density fiberboard with single-sided lamination (MDF-L), and spruce edge-glued panel (SEGP)). The edge milling was carried out with various parameters: feed rate (4, 8, and 11 m/min); cutting speed (20, 30, 40, and 60 m/s); and blade type (tungsten carbide HW1, HW2, and HW1 coated with CrTiN (HW1 + CrTiN)). The results indicated that the increase in the cutting speed and feed rate cause the increase in cutting power. The highest cutting power values were observed with the milling of MDF; slightly lower values were observed with MDF-L, and the lowest values were observed with SEGP. Very similar cutting power values during milling were noted with HW1 and HW2 blades, whereas milling with the HW1 + CrTiN resulted in slightly higher values (*e.g.*, 1% higher).

Keywords: Edge milling; Cutting power; Medium-density fiberboard (MDF); Spruce edge-glued panel (SEGP); Cutting speed; Feed rate

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INTRODUCTION

Wood is a natural composite material composed of bundles of cellulosic fibers surrounded by lignin and hemicelluloses, and its unique features predetermine it for versatile use. However, natural wood sources are generally diminishing. Thus, alternative materials that have similar characteristics in certain aspects are being created and used to replace wood. These alternative materials are referred to as wood-based materials.

Wood-based materials are composites that are made by either pressure and heat applied to wood particles (sawdust, shavings, fibers, particles) mixed with resins, or by gluing and subsequently pressing smaller pieces of wood and veneers together.

The first group of materials (*e.g.*, fiberboard, medium-density fiberboard, particleboard, and oriented strand board) is used mostly in the furniture and construction industries. In general, these materials are more homogeneous in comparison to natural wood, which is anisotropic (Boucher *et al*. 2007). Medium-density fiberboard is a typical example of this material. Medium-density fiberboard (MDF) is a universal wood-based material, which is characterized by its high dimensional stability, good machinability, and high surface smoothness. It is used for non-load-bearing purposes in the production of furniture, joinery, insulating panels, and other interior applications (Kowaluk *et al*. 2009; Tratar *et al*. 2014; Bendikiene and Pupelis 2016). MDF has a higher density than natural wood and contains a high proportion of resin; these factors cause higher tool wear when cutting and milling (Morita *et al*. 1998). Moreover, the nature of MDF is not completely isotropic, but rather isotropic in certain layers (Aguilera *et al.* 2000; Zerizer *et al*. 2003;

Boucher *et al*. 2007; Davim *et al*. 2009).

The second group of materials (*e.g*., plywood, blockboard, and edge-glued panel) is used in specific applications or for specific components. These materials exhibit properties similar to wood; these composites contain a minimal amount of auxiliary chemicals (*e.g*., adhesives). For example, edge-glued panels (sometimes called an edge laminated panel or solid wood panel) are the structural materials in which the total width or length can be made as needed. Each panel item consists of small pieces of wood with a square or rectangular cross-section, glued side by side to each other. The individual pieces of wood can be joined lengthwise by finger joints. Edge-glued panels are used for kitchen cabinets and tables, doors, stairs, windows and window sills (Mitchell and Lemaster 2002; Sofuoglu 2017). Although edge-glued panels have more heterogeneous structure than natural wood, their properties are similar (Sütçü 2013), and they are machined with the same tools.

Milling is a basic type of woodworking in which the rotating milling head cuts the layers of the material, resulting in a change of its dimensions and shape (Jamberová *et al.* 2016; Krauss *et al.* 2016; Vančo *et al*. 2017). The optimum result of milling is a high quality machined surface that is suitable for further technological processes. Plain milling is a process suitable for wood and wood materials (such as edge-glued panels), where the surface quality is particularly important for its subsequent treatment and finishing (Rousek and Kopecký 2005). Edge milling is a typical process for wood-based materials produced by pressing (MDF, particleboard, fiberboard), which is especially important for the following edge banding operation. Generally, the quality of the milled surface depends on the properties of the wood (*e.g*., wood species and milling direction) or the wood materials (*e.g*., material type and surface treatment), milling parameters (*e.g*., cutting depth, cutting speed, feed rate, blade type, and position of the blade relative to the milling direction), and the tool properties (*e.g*., material, tool geometry and adjustment) (Darmawan *et al.* 2001; McKenzie *et al.* 2001; Huang *et al.* 2003; Söğütlü 2010; Warcholinski *et al*. 2011; Söğütlü *et al*. 2016). The combination of material properties and milling parameters also contribute to the total power consumption during milling. Power consumption, often represented as the cutting power, is an important factor in the process that contributes to production costs (Quintana *et al.* 2011; Mandic *et al.* 2015; Kubš *et al*. 2016). It can be affected by using appropriate tools and by setting the optimal milling parameters, specifically the cutting speed and feed rate (Darmawan *et al.* 2011).

This research work examined the cutting power during edge milling of medium-density fiberboard (MDF), medium-density fiberboard with single-sided lamination (MDF-L), and spruce edge-glued panel (SEGP). Cutting blades made of different materials were used for the milling processes (*i.e*., HW-05, HW-03F and HW-05 CrTiN) and tested at various cutting speeds (*i.e*., 20, 30, 40, and 60 m/s) and feed rates (*i.e*., 4, 8, and 11 m/min).

EXPERIMENTAL

Materials

The research work examined three types of construction material: medium-density fiberboard (MDF), medium-density fiberboard with single-sided lamination (MDF-L), and edge-glued panel (SEGP) from Norway spruce (*Picea abies* L.). The sample dimensions were 500 mm × 500 mm × 18 mm. The densities of the materials were determined according to the EN 323 (1993) standard; the densities of the materials and their manufacturers are listed in Table 1. Samples were preconditioned for 2 weeks in a conditioning room (ϕ = 65±3% relative humidity and t = 20± 2 °C) in order to achieve a 12% equilibrium moisture content.

Table 1. Properties of Construction Materials

Marking	Construction material	Density (kg/m^3)	Producer
MDF	Medium-density fiberboard	750	DDL - Dřevozpracující družstvo (Lukavec, Czech republic)
MDF-L	Medium-density fiberboard with single-sided lamination	730	DDL - Dřevozpracující družstvo (Lukavec, Czech republic)
SEGP	Edge-glued panel from spruce wood	432	Holzindustrie Schweighofer s. r. o., (Tábor, Czech republic)

Methods

Edge milling

The edgewise milling process was carried out using a single-spindle cutter (FVS) with a STEFF 2034 feeding system (Maggi Technology, Certaldo, Italy). Three double-blade milling cutter heads (Felder, Hall in Tirol, Austria) with replaceable blades were used (Fig. 1). A milling depth of 1 mm was kept during the edge milling. The edge milling parameters, as well as the cutting tool geometry, are listed in Table 2.

Fig. 1. The cutter head

Table 2. Cutting Parameters of Edge Milling and Cutter Head Geometry

Single-spindle cutter (FVS)		Cutter head (diameter = 125 mm)	
Input power	3.8 kW	Clearance angle α	10°
Revolutions per minute	3000, 4500, 6000 and 9000	Cutting angle of wedge β	60°
Cutting speed	20, 30, 40 and 60 m/s	Rake angle γ	20°
Feed rate	4, 8, and 11 m/min	Cutting angle δ	70°

The milling heads were manufactured with the given material composition with and without special treatments. All three blade types were manufactured and supplied by Leitz GmbH & Co. KG, (Oberkochen, Germany) (Fig. 2). HW1 and HW2 were standard blades without any additional treatment. The third blade type (HW1 + CrTiN) was made of the same material composition as HW1 but was treated with a special CrTiN coating. The special coating was applied by PVD (physical vapor deposition) at SHM, s.r.o. (Šumperk, Czech Republic). According to the scientific literature (Navinšek *et al.* 1995; Su *et al.* 1996), the CrTiN coating applied by the PVD method improves the anti-dulling and durability of the tool when cutting harder wood-based materials. The dimensions and basic characteristics of the blades specified by the manufacturer are listed in Table 3.

Fig. 2. Blade types for edge milling

Table 3. Properties of the Milling Blades

Marking	Cutting material	Blade type	Dimensions (mm)	Micro-hardness HV_m (GPa)
HW1	Tungsten carbide HW-05	5086	50 × 12 × 1.5	17
HW2	Tungsten carbide HW-03F	6906	50 × 12 × 1.5	22
HW1 CrTiN	Tungsten carbide HW-05 + CrTiN	5086	50 × 12 × 1.5	30

Cutting power measurement

The power consumption was quantified by the cutting power of the milling machine. The cutting power of the edge milling was measured by the digital power meter METREL Power Q plus MI2392 (METREL D.D., Horjul, Slovenia) both in work and idle state. The measurements were made each second from the idling state to the end of the milling process. The measured data were automatically transferred into a PC that was connected to the milling machine and the power meter. The cutting power represents the total energy consumed by the edge-milling of the wood-based materials.

Based on a combination of parameters for the milling cutter (*e.g.*, cutting speed and feed rate), tool (*e.g.*, type of material and treatment), and machined materials (*i.e.*, MDF, MDF-L, and SEGP), 108 samples were made for edge milling. The side of each sample was milled 3 times along the entire length.

The effect of the milling factors on the cutting power was analyzed with the STATISTICA 13 software (Statsoft Inc., Tulsa, OK, USA); a MANOVA (multivariate analysis of variance) statistical approach was used in the data analysis. The statistical analysis used a 95% confidence interval, which reflected a significance level of 0.05 ($p < 0.05$).

RESULTS AND DISCUSSION

The results of the MANOVA statistical analysis confirmed that all factors, as well as their interaction, had a statistically significant ($p < 0.05$) effect on the cutting power during edge milling of wood-based materials (Table 4).

Table 4. The Effect of the Factors on the Cutting Power

Factors	Sum of Squares	Degrees of Freedom	Variance	Fisher's *F*-Test	Significance Level *p*
Intercept	603,626,871.3	1	603,626,871.3	1,756,682.0	0.00
Cutting speed	46,131,441.5	3	15,377,147.2	44,750.8	0.00
Feed rate	773,732.7	2	386,866.3	1,125.9	0.00
Material type	496,738.6	2	248,369.3	722.8	0.00
Tool type	10,942.3	2	5,471.2	15.9	0.00
Cutting speed × Feed rate × Tool type × Material type	95,664.1	24	3,986.0	11.6	0.00
Error	519,549.8	1,512.0	343.6		

The effect of the cutting speed on the cutting power is shown in Fig. 3. As the cutting speed increased, the cutting power also increased. The increase in the cutting power achieved at cutting speeds of 20 and 30 m/s was small (*i.e*. 17.7%). However, the cutting power requirements for cutting speeds of 30 and 40 m/s was the greatest, *i.e*. 38.2%. The cutting power values observed at the highest cutting speed (60 m/s) reached 681 W, which was in 25.5% higher than at a cutting speed of 40 m/s. The difference in cutting power values between the lowest and highest cutting speed was 103.6%. During the milling process, the cutting power generally increased herewith with the cutting speed, which is consistent with the findings of Morita *et al*. (1998), Aguilera and Martin (2001), Iskra *et al*. (2005), and Barcík *et al*. (2010).

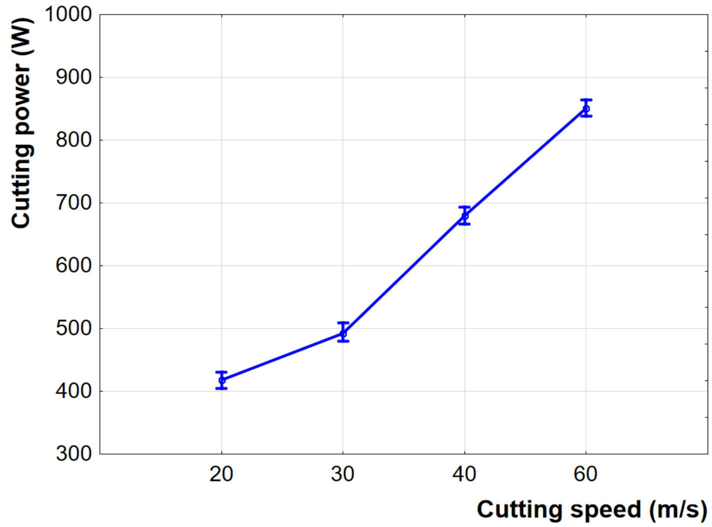

Fig. 3. The effect of the cutting speed on the cutting power

The effect of the feed rate on the cutting power had the same character as that of cutting speed; *i.e*., as the feed rate increased, cutting power increased as well (Fig. 4). On the other hand, the increase was not so great, and the differences in cutting power at each feed rate were lower than in cutting speed. It was observed that the cutting power at the 4 m/min feed rate cutting power reached 582 W, while at 11 m/min 635 W, which implies a total increase of 9.1 %.

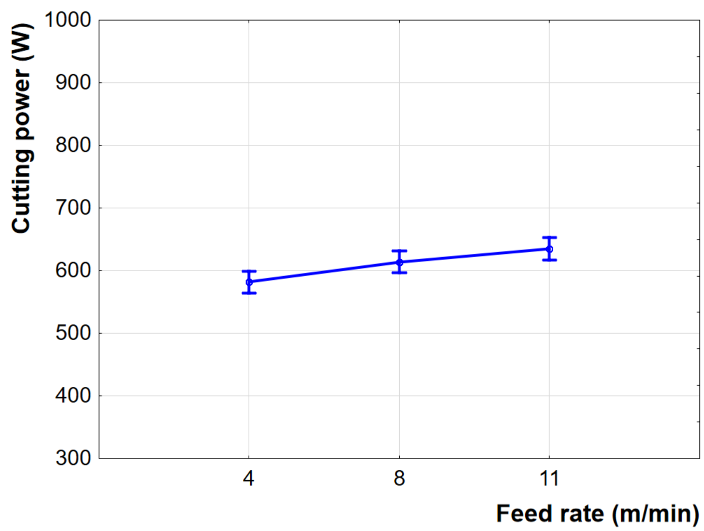

Fig. 4. The effect of the feed rate on the cutting power

The effect of the feed rate on the cutting power has been confirmed by other research studies. Barcík *et al*. (2010) examined the effect of various feed rates and cutting speeds on the power consumption during the surface milling of beech wood. It was observed that an increasing feed rate at a constant rake angle resulted in increased power consumption. Salca (2015), who studied the optimization of the milling process of black elder wood, reported that cutting power increased when the feed rate increased.

The effect of the tool material type (Fig. 5) was shown to be a statistically significant factor, but the effect of this factor was the lowest. The difference in cutting power between tool materials HW1 and HW2 was only 0.7%. HW1 is a cutting blade designed for milling common wood or wood-based materials, whereas HW2 is designed for harder wood-based materials. HW1 coated with CrTiN (HW1 + CrTiN) had slightly higher (1%) cutting power values in comparison to HW1. This coating is designed to increase the hardness, wear and corrosion resistance of the blade while reducing blade dulling (Labidi *et al*. 2005, Nouveau *et al*. 2007). However, the coating resulted in an uneven blade surface, which affected the coefficient of friction of the blade during milling. Increased friction resulted in increased power consumption. This phenomenon caused by the blade coating has been reported in the studies of Su *et al*. (1996), Faga and Settineri (2006), and Warcholinski *et al*. (2011); however, the extent of this effect depends on its composition, thickness and method of application.

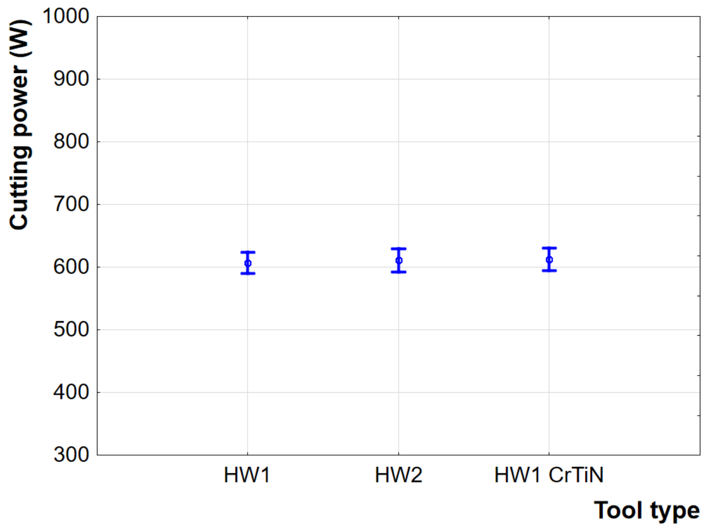

Fig. 5. The effect of the tool type on the cutting power

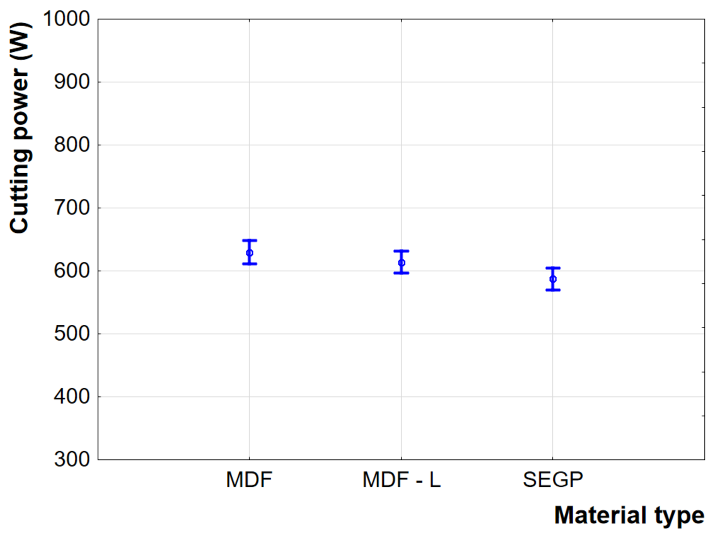

Fig. 6. The effect of the material type on the cutting power

The cutting power measured with different wood-based materials (Fig. 6) depended strongly on their densities, which, in turn, was affected by their compositions. As expected, the highest average cutting power, 630 W, was observed with the MDF, which had the highest density.

A slightly lower cutting power, 624 W, was noted with the single-sided laminated MDF (MDF-L), which had a slightly lower density than MDF. The differences between the cutting power values were only 2.5%. SEGP had the lowest cutting power of 587W, which was expected since it had a lower density when compared to MDF.

Figures 7 to 9 show the effects of all the examined factors on the cutting power of MDF, MDF-L, and SEGP. It is clear that the highest cutting power was observed with non-laminated MDF (Fig. 7 and Table 5), which was mainly related to its density. The density of MDF alone is a function of the amount of wood fibers and resin in the composite; the resin is largely responsible for its more abrasive character. In addition, isotropy of MDF in certain layers, where the outer layers are harder than the middle layers (Khazaeian *et al*. 2010), leads to different friction and uneven material removal. Both of these phenomena accelerate tool dulling and increase power consumption (Aknouche *et al*. 2009).

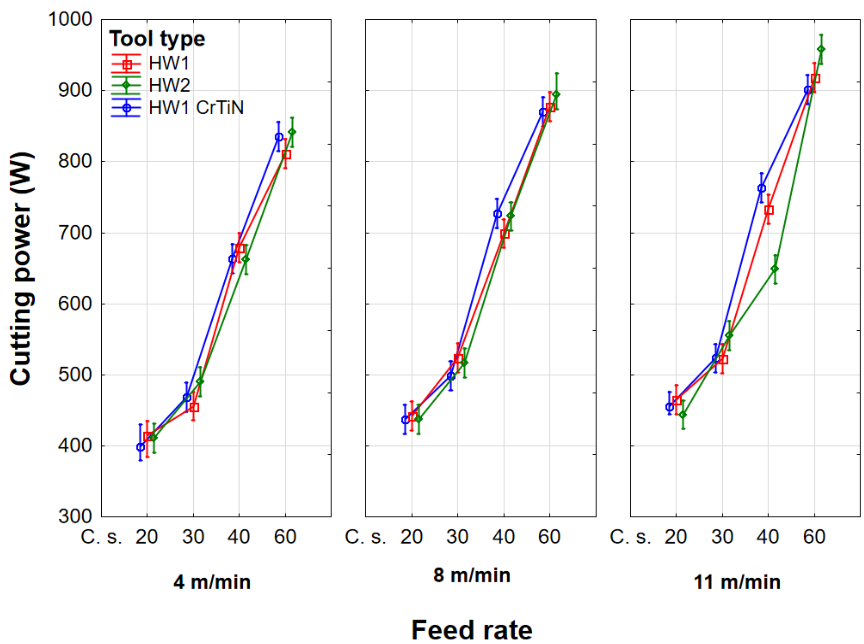

Fig. 7. The effect of the cutting speed, feed rate and tool type on the cutting power during edge milling of MDF

In comparison to what was observed with the single MDF, the lamination of MDF-L did not significantly affect the cutting power (Fig. 8 and Table 5). Cutting power values of MDF-L were slightly lower compared to single MDF. The MDF-L is laminated on the one side and the lamination layer is not very thick; thus, the surface lamination should not affect the cutting power as much during edge milling. The difference in cutting power values for MDF versus MDF-L could be caused by material densities. MDF-L had slightly lower density when compared to untreated MDF.

The lowest cutting power was noted with the edge milling of SEGP (Fig. 9 and Table 5). As previously reported, SEGP had the lowest density of the materials examined; so, it is assumed that cutting power should be the lowest based on the positive correlation of material density and cutting power during milling (Aguilera and Martin 2001). However, it is clear from the comparison of the densities of MDF and SEGP that the cutting power did not depend entirely on this factor. Differently than MDF, SEGP is anisotropic due to the wood slats that are glued together to make this composite. These slats are not identical because they are oriented differently to each other and also contain knots, resin ducts, or various widths of annual rings. These differences affect the milling process with each pass of the milling head, which eventually affects the overall power consumption.

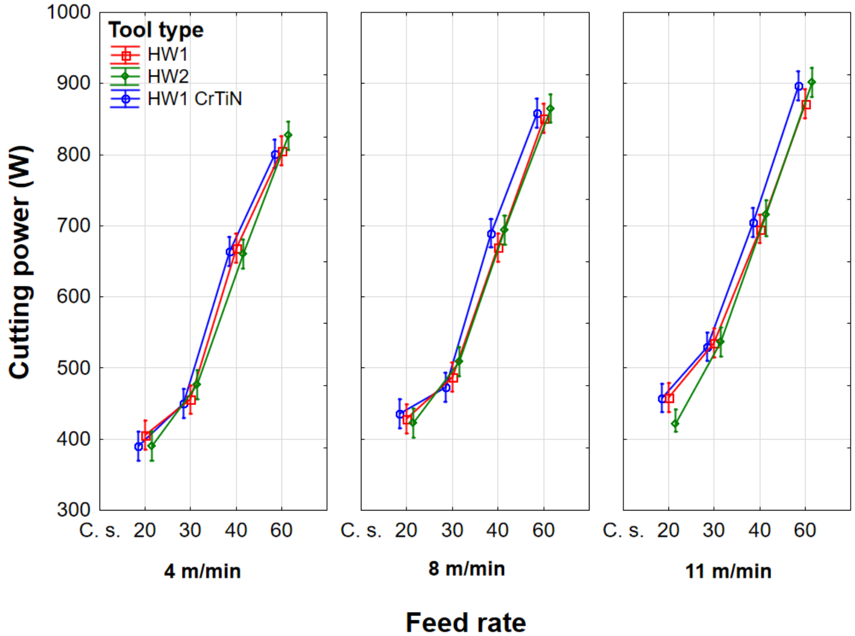

Fig. 8. The effect of the cutting speed, feed rate and tool type on the cutting power during edge milling of MDF-L

In general, EGP has a more heterogeneous structure than natural wood itself (Sütçü 2013). This property can be explained by a certain degree of densification that occurs when gluing EGP.

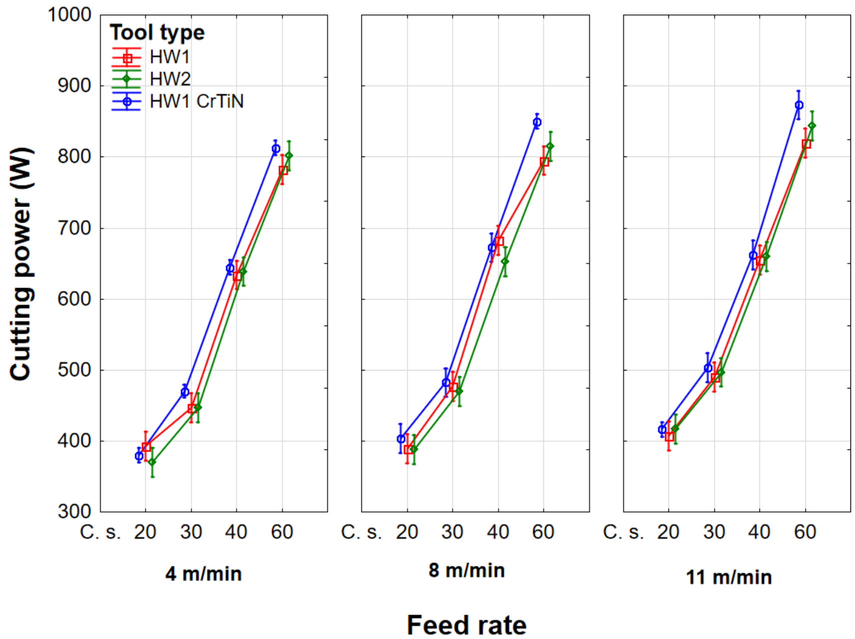

Fig. 9. The effect of the cutting speed, feed rate and tool type on the cutting power during edge milling of SEGP

Table 5. Mean Cutting Power Values

Cutting speed (m/s)	Feed rate (m/min)	Material type	Tool type	Cutting power (W)	Tool type	Cutting power (W)	Tool type	Cutting power (W)
20	4	MDF	HW1	414 (3.2)	HW2	411 (2.2)	HW1 CrTiN	399 (3.6)
30	4		HW1	456 (2.1)	HW2	490 (1.8)	HW1 CrTiN	469 (5.2)
40	4		HW1	679 (16.5)	HW2	662 (2.3)	HW1 CrTiN	664 (2.9)
60	4		HW1	811 (2.2)	HW2	841 (2.2)	HW1 CrTiN	835 (1.7)
20	8		HW1	442 (3.4)	HW2	437 (3.9)	HW1 CrTiN	438 (7.8)
30	8		HW1	524 (6.5)	HW2	516 (4.4)	HW1 CrTiN	499 (7.2)
40	8		HW1	699 (7.5)	HW2	723 (1.3)	HW1 CrTiN	727 (2.3)
60	8		HW1	878 (5.4)	HW2	894 (5.9)	HW1 CrTiN	870 (7.3)
20	11		HW1	465 (4.0)	HW2	444 (6.4)	HW1 CrTiN	455 (6.0)
30	11		HW1	523 (10.9)	HW2	555 (4.9)	HW1 CrTiN	523 (5.8)
40	11		HW1	733 (4.6)	HW2	648 (8.9)	HW1 CrTiN	763 (3.3)
60	11		HW1	918 (4.8)	HW2	958 (3.7)	HW1 CrTiN	902 (4.2)
20	4	MDF- L	HW1	406 (2.5)	HW2	390 (2.4)	HW1 CrTiN	390 (3.9)
30	4		HW1	456 (2.1)	HW2	477 (2.6)	HW1 CrTiN	450 (4.3)
40	4		HW1	669 (1.1)	HW2	661 (1.9)	HW1 CrTiN	664 (1.1)
60	4		HW1	805 (2.2)	HW2	827 (1.8)	HW1 CrTiN	801 (3.5)
20	8		HW1	429 (6.2)	HW2	423 (5.5)	HW1 CrTiN	436 (4.9)
30	8		HW1	487 (3.8)	HW2	509 (5.5)	HW1 CrTiN	473 (6.5)
40	8		HW1	672 (1.1)	HW2	694 (3.8)	HW1 CrTiN	699 (5.3)
60	8		HW1	851 (4.5)	HW2	865 (5.3)	HW1 CrTiN	859 (4.2)
20	11		HW1	458 (5.1)	HW2	421 (8.2)	HW1 CrTiN	458 (1.8)
30	11		HW1	535 (6.2)	HW2	537 (6.5)	HW1 CrTiN	530 (5.7)
40	11		HW1	696 (6.5)	HW2	716 (8.5)	HW1 CrTiN	704 (7.1)
60	11		HW1	872 (5.2)	HW2	902 (4.2)	HW1 CrTiN	897 (1.8)
20	4	SEGP	HW1	393 (2.4)	HW2	370 (4.6)	HW1 CrTiN	380 (3.0)
30	4		HW1	447 (3.1)	HW2	447 (2.1)	HW1 CrTiN	470 (3.0)
40	4		HW1	634 (2.2)	HW2	639 (3.8)	HW1 CrTiN	644 (2.5)
60	4		HW1	782 (2.3)	HW2	801 (3.0)	HW1 CrTiN	813 (1.5)
20	8		HW1	389 (7.8)	HW2	387 (5.7)	HW1 CrTiN	403 (1.4)
30	8		HW1	477 (2.4)	HW2	470 (3.0)	HW1 CrTiN	482 (3.1)
40	8		HW1	682 (3.2)	HW2	652 (2.3)	HW1 CrTiN	672 (3.5)
60	8		HW1	795 (2.4)	HW2	815 (2.6)	HW1 CrTiN	850 (4.2)
20	11		HW1	407 (6.5)	HW2	417 (3.7)	HW1 CrTiN	417 (1.4)
30	11		HW1	490 (3.5)	HW2	497 (8.1)	HW1 CrTiN	503 (1.2)
40	11		HW1	655 (5.4)	HW2	660 (6.4)	HW1 CrTiN	663 (6.2)
60	11		HW1	820 (1.2)	HW2	843 (4.5)	HW1 CrTiN	873 (1.7)

The values in parentheses are the coefficients of variation (CV) in %.

The total power consumption during the milling process can be affected differently. The most common method is to change the tool geometry or increase the number of blades in the milling head. The same effect can be achieved by the placement or positioning of the blade in the tool relative to the direction of the milling or the milled surface. Straight edge cutting tools are generally used. A straight cutting edge causes uneven distribution, compression, and damage to the wood fibers near the surface, which results in an increase in the required cutting force (Darmawan *et al.* 2011). Tilting the cutting edge might change not only the cutting power, but also affect the surface quality, since a slight change in the inclination angle of the cutting edge reduces the cutting power. The inclination angle of the cutting edge is especially important for particleboards and MDFs with single- or double-sided lamination; these laminates are susceptible to surface damage caused by milling (Boucher *et al*. 2007).

CONCLUSIONS

1. The highest cutting power was observed during the edge milling of MDF. MDF-L had a slightly lower value, and the lowest value was observed with SEGP. The cutting power during the edge milling of SEGP was 7.3% lower than that of MDF.
2. The type of cutting blade tool in relation to the milled material and to the blade treatment did not affect significantly the cutting power during milling. However, the highest cutting power values were observed with an HW1 blade coated with CrTiN (HW1 + CrTiN). The HW2 blade was noted to have slightly lower values, and the lowest values were observed with the untreated HW1 blade (HW1). However, the difference between the highest and lowest cutting power was only 1%.
3. Increasing the cutting speed led to an increase in the cutting power. The most significant increase 38.2%) was observed when the cutting speed increased from 30 to 40 m/s.
4. The feed rate had the same effect on the cutting power as the cutting speed, although the differences in the values among the individual feed rates were not noteworthy. The difference in cutting power found at the lowest and highest feed rate was 9.1%.

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