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Cutting forces during drilling and selected physical and mechanical properties of the finish coating based on epoxy resin

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Abstract: *Cutting forces during drilling and selected physical and mechanical properties of the finish coating based on epoxy resin.* Paper presents selected tests of epoxy resin coating applied to American walnut wood (*Juglans nigra* L.). The aim of the study was to assess the machinability of wood flooded with resin during drilling. The axial forces and torque values were adopted for the machinability criteria. The idea of the research was the thesis questioning the possibility of processing epoxy resin coatings with the application of tools and parameters used during wood processing. In addition, the influence of UV light on the obtained coating was examined and abrasion tests were carried out. It was found the resin changes its colour under the influence of UV radiation, but the change is imperceptible to an average observer. Epoxy resin is characterized by low abrasion resistance compared to commonly used paint and varnish coatings. Although solid resin is characterized by high cutting resistance while drilling, the force values do not exceed the commonly cut wood-based materials.

Keywords: epoxy resin, coating, cutting forces, drilling

INTRODUCTION

The surfaces of wood and wood-based materials used in the production of furniture are covered with various types of coatings. In the case of wood, these are paint and varnish coatings. For wood-based materials, these are various types of laminates and veneers. The purpose of paint, varnish coatings and laminates is to protect against unfavourable chemical and mechanical factors as well as to give the surface aesthetic value. The finished surface of the furniture requires sufficiently hard, UV light and chemical resistant coat (Mojgan et al. 2017).

During the production of solid wood furniture, painting and varnish products are applied to the elements intended for assembly or the finished piece of furniture. In other words, the wood after the coating process is not machined or is treated to a limited extent. In the production of furniture from laminated wood-based panels, there is a need to process the raw material with the coating. Then, not only the plate is machined, but also the laminate applied to it, what causes numerous problems with processing quality. A common matter is the chipping of the laminate, which in turn reduces the aesthetic value of the semi-finished product. The problem of delamination is widely studied. The number of attempts was made to describe this issue during drilling (Zielińska-Szwajka, Szwajka 2014, Prakash et al. 2009) or milling (Śmietańska et al. 2020).

In recent years, there has been a tendency to finish furniture with epoxy resins used to protect furniture surfaces, fill knots and all kinds of imperfections, or even flooding pieces of wood to obtain a composite with irregular internal structure. The procedure is especially popular in the production of custom table tops, wooden accessories and wooden jewellery. Epoxy resin has been known for many years, it was obtained in 1936 as a result of the reaction of dian and epichlorohydrin. Since then, its popularity has been constantly growing. Due to their versatility in terms of chemistry and processing, the utility of epoxy resins is appreciated in industries where high strength materials are required. It is widely used in aviation, renewable energy sectors. Epoxy resins are widely used to strengthen fibres, composites produced for the structural parts of aircraft and wind turbines. Epoxy resins are used to a large extent in more conventional applications like engineering adhesives, coatings and paints (Jaworski et al. 2019).

In the production of furniture coated with epoxy resins, wood and resin are machined. The resin's thickness is sometimes equal to the nominal thickness of the product. These operations are carried out with using of standard tools, machine tools and equipment dedicated to wood processing, despite the fact the resin is a material with relatively high mechanical parameters. Wood and resin table are subjected to standard operations like sawing, grinding, polishing and drilling. Materials with high mechanical parameters may cause the tools to twist when drilling with small diameter burs.

The knowledge about the processing of wood-based materials from epoxy resin is grossly low comparing to the previous research on paint and varnish products. The research focuses on the chemical aspects and the lack of scientific research focusing on the treatment of epoxy resin. The aim of the work was to examine the axial force and torque during drilling, to assess the colour change under UV and to determine the abrasion.

MATERIALS AND METHODS

Cutting force during drilling

During the tests, samples subjected to drillability assessment according to criterion of cutting forces. During the research two comparisons were made:

1. The effect of a resin coating on wood on cutting
2. The cutting forces were compared when drilling epoxy resin and MDF

American walnut (*Junglans nigra* L.) and Epidian Deco (Ciech, Warsaw, Poland) epoxy resin were used for the first tests. Resin-coated and uncoated wood samples were used in the experiment.

Epidian Deco is a medium viscosity resin in the form of a clear liquid with a light yellow colour, dedicated to deep pouring. It is transparent, and after hardening it creates a smooth, waterproof surface resistant to chemical and mechanical factors. Table 1 shows the specification of the resins declared by the manufacturer.

Table.1. Product safety data sheet according to Ciech

Curing time	7 days at room temperature	6h at 80°C
Flexural strength, [MPa] PN-EN ISO 178:2006	66.6	72.6
Modulus of elasticity in bending, [MPa] PN-EN ISO 178:2006	2380	2480
Compressive strength, [MPa] PN-EN ISO 604:2006	63.7	64.2
Epoxy number	0.488-0.513 mol/100g	
Viscosity at 25 ° C:	500 – 900 mPa s	
Density at 25 ° C:	ok. 1100 kg/m^3	

To make the samples, it was mixed according to the manufacturer's recommendations in the proportion of 100:30 parts by weight with the hardener. Walnut samples were taken from random pieces of wood with a rectilinear grain pattern, without cracks, defects and uniform colour. Wood samples were tested for static bending strength and the modulus of elasticity was determined in accordance with PN-79 / D-04104, PN-63 / D04117. The test results are presented in the table 2.

Table.2. Some mechanical and physical properties of walnut wood which machinability was tested

Density [kg/m^3]	Modulus of rupture [MPa]	Bending strength [MPa]
650	16500	103.4

Wood samples was cover epoxy resin. Thickness of the epoxy resin layer was 0.2mm. The thickness measured on microscope Mitutoyo (model Tm-505, Kanagawa, Japan).

The second experiment used samples of solid resin and MDF board. MDF samples were tested for static bending strength and the modulus of elasticity according PN-EN 310:1994. The test results are presented in the table 3.

Table.3. Some mechanical and physical properties of MDF which machinability was tested

Density [kg/m^3]	Modulus of rupture [MPa]	Bending strength [MPa]
760	4200	3.5

For cutting forces test all samples with dimensions of 100x40x20 [mm] was used. Machinability tests were carried out on a CNC machining centre BUSELLATO model JET 130 (Italy 2004) using a drill (Faba, model:K0500009, apex angle 60 degrees, spiral angle 15 degrees, front face angle of 10 and 35 degrees) with a diameter of 8 [mm] made of HW. Through holes were drilled in the samples. The samples were mounted on a measuring platform (Fig. 1) equipped with a piezoelectric sensor (Kistler 9345A). Measurement signals from the sensor were recorded using a data acquisition card (National Instruments PCI-6111) installed on a PC and the signals were recorded in the LABVIEW software (LabVIEW, version 7, Austin, TX, USA). The sampling frequency was 50 kHz. Example of recorded signal was shown on figure 2. Axial forces and torque were tested for three different feed speed parameters: 1.0 [m / min], 1.3 [m / min] and 1.7 [m / min], the spindle speed was 4500 [rpm]. The series of 10 measurements was performed for each parameter during the tests. The RMS value of the recorded signal was taken as the measurement result. The STATISTICA software was used for statistical analysis.

For samples covered epoxy resin It was observed that five major phases of the variation of the thrust force value can be identified during drilling (stage A-E in Figure 2).
Stage-A, the chisel edge of the drill penetrates into the material producing a rapid increase in the value of the thrust force. During this phase, instead of cutting, the chisel edge of the drill is pressed into the material. Stage-B, the drill penetrates to a depth of h= 7 mm, which is equal to the height of the cutting blades of the drill. Stage-C, cutting with a constant cross-section of the cutting layer in the epoxy layer. Stage-D, cutting with a constant cross-section of the cutting layer in the wood layer. Stage-E, the value of the axial force and torque drops to zero when thecutting edges of the drill have left the workpiece. To evaluate the effect of covering the wood with resin, analyze step A-C.

For the comparison of solid epoxy resin and MDF board, the entire measuring range was examined without division into steps. Based on the gained results, the relative cutting index (CFPI) proposed by (Podziewski et al. 2018) according to the equation:

$$CFPI_{X} = 0,5\ (F_{X} / F_{MDF} + T_{X} / T_{MDF})\ *\ 100\% \qquad (1)$$

where the CFPI index denotes the relative difficulty of machining material X in relation to the cutting forces (the lower the index, the better the machinability of the material

X); F_X and T_X are axial force and torque for material X; F_{MDF} and T_{MDF} describe the axial force and torque of the reference material for which the MDF board is taken.

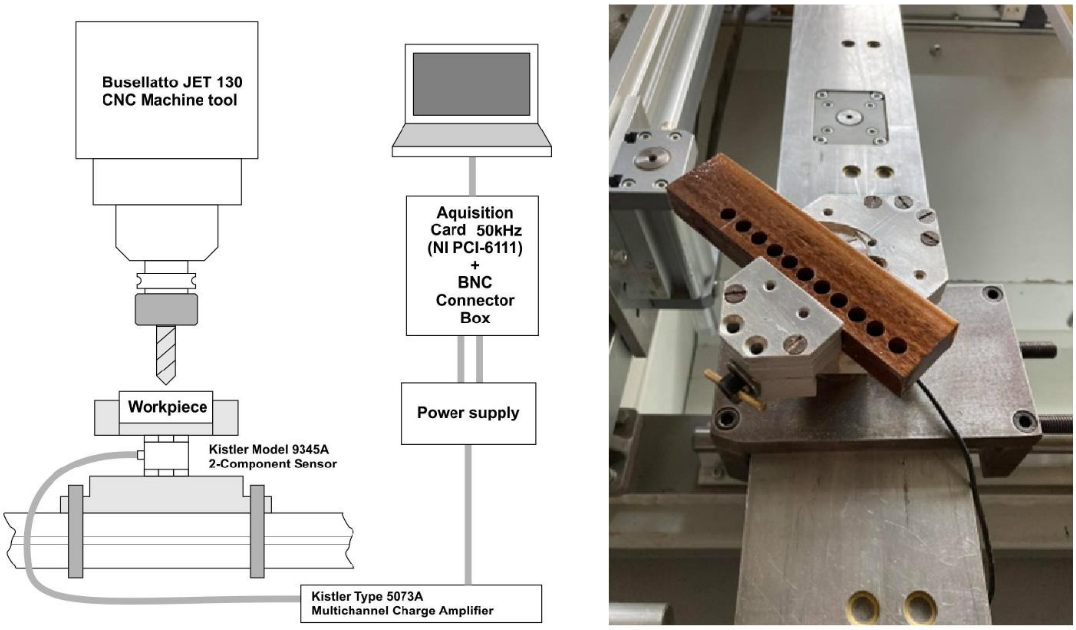

Figure 1. Schema of measurement platform used to measure feed force and torque and view of the mounted sample

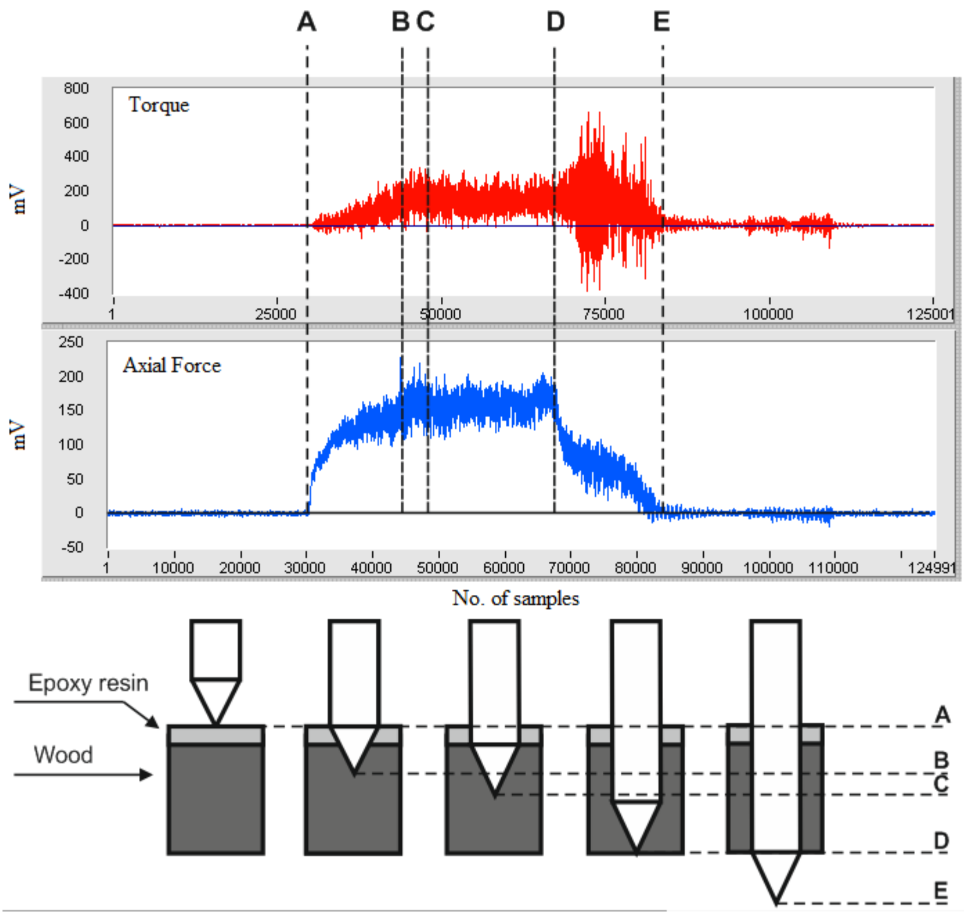

Figure 2. Example of recorded signal and thrust force and torque evolution over sampling for a drill

Abrasion

The abrasion test was based on the Taber method. The test was carried out in accordance with the PN-EN ISO 7784-1: 2006 standard. The machine load was 1000g. The number of sample rotations for each cycle was 200 and the number of cycles was 5. For comparative purposes, the tests were carried out for three different varnishes: acrylic varnish by Vidaron, acrylic-polyurethane varnish Dragon, polyurethane varnish for parquet HartzLack. Samples before coating were sanded with paper of 180 grit. After cleaning, three layer of coat were applied, as required by product.

Colour change

The colour change measurement was tested on samples of walnut wood with dimensions of 150x40x20 [mm] covered with resin. The samples were subjected to UV radiation. A Solarbox 1500e chamber for artificial UV radiation (CO.FO.ME.GRA., Milano, Italy) was used for the tests. The radiation power used was 550 W / m^2 and the exposure time was 50 hours. Then, using a 3nh Envi Sense colorimeter, three parameters L *, a *, b * were measured:

L – brightness level coordinate,
a – coordinate of the yellow colour,
b – coordinate of the red colour

The total colour difference DE between the two surfaces (UV-treated and untreated) is the geometric distance between their positions in the CIE 1976 colour space (L * a * b *). This difference was calculated using the formula

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (2)$$

ΔE - average colour change,
$0<\Delta E<1$- observer does not notice the difference,
$1<\Delta E<2$- only experienced observer can notice the difference
$2<\Delta E<3.5$- inexperienced observer also notices the difference,
$3.5<\Delta E<5$- clear difference in colour is noticed,
$5<\Delta E$- observer notices two different colours.

On this basis, the differences in colour between the fields of the resin subjected to UV radiation and those not subjected to UV radiation were calculated.

Cutting forces results

Figures 3 and 4 show the effect of feed speed on the value of axial force and torque when drilling wood and wood covered with resin.The results were subjected to multi-factor Anova statistical analysis (table 4 and 5).The obtained results turned out to be statistically insignificant (for p, 0.05), which proves that the epoxy resin paint and varnish coating does not affect the value of the axial force and torque during drilling.

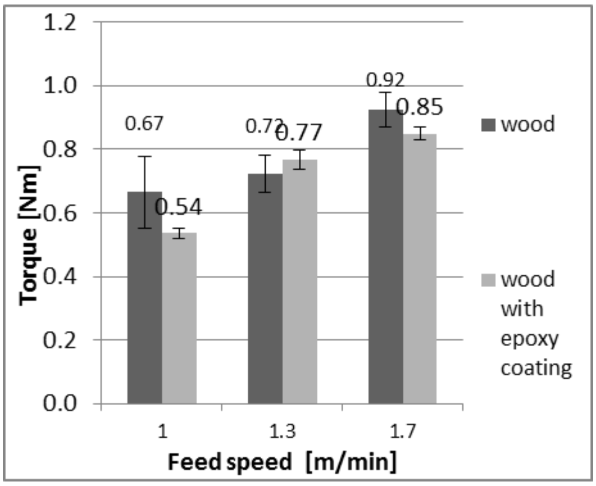

Figure 3. Influence of feed on the value of the torque during drilling wood and wood coated epoxy resin

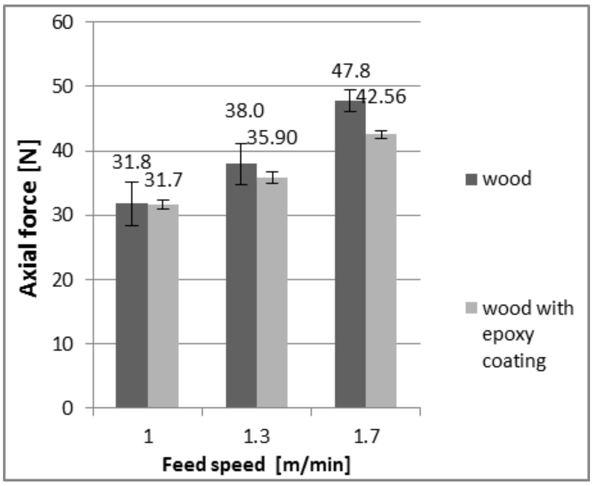

Figure 4. Influence of feed on the value of the axial force during drilling wood and wood coated epoxy resin

Table 4. Analysis of variance for selected factors and interactions between factors influencing the drilling torque wood and wood coated epoxy resin

Factor / Interaction	SS	Df	MS	F	p
Material	0.04408	1	0.04408	2.308	0.134127
Error	1.10753	58	0.01910		

SS – sum of squared deviations from mean value , Df – the number of degrees of freedom , MS – mean square of the deviations (MS=SS/Df), F – test value, p – probability of error, X – the percentage influence of factors on the examined property of chipboards

Table 5. Analysis of variance for selected factors and interactions between factors influencing the drilling torque wood and wood coated epoxy resin

Factor / Interaction	SS	Df	MS	F	p
Material	92.97	1	92.97	2.480	0.120765
Error	2174.48	58	37.49		

Figures 5 and 6 show the results of measuring the axial force and torque when drilling solid epoxy and MDF board. Results were subjected to multi-factor Anova statistical analysis (table 6 and 7). The presented analysis shows that statistically significant differences occur during the measurement of the torque. The significience of the material influence on the torque was 76%.

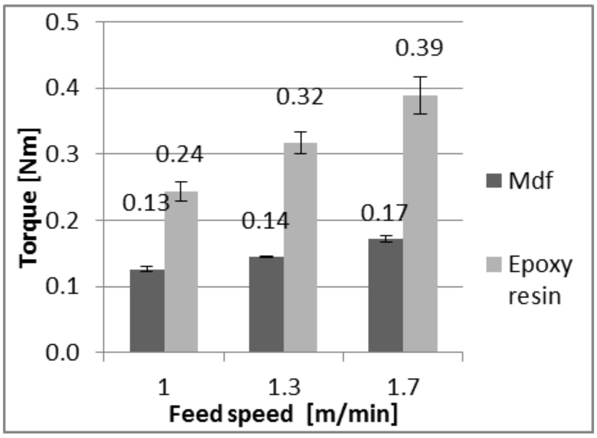

Figure 5. Influence of feed on the value of the torque during drilling mdf and epoxy resin

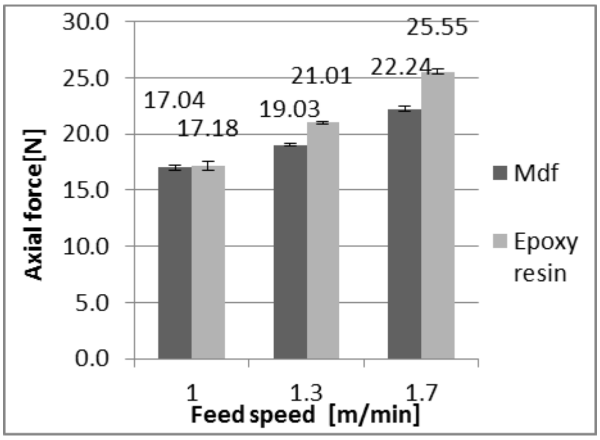

Figure 6. Influence of feed on the value of the axial force during drilling mdf and epoxy resin

Table 6. Analysis of variance for selected factors and interactions between factors influencing the drilling torque mdf and epoxy resin

Factor / Interaction	SS	Df	MS	F	p	X
Material	0.213805	1	0.213805	91.6729	0.000000	76.7
Error	0.065303	28	0.002332			23.3

Table 7. Analysis of variance for selected factors and interactions between factors influencing the drilling torque mdf and epoxy resin

Factor / Inaction	SS	Df	MS	F	p
Material	24.45	1	24.45	2.783	0.106420
Error	246.01	28	8.79		

The value of the CFPI index for the whole considered range of feed was 238% on average, which in relation to the results obtained by (Podziewski et al. 2018) ranks epoxy resin among hard to cut materials (Fig. 7). However, it should be emphasized that wood-based materials as transformer plywood (CFPI over 300%) or compreg (CFPI less than 500%) are normally processed with tools dedicated to wood.

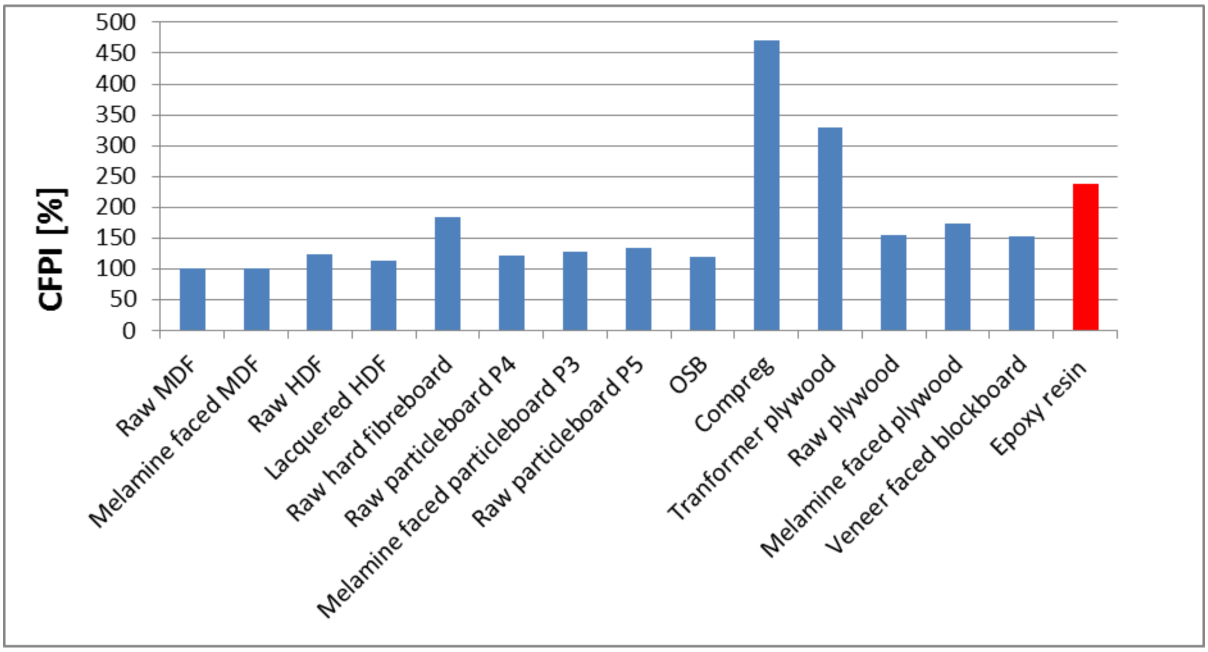

Figure 7. Differentiation od wood-based board and epoxy resin in terms of difficulty in machining determined by CFPI index [results based on Podziewski et al.2018]

Colour change results

The samples with the resin irradiated with UV rays changed their colour, the difference between the irradiated and non-irradiated samples was DE = 0.188. Comparing the obtained results to the works of other authors (Borysiuk et al. 2015) shows that epoxy resin is a material with high resistance to UV radiation. The authors of the study, comparing the colour changes for samples covered with acrylic paint, indicated a colour change for pine wood $\Delta E = 6.04$, and for beech wood $\Delta E = 5.70$. In the case of the presented results concerning the tested epoxy resin, the change is significantly lower.

Abrasion results

Abrasion of the resin-coated wood sample was 0.0138 g of the mass, the average abrasion resistance T = 63. Figure 8 shows the results of the average abrasion resistance. It can be noticed that the tested epoxy resin, in relation to the remaining paint coatings, is characterized by a similar abrasion resistance as polyurethane paint.

With regard to the results [Kieblesz, 2017], it appears that the abrasion resistance of the epoxy resin is at the level of the ICA OP 395P polyurethane varnish. At the same time, it should be emphasized that among the tested paint and varnish coatings, i.e. Oil 90, Pokost, Luxens, Aquaréthane or Velvet, the result obtained by the tested epoxy resin is the lowest result.

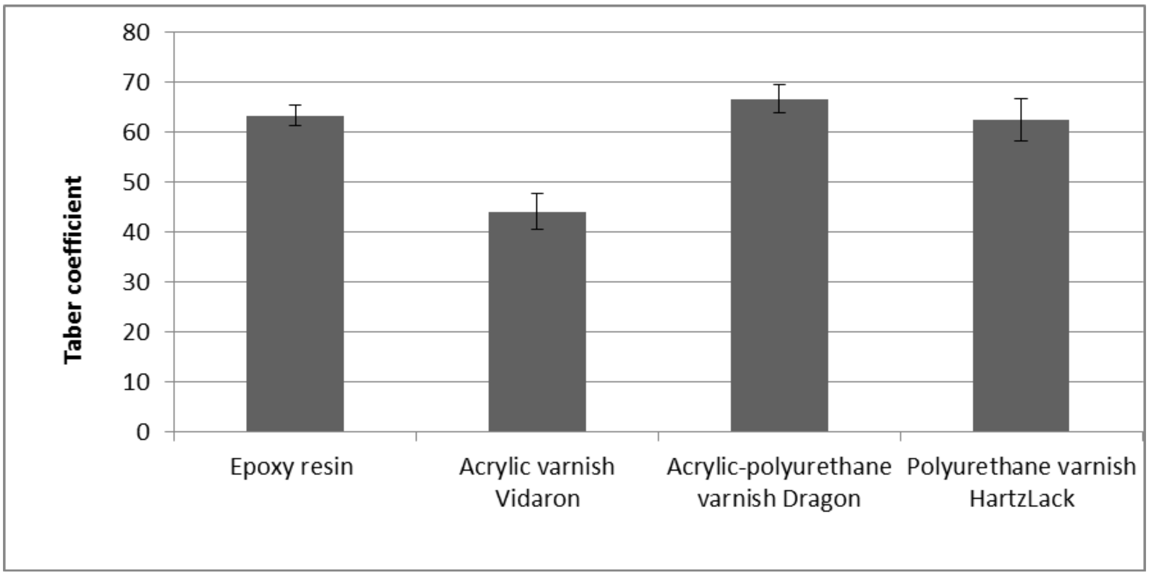

Figure 8. Average abrasion resistance (Taber) of tested coatings

CONCLUSION

Based on the performed analyses the following conclusions can be drawn:

1. The application of the epoxy resin coating does not statistical affect the axial force and torque values during drilling.
2. The relative machinability index CFPI for the solid resin was 238%, which proves high cutting resistance during drilling, it should be emphasized that there are commonly available wood-based materials characterized by a higher index, and therefore more difficult to cut than epoxy resin.
3. Samples covered with the resin under the influence of UV rays slightly change their colour, but the colour change is not visible to the human eye.
4. Epoxy resin is characterized by a high Taber coefficient, which proves its relatively low abrasion resistance among paint and varnish materials used in the furniture industry. The abrasion resistance of the tested epoxy resin is at the level of polyurethane varnishes

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Streszczenie: *Siły skrawania podczas wiercenia oraz wybrane właściwości fizyko-mechaniczne powłoki wykończeniowej na bazie żywicy epoksydowej.* W pracy przedstawiono wybrane badania powłoki z żywicy epoksydowej naniesionej na drewno orzecha amerykańskiego (*Juglans nigra* L.) Celem pracy była ocena skrawalności żywicy epoksydowej oraz drewna pokrytego żywicą epoksydową podczas wiercenia. Za kryterium skrawalności przyjęto wartości siły osiowej oraz momentu obrotowego. Genezą badań była teza stawiająca pod znakiem zapytania możliwość obróbki powłok z żywicy epoksydowej przy pomocy narzędzi i parametrów stosowanych podczas obróbki drewna. Ponadto zbadano wpływ światła UV na uzyskaną powłokę oraz przeprowadzono badania ścieralności. W wyniku badań stwierdzono, że pod wpływem promieniowania UV żywica zmienia swoją barwę, jednak zmiana jest niezauważalna dla przeciętnego obserwatora. Żywica epoksydowa charakteryzuje się niską odpornością na ścieranie w odniesieniu do powszechnie stosowanych

powłok malarsko lakierniczych. Mimo iż lita żywica epoksydowa charakteryzuje się wysokimi wartościami siły osiowej i momentu obrotowego podczas wiercenia, jednak wartości sił nie wykraczają poza powszechnie skrawane materiały drewnopochodne.

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