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ORIGINAL ARTICLE

Turning of wood plastic composites by water jet and abrasive water jet

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Abstract The paper deals with the verification of suitability of water jet and abrasive water jet application for the disintegration of rotating samples of wood plastic composites (WPCs) with diameter d=36 mm. The influence of selected technological factors (traverse speed of cutting head v [mm/min] and size of abrasive particles [MESH]) on the topography of resulting surfaces has in particular been studied. Surface topography and quality have been assessed using the methods of optical and confocal microscopy and optical profilometry. The presented procedures and results of experiments demonstrate the technology of abrasive water jet as an appropriate tool for the rough machining of WPCs and similar composite materials. In addition, the application of this technology can effectively solve the problem of the melting of the polymer matrix and its subsequent sticking to the functional parts of a cutting tool resulting from conventional turning.

Keywords Wood plastic composite · Water jet · Turning · Traverse speed · Size of abrasive particles · Surface quality

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1 Introduction

The paper focuses on the application of water jet (WJ) and abrasive water jet (AWJ) technologies for the turning of wood plastic composites (WPCs). These composite materials are formed by the combination of two main components—the polymer matrix and cellulose-based reinforcing particles (wood flour, chips, or fibers) and chemical additives (lubricants, binders, flame retardants, fungicides, light stabilizers, pigments, etc.). The components are mixed together at high temperature, and then techniques of extrusion, injection molding, or calendering are used for the shaping of final products [1].

The WPCs are used for the production of deck boards, industrial boarding, cladding, window and door profiles, indoor furniture, fences and railings, park benches, landscaping timbers, and many other products such as pallets, flowerpots, and tool handles [2].

Adding wood to the polymer matrix reduces its price and increases mechanical properties such as stiffness, strength, and elongation. Compared to solid wood, WPCs have better fungal resistance and dimensional stability when exposed to moisture. Good insulation properties, high durability, lack of cracking or splintering, and low maintenance also represent the important advantages of these materials [2].

In many cases, it is necessary to apply conventional machining technologies (such as drilling, grinding, milling, or turning) in addition to the sheet or profile extrusion used to shape the end WPC products (in the case of low volume production, extrusion technologies are considered to be inappropriate due to the high cost of special extrusion die production).

During the conventional machining of composite materials based on synthetic resins and natural fibers, the problem of the melting of the plastic matrix and its subsequent sticking to the functional parts of cutting tools occurs. This problem can be solved by the application of high-speed water jet turning technology. In principle, water jet turning is similar to conventional turning with a single-point tool. The workpiece is rotated while the cutting tool (water jet) is continually fed parallel to the axis of rotation. In contrast to conventional turning, the water jet can be moved in all directions with much larger lateral increments. Jet forces on the workpiece are negligible. By water jetting, the removed material is converted into very fine debris, as opposed to the chips formed in conventional machining [3, 4]. An important advantage of water jet technology is that no heat is released [5].

A large range of materials can be cut and machined using the WJ and AWJ [6–14]. In terms of wood and wood products, these technologies have so far only been used for material cutting. For example, Szymani and Dickinson [15] in their work compared methods of wood cutting using vibration cutters, water jet, and laser beam. According to Mazurkiewicz [16], the mechanical operations of wood grinding and chopping can be substituted by the hydromechanical working of high-pressure water nozzles. In such a way, wood fibers are thus separated without damage to their structural integrity, while the power consumption is comparable to that of conventional methods. DuPlessis and Hashish [17] dealt with the mathematical modelling of the water jet cutting process for wood materials. Other authors who are currently investigating the WJ/AWJ cutting technology for wood and wood materials include for example Lee [18], Wang [19], Barcík et al. [20], and Kminiak and Gaff [21]. The work of such authors is primarily focused on investigating the effects of various technological factors (traverse speed, water pressure, abrasive mass flow rate, etc.) on the results of water jet machining for various wood types.

Not only wood but also wood-based agglomerated materials can be machined by water jet [22, 23]. However, the application of WJ/AWJ technology for the turning of these materials, as well as composite materials with natural fibers, has yet to be adequately studied.

In this paper, the effects of selected technological factors (traverse speed of cutting head and size of abrasive particles—MESH) on the surface quality of a WPC material after turning with WJ and AWJ technologies are investigated. The surface topography and quality are assessed using the methods of optical and confocal microscopy and optical profilometry.

2 Experimental setup

In the experiment (Table 1), WPC samples (profiles) with dimensions of 40×60×3,600 mm were used (Fig. 1). The material consists of high-density polyethylene (HDPE) matrix reinforced with wood chips in a ratio of 25:75 vol%. Wood chips with a length of several tens of microns to about 2 mm are evenly dispersed in the polymer matrix. The chips are partially or completely saturated with the polymer and are mostly situated in the direction of polymer flow during the extrusion process (Fig. 2a). The matrix is solid, without bubble pores. The material contains microcracks, which are mostly localized on the contact between the wood and plastic (Fig. 2b). Occasionally, the microcracks pass through the wood chips in the direction of their longitudinal axis. The length of cracks ranges from 20 μm to 4 mm and are sparsely and unevenly distributed over the material volume. As well as the cracks, sporadic elongated cavernous spaces of up to 0.3× 2 mm can also be found in the material.

Before the AWJ/WJ turning process, experimental samples were cut to a length of 150 mm with an ERGONOMIC 275.230 band saw and subsequently milled to a square cross section of 40×40 mm using CNC machining center Pinnacle VMC 650S. The samples were subsequently machined from a square to circular cross section with a diameter of about 36 mm (using the SUI 40 conventional lathe), and the sample faces were flattened (Fig. 3). The HDPE matrix was melting and sticking to the saw blade and cutting tool during the sawing and turning process.

Table 1 Marking of test samples and values of variable factors of AWJ/WJ turning process

Sample no.	Revolution (rpm)	Traverse speed v (mm min^{-1})	Abrasive mass flow rate m_a (g min^{-1})	Size of abrasive particles (MESH)
1	34	20 (surface 1) 30 (surface 2) 40 (surface 3) 50 (surface 4) 60 (surface 5)	400	80
2	34	20 (surface 1) 30 (surface 2) 40 (surface 3) 50 (surface 4) 60 (surface 5)	400	120
3	34	20 (surface 1) 30 (surface 2) 40 (surface 3) 50 (surface 4) 60 (surface 5)	400	Without abrasives

Fig. 1 WPC samples used in the experiment (profiles of 40×60× 3,600 mm)

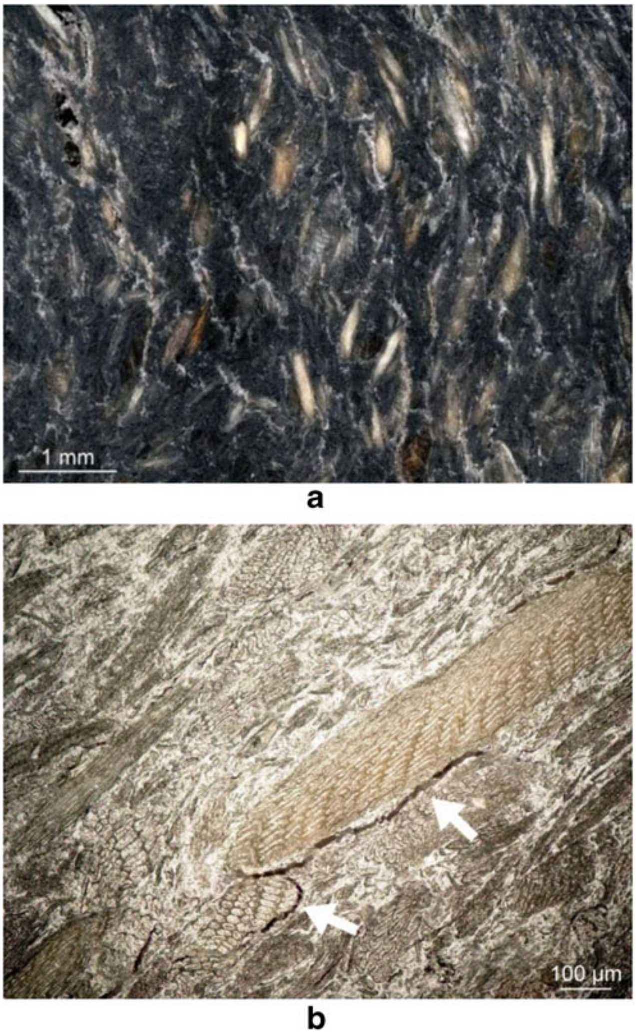

Fig. 2 Microscopic structure of WPC samples used in the experiment. **a** Wood chips situated in the direction of polymer flow. **b** Microcracks localized on the contact between the wood and plastic (Nikon Eclipse 80i optical microscope, reflected light, dark field technique)

Fig. 4 Samples clamping in chucks before AWJ/WJ turning

The 2D *X-Y* cutting table PTV WJ2020-2Z-1×PJ was used for the AWJ/WJ turning of prepared samples. Additional devices were used for the rotation of the workpiece, namely the pneumatic chucks and electrical motor for the rotational speed control (Fig. 4). The required water pressure (of 400 MPa) was supplied by a PTV 75-60 pump. Abrasive particles (Australian garnet) were fed from a hopper through an abrasive feeding system by a tube with an inner diameter of 6.4 mm and a dosing accuracy of ±2.0 g. The constant abrasive flow rate was m_a=400 g min^{-1}. The inclination of the cutting head was φ=90°, the diameter of the water jet nozzle d_n=0.33 mm, and the diameter of the focusing tube d_f=1.02 mm. The following two factors varied in the course of the experiment:

- Traverse speed of cutting head *v* (mm.min^{-1})
- Size of abrasive particles in MESH (or WJ turning without abrasives)

Revolutions were set at the constant value of 34 rpm (the maximum value of the experimental device). The marking of

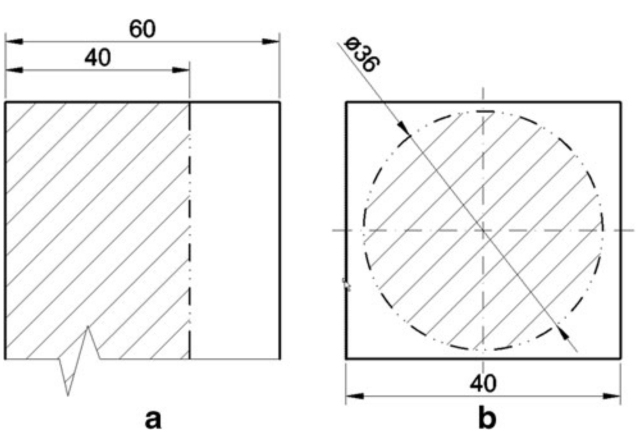

Fig. 3 Preparation of samples before AWJ/WJ turning. **a** Volume of material milled. **b** Conventional turning to circular cross section with diameter of 36 mm

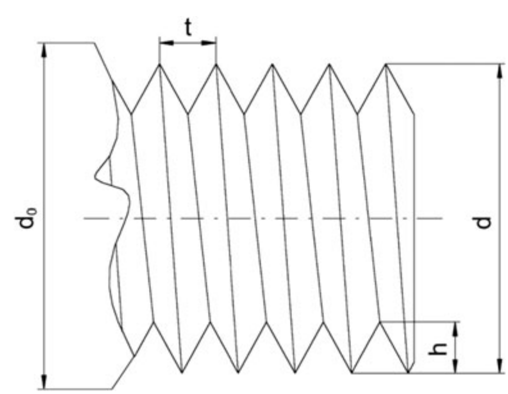

Fig. 5 Quantitative parameters used for the description of surfaces of WPC samples turned using AWJ/WJ technology: d_0 diameter of original unmachined cylindrical workpiece (mm), *d* major diameter of thread (mm), *t* average pitch of thread (μm), *h* average depth of thread (μm)

Table 2 Basic parameters of surfaces created on WPC samples by AWJ/WJ turning technology at various traverse speeds *v* and with different size of abrasive particles (definitions of parameters are given in the text and in Fig. 5)

Sample no.	Surface no.	*v* (mm min^{-1})	Ra (μm)	Rz (μm)	Approximate shape of thread profile	Δd (%)	*t* (μm)	*h* (μm)
1 (abrasive of 80 MESH)	1	20	7.4	35	–	11.5	–	–
	2	30	10.9	48.3	Irregular isosceles triangle	10.4	850	106
	3	40	6.9	31.7	Irregular isosceles triangle	9.4	1,169	101
	4	50	26.6	103.1	Irregular isosceles triangle	6.5	1,454	458
	5	60	69.4	302.5	Round shape to isosceles trapezium	1.9	1,715	1,395
2 (abrasive of 120 MESH)	1	20	5.5	24.3	–	7	–	–
	2	30	10.9	45	Irregular isosceles triangle	6.3	867	97
	3	40	10.8	45.1	Irregular isosceles triangle	5.6	1,189	124
	4	50	44.6	152	Round shape to isosceles triangle	2.8	1,427	459
	5	60	92.6	303.8	round shape	0.7	1,720	1,022
3 (without abrasive)	1	20	13.9	70.4	–	3.8	–	–
	2	30	54.6	228.8	Irregular scalene triangle	2.4	848	196
	3	40	88	344.5	Irregular isosceles triangle	0.3	1,161	356
	4	50	80.4	318.2	Irregular scalene trapezium	0.2	1,438	367
	5	60	68.5	288.9	Irregular isosceles trapezium	0.1	1,789	323

test samples and values of variable technological factors are given in Table 1.

Surfaces created with various configuration settings of the WJ and AWJ system were qualitatively described using a Nikon SMZ 25 stereomicroscope. The change in machined workpiece diameter Δd was determined with a digital caliper:

$$\Delta d = \frac{d_o - d}{d_o} \times 100 \ [\%]$$

where

d_0 Diameter of the original unmachined cylindrical workpiece (mm)

d Major diameter of the "thread" created by WJ/AWJ turning (mm) (Fig. 5)

The surfaces were then scanned with an OLYMPUS Lext OLS 3100 laser confocal microscope. The average pitch of the resulting "thread" t (μm) and its average depth h (μm) (Fig. 5)

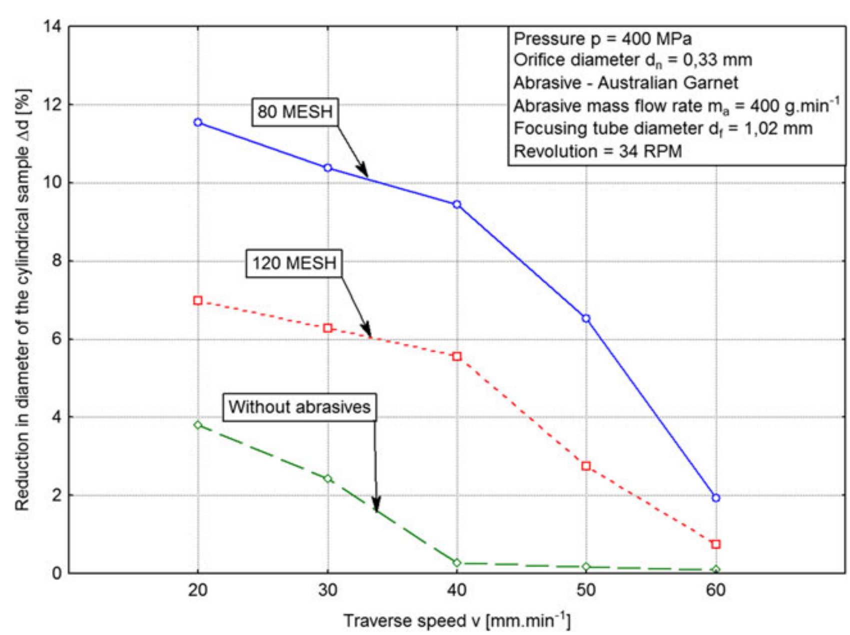

Fig. 6 Change to diameter Δd of the original cylindrical WPC sample depending on the traverse speed of AWJ/WJ after turning with abrasive of 80 MESH, 120 MESH, and without the use of abrasives

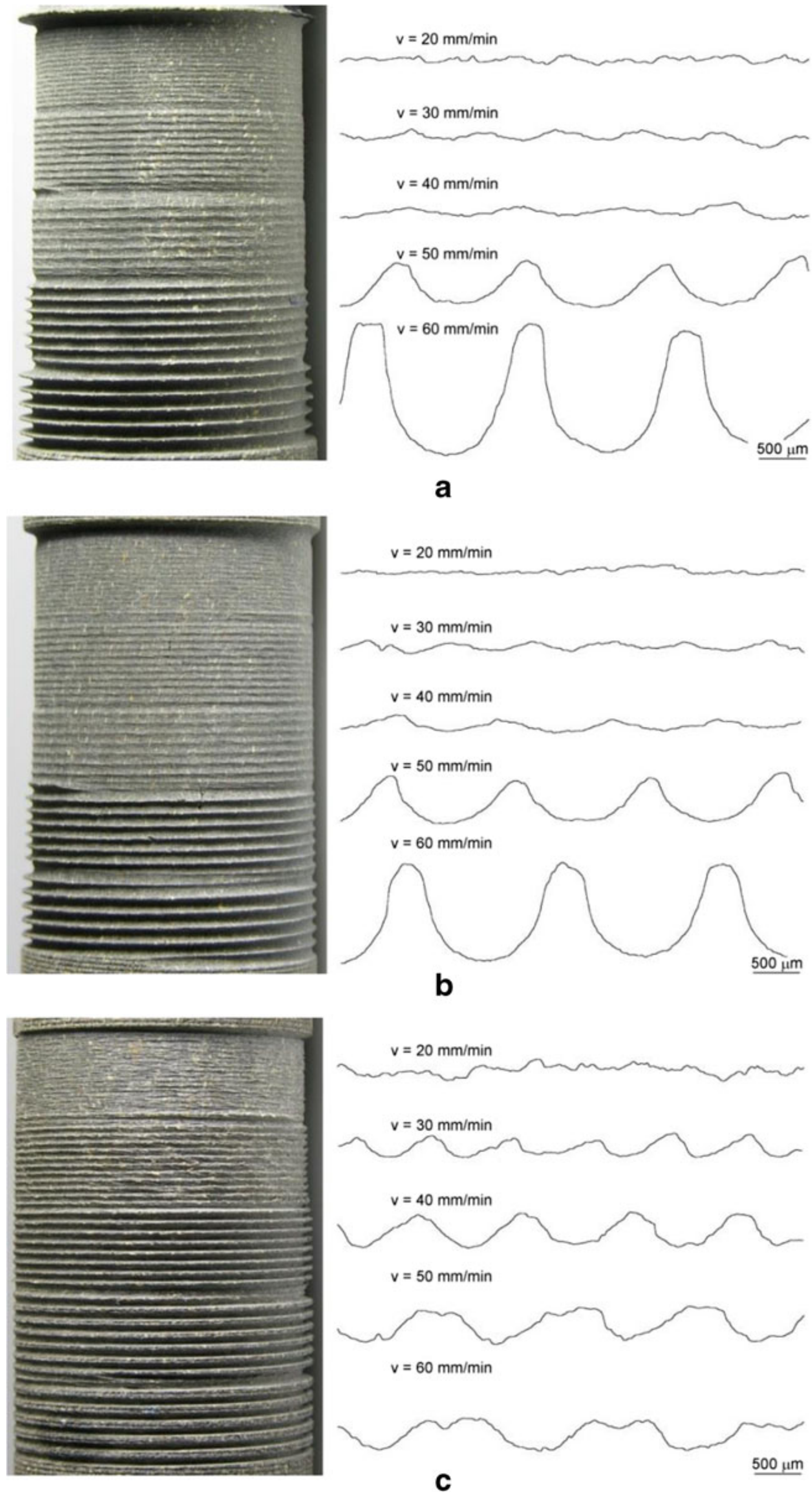

Fig. 7 Typical surface profiles of WPC samples turned at different traverse speeds of AWJ using abrasive of 80 MESH (**a**), abrasive of 120 MESH (**b**), and using WJ without abrasive (**c**) (the profiles were constructed using the OLYMPUS Lext OLS 3100 laser confocal microscope)

were measured on the created microscopic 3D models using the Lext OLS v. 6.0.3 software.

The basic surface roughness profile parameters Ra (arithmetic mean deviation of the profile) and Rz (maximum height of the profile) were determined in accordance with ISO 4287 using a MicroProf FRT optical profilometer.

3 Results and discussion

Surfaces which can be described as irregular threads of different dimensions, different profile shapes, and different surface quality are created when cylindrical WPC samples are turned with the AWJ and WJ technology.

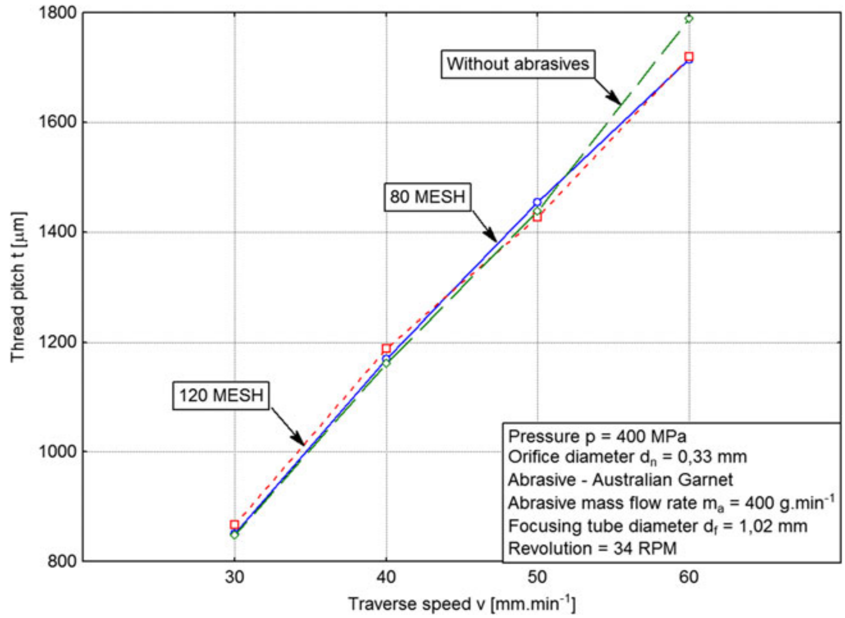

Fig. 8 Dependence of pitch size *t* of the thread created on the surface of machined WPC samples on traverse speed of AWJ/WJ

The basic parameters of the surfaces formed using various configurations of the water jetting system are listed in Table 2.

When using AWJ, the character of the surface changes depending on the increasing traverse speed of the water jet. At the traverse speed of v=20 mm min^{-1}, material removal is the highest. The diameter of the original cylindrical sample is reduced by Δd=11.5 % using the abrasives of 80 MESH and by Δd=7 % using the abrasive of 120 MESH. When the traverse speed increases, the value of Δd decreases, whereby the abrasive of 80 MESH causes higher material removal (higher values of Δd) than the abrasive of 120 MESH at all tested traverse speeds (Fig. 6).

Some evidence of an irregular shallow thread on the surface created by AWJ at the lowest traverse speed can be observed by a side illumination of samples on both the micro- and macroscopic scale. On the microscopic cross section of the surface, however, the profile of the thread cannot be clearly distinguished (Fig. 7a, b). The thread becomes more distinct with the increasing traverse speed of the AWJ, and the pitch and depth of the thread profile increase accordingly (Figs. 8 and 9). The profile shape mostly evokes an irregular equilateral

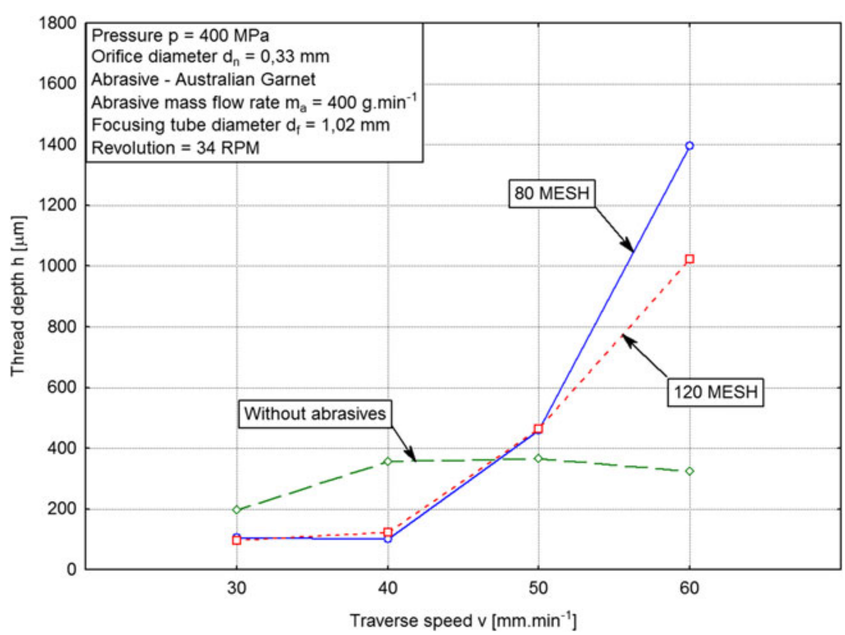

Fig. 9 Dependence of depth *h* of thread created on the surface of machined WPC samples on traverse speed of AWJ/WJ

triangle. The shape of profiles formed at the highest traverse speed of v=60 mm min^{-1} is rather trapezoidal to round.

The surface has a rough appearance (Fig. 10a). Exposed wood particles generally do not exceed the surrounding topography. The surface is sporadically damaged by the partial chipping of wood particles from the polymer matrix. Individual short, thin fibers of wood or plastic can be found on the surface. Here and there, small frayed bunches of short wood fibers occur. In some places, the workpiece surface is disrupted by macroscopic cracks oriented parallel or obliquely to the longitudinal axis of the cylindrical sample. These are the original cracks formed during material production which do not significantly affect the morphology of the machined surface. The original microcracks on the contact between the wood and plastic may predetermine the chipping of wood particles from the matrix. However, this assumption cannot be clearly confirmed.

The values of roughness parameters Ra and Rz remain approximately the same for both abrasives up to a traverse speed of v=40 mm min^{-1}. These values begin to rise significantly with a further increase in traverse speed (Fig. 11).

When using the WJ without abrasives, the character of created surfaces is different. Material removal is smaller than by turning with abrasives. The change in the diameter Δd of the cylindrical sample is most significant at a traverse speed of v=20 mm min^{-1} again. The values of Δd decrease with increasing traverse speed, and they become completely negligible at traverse speeds above v= 40 mm min^{-1} (Fig. 6). Similar to the AWJ turning, a sign of irregular shallow thread is visible on the surface created at the lowest traverse speed, but its profile is not clearly distinguishable in the microscopic cross section (Fig. 7c). With increasing traverse speed of the WJ, the thread becomes more distinct. The pitch of the thread increases with increasing traverse speed (Fig. 8). As far as the depth of the thread is concerned, no correlation with traverse speed is apparent (Fig. 9). The shape of the thread profile evokes irregular isosceles or scalene triangle. At a traverse speed of 50 mm min^{-1} or more, the created profile is shaped like a trapezium, where the wide crest of the thread is formed by the original surface of the unmachined cylindrical sample. Thread flanks are uneven—markedly undulated or roughly grooved. The surface has a felt-like appearance, being mostly formed by frayed bunches of short wood and plastic fibers (Fig. 10b). Macroscopic cracks in the surface of the sample were not observed. The values of roughness parameters Ra and Rz are higher than by turning with abrasives. However, there is no clear evidence of their dependence on traverse speed. Up to a traverse speed of v=40 mm min^{-1}, the roughness values increase; while above this speed, they start to decrease (Fig. 11).

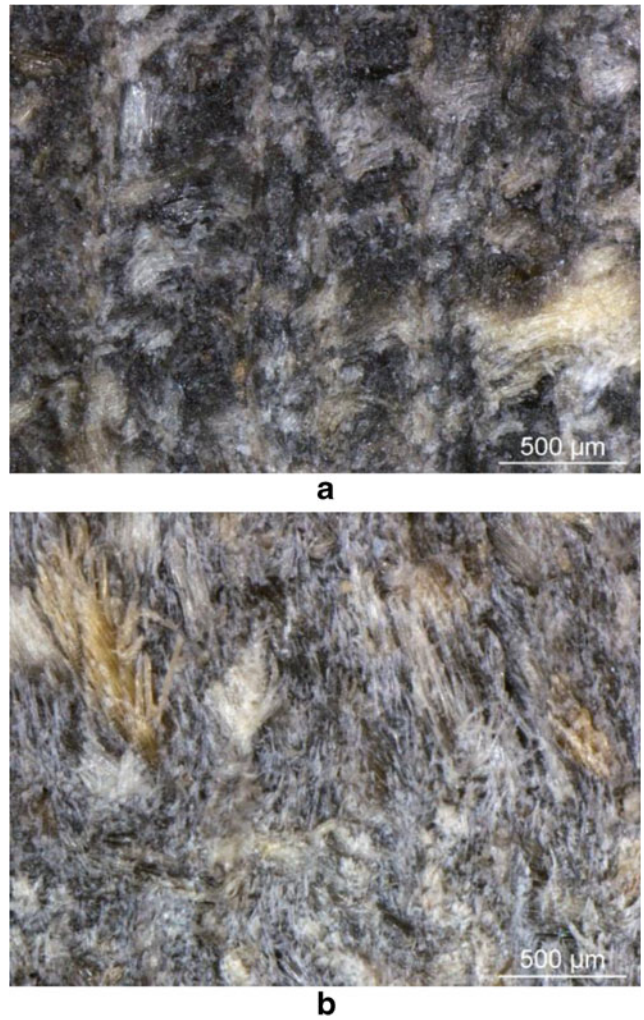

Fig. 10 Rough appearance of surface on the sample turned using AWJ at traverse speed of 20 mm min^{-1} with abrasive of 80 MESH (**a**) and felt-like appearance of surface on the sample turned using WJ at same traverse speed without addition of abrasive (Nikon SMZ25 stereomicroscope)

4 Conclusion

Based on the experiments, it can be concluded that the AWJ turning technology can successfully eliminate the problem of tool wear that occurs in the conventional turning of WPCs—as far as the melting of the plastic matrix of the composite and its subsequent sticking to functional parts of a machining tool are concerned. Created surfaces have the character of irregular threads with different shapes and dimensions of the profile. The surfaces of highest quality are achieved at lower traverse speeds of AWJ (up to v=40 mm min^{-1}), where material removal is the highest and the roughness of created surfaces reaches relatively low values, regardless of the particle size of used abrasives. At higher traverse speeds, material removal and surface quality decrease—the thread becomes more distinct and values of roughness parameters increase. The used experimental device allowed maximum rotational speed of

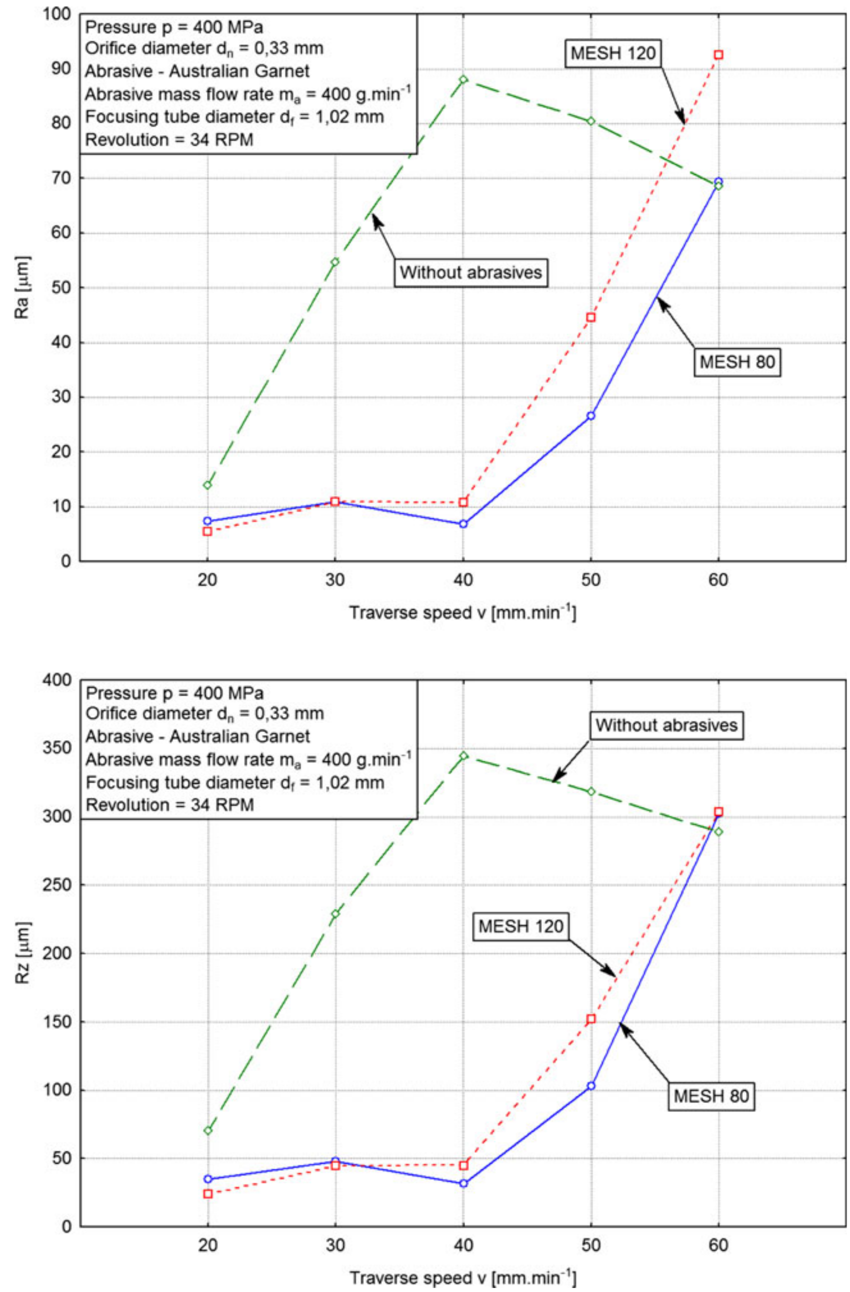

Fig. 11 Dependence of values of surface roughness parameters (Ra, Rz) of machined WPC samples on traverse speed of AWJ/WJ

34 rpm. It can be assumed that machined surfaces will show better surface quality and lower values of surface roughness parameters at higher rotational speeds.

It was also found that abrasive with larger particles causes greater material removal and lower values of Ra parameter at higher traverse speeds of AWJ. However, only two grain sizes of abrasives were used in the experiment; therefore, the effect of particle size on the quality of a machined surface must also be tested with abrasives of other grain sizes. Surface quality is also influenced by the different physical properties of the two main components of the composite material—wood and plastic. The surface is disrupted in some places by the partial chipping of wood particles from the plastic matrix. In addition, small frayed bunches of wood fibers can be found.

The impact of WJ without abrasives on the tested WPC is less effective. Material removal is generally lower, and part of the surface (crests of thread) remains unmachined at traverse speeds above 40 mm min^{-1}. Surfaces are of higher roughness than by abrasive water jets, and the abovementioned dependences of morphological parameters on the WJ traverse speed are applicable only to a limited extent. Most of the surface is formed by frayed bunches of fibers, resulting in its undesirable felt-like appearance.

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