Reduction of Pollution During Composite Machining

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Abstract

Machining of composite materials through classical way, i.e. using conventional tools for turning, drilling, milling, grinding and polishing, produces a lot of very small particles - dust. These particles enter the air, because machining should be performed with a minimum of sprinkling to protect composite material properties and to avoid delamination or swelling. Sometimes, even some burning of epoxide used as binder takes place during machining. Dust produced during machining of the composite material might have negative impact on health and may cause explosion. Skin inflammation or inhalation of the toxic epoxide resin, are some of the examples. Common solution of this problem is suction of particles and fume using machines creating negative pressure. Subsequent removing of these harmful substances from air is quite demanding and expensive. Moreover, using of common suction systems is many times less efficient than declared by producers.This contribution presents a new way of fighting with pollution caused by composite machining. The alternative machining tool for composite machining is abrasive water jet (AWJ). This tool is efficient in all basic machining processes and produces in air only about 1% of dangerous pollution comparing to classical tools. Progress of the AWJ machining system based on robot as a movement device is presented and the first results are commented. The main attention is aimed at machining quality possibilities. However, a part of the contemporary research focused on pollution suppression is also presented in the contribution.

Keywords: *composite, abrasive water jet, cutting, turning, pollution*

Introduction

Abrasive water jet (AWJ) machining is a technique known since eighties of the twenties century when firstly introduced, described and presented by Hashish (1984). It is used namely for cutting, but applications of abrasive water jets for milling (Rabani et al., 2016), turning (Zohourkari et al., 2014), grinding (Liang et al., 2015) or polishing (Che et al., 2008) are tested more and more often, because they bring some benefits regarding classical machining processes. Utilization of abrasive water jet as a machining tool for composite materials is tested more and more often (Ming et al. 2018, Wong et al. 2018, Ruiz-Garcia et al., 2019). One of the most important benefits of AWJ utilization is substantial reduction of dust pollution in air. Dust pollution, often carcinogenic or silicosis causing, arising from classical machining of composites, though reduced by exhausters, is a quite serious problem. The dust removal from the air and its subsequent storage and/or neutralization, disposal of clogged filters and other measures to reduce the risk of operator injury could be substantially reduced applying AWJ. Therefore, some of the most dangerous materials, like glass fabric with epoxy, have been tested to check precision of their machining by AWJ with a view to changing from conventional machining to unconventional one.

Theoretical background

The theoretical base of the new procedures applied during solving the problems with AWJ machining of composites has been published by Hlavac et al. (2012) and Hlavac et al. (2015). They are focused on the two main problems of AWJ machining accuracy – the trailback and taper. The typical simplistic description of jet penetration through material is replacement of the real trajectory by simple curves, namely parabolic shape. The respective equations describing the trailback and the taper are presented in the shapes published in Hlaváč et al. (2012) and Hlaváč et al. (2015) respectively:

$$\sigma = \frac{2}{5} H \,\mathrm{tg}\left[\theta_{lim}\left(\frac{v_P}{v_{Plim}}\right)^{\frac{3}{2}}\right] \qquad (1)$$

σ – the trailback, H – material thickness, θ_{lim} – the limit declination angle, v_P – the actual traverse speed, v_{Plim} – the limit traverse speed for material thickness H;

$$\varphi = \varphi_{\lim}\left(\frac{h}{h_{\lim}}\right)^{\frac{2}{5}} + q \qquad (2)$$

φ – the inclination angle, φ_{lim} – the limit inclination angle, h – actual depth of AWJ penetration into material, h_{lim} – the limit depth of penetration of AWJ into material for selected traverse speed (namely material thickness H), q – a constant characterizing ductility and brittleness of material.

The resulting theoretical equation combining influence of trailback and taper has been presented in Hlaváč et al. (2018) enables calculation of the bottom diameter in the curved parts of trajectories:

$$D_{bc} = 2\left[\sqrt{\left(\frac{2}{5}H\tan\theta\right)^2 + R^2} + \frac{2}{5}H\tan\varphi\right] + d_a \qquad (3)$$

D_{bc} – the bottom diameter of the circular part of cutting trajectory, variables H, θ and φ are identical with to those used in Eq. (1) and (2), R – set radius of cutting trajectory, d_a – the diameter of an abrasive focussing tube.

Experimental results

Experiments were performed with two abrasive water jets having different origin pressure and flow rate. The deforma-

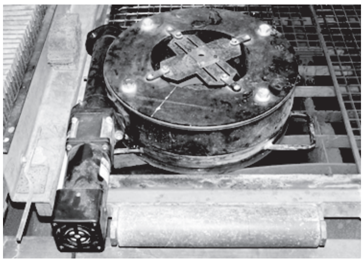

Fig. 1. Device for rotating with sample under the AWJ cutting head
Rys. 1. Urządzenie do obróbki z głowicą tnącą AWJ

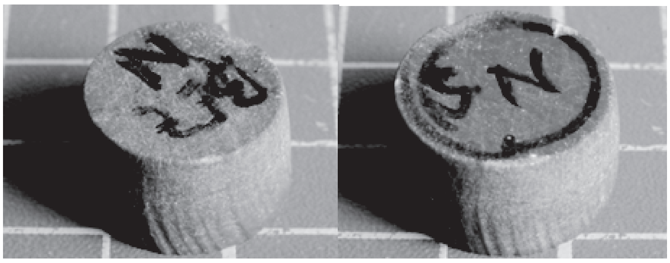

Fig. 2. Column cut without AWJ head tilting (left) and with tilting (right)
Rys. 2. Cięcie kolumny bez przechylania głowicy AWJ (po lewej) i przechyleniu (po prawej)

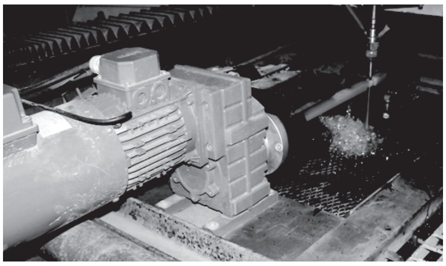

Fig. 3. Device with horizontal axis for sample turning
Rys. 3. Urządzenie z osią poziomą do obracania próbki

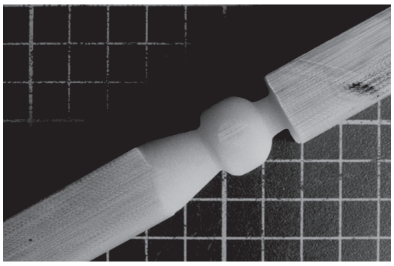

Fig. 4. Sample documenting possibility of composite with glass fibre turning by AWJ
Rys. 4. Przykładowa dokumentacja możliwości toczenia kompozytu z włóknem szklanym przez AWJ

tion of column samples and reduction of difference between top and bottom diameter has been tested using low pressure but high flow rate pump. A special device for sample rotation under the tilted cutting head has been used for this test (Fig. 1). The experimental conditions are summarized in Table 1. Results of column cutting with cutting head without and with tilting are presented in Fig. 2.

Figure 2 shows the typical striations on the samples' walls. It is evident that non-tilted jet makes more noticeable striations and the sample is rather truncated cone shaped then "column" shaped. By contrast to it the tilted jet produces rather barrel shaped samples with striations better visible even in the bottom part. It can be also mentioned that diameter of the top base of the sample produced by a non-tilted jet is smaller than that of the tilted jet and some slight increase of the diameter of the bottom base can be also noticeable.

Several columns were cut: one half of them with jet axis perpendicular to the surface of the plan-parallel sheet of composite plate, the second half with tilting of the cutting head compensating deformation caused by trailback. Both sets of samples were measured on the top and bottom to compare their diameters with each other. The respective average top and bottom diameters for a non tilted jet are 16.46 mm and 18.58 mm. Values for tilted jet are 18.26 mm and 19.28 mm. The set-up diameter was 20 mm for all experimental tests. The increase of top and bottom diameters for tilted regarding the non-tilted

Tab. 1. Parameters used in experiments
Tab. 1. Parametry stosowane w eksperymentach

	Constant cutting parameters on two testing workplaces	
Factor	Low pressure workplace	High pressure workplace
Pressure in pump	23 MPa	380 MPa
Water jet diameter	1.2 mm	0.254 mm
Focusing tube diameter	3 mm	1.02 mm
Focusing tube length	152 mm	76 mm
Abrasive mass flow rate	300 g/min	250 g/min
Mean abrasive grain size[a]	0.375 mm (50 mesh)[b]	0.25 mm (80 mesh)[b]
Abrasive type	Australian garnet (almandine)	Australian garnet (almandine)
Traverse speed	100 mm/min	50 mm/min
Rotational axis	vertical	Horizontal
Revolutions	1.6 min^{-1}	600 min^{-1}
Stand-off distance	2 mm	2 – 5 mm

[a] Mean grain size is determined on the commercial particles size analyzer.
[b] The "mesh" specification is commercial indication provided by suppliers.

jets correlated with findings presented by Hlaváč et al. (2018).

The second experiment was performed with high-pressure and low flow rate pump and device used for turning of material (see Fig. 3). The experimental conditions are also summarized in Table 1. Sample result of material turning is presented in Fig. 4. The testing shape has been prepared so that it includes all basic possible movements applied during material turning. Movement of the tool towards rotational axis, along it, combined movement towards and/or from the axis necessary for turning spherical or conical shapes. The testing shape has been prepared from prism to test also deformation caused by deflection of the jet on the edges. The testing trajectory has been set so, that the spherical part exceeds the dimensions of prism to study the influence of the partial material removing on the resulting quality of surface.

All results have proved that the quality is very good and difference in shape dimensions is negligible.

Discussion

Preliminary results aimed at column sample distortion proved that tilting of the cutting head is a proper way for reduction of trailback and the taper. The difference between diameters of column bases on the inlet and the outlet surface has been reduced by 208% eliminating the trailback. Elimination of the taper causes additional 50% of reduction. The resulting average diameters after tilting in both directions (compensation of trailback and taper) are 18.46 mm on the top and 18.56 mm on the bottom, i.e. the diameter difference is only 0.1 which means 0.54% of real top diameter (0.50% for set-up diameter). Difference between set-up and real diameter is caused by leaving out the jet radius being about 1.5 mm. For real object diameter 20 mm the set-up diameter should be approximately 21.5 mm. The experiments have also proved that even low pressure AWJ can efficiently cut composite materials. Therefore, cutting costs can be reduced, because pump pressure can be lowered and it means much lower capital costs and also operational costs (pump maintenance). The benefit of the AWJ composite cutting is negligible production of air pollution, namely composite material dust and fumes.

Very good results were obtained also with turning. The shape distortion is below 0.5% for non-optimized set of parameters. The surface roughness Ra is below 3.2 µm and it can be further improved by tuning respective parameters. The most important and closely connected parameters are the traverse speed (i.e. the velocity of jet movement along the rotational axis simultaneously with movement to this axis and from it) and the angular velocity (given by revolutions). Optimization of these two parameters is the main task to be solved on the way to commercial application of AWJ for turning. Nevertheless, the most important benefit of AWJ machining tool is elimination of the dangerous dust, namely glass particles, and toxic fumes from burning epoxy binder produced by conventional tools. Thus the application of AWJ machining can substantially reduce capital and operational costs necessary for exhausters and filters.

Provided that robot is used for manipulation with cutting head the possibilities of 3D machining will be increased substantially. Unfortunately, programming of cutting of the 3D objects by abrasive water jet is quite difficult, because it is necessary to take into account that residual energy of the AWJ is still efficient in material damage. Therefore, the programming process needs to calculate with anticipated directions of residual jet deflection. The merit of 3D AWJ machining is namely reduction of pollution, but some operations, when well prepared, can be less time consuming and more precise. However, the proper programming is not possible without deep and exact knowledge of deflected jet behaviour.

To obtain all necessary information the further research of AWJ, both theoretical and experimental, is inevitable.

Conclusions

The preliminary experiments aimed at AWJ machining of composite materials proved that such machining is possible with a relatively high precision and inconsiderable amount of dust pollution in air. The accuracy of the machining is limited by precision of used machines and respective operation software. Nevertheless, the first tests show that product distortion and/or difference from entered contour can be substantialy lower than 1 %. All these results indicate that correct optimization process can improve production of final products by AWJ to be competitive with classical machining tools producing, simultaneously, much lower amount of health hazardous and risky by-products like dust and fumes. Therefore, further research and development aimed at improvement of AWJ machining for composite materials is strongly recommended.

Acknowledgements

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Redukcja zanieczyszczenia podczas obróbki kompozytów

Obróbka materiałów kompozytowych klasycznym sposobem, tj. przy użyciu konwencjonalnych narzędzi do toczenia, wiercenia, frezowania, szlifowania i polerowania, powoduje powstawanie bardzo małych cząstek – pyłu. Cząsteczki te dostają się do powietrza, ponieważ obróbkę należy wykonywać przy minimalnym zraszaniu, aby chronić właściwości materiału kompozytowego i uniknąć rozwarstwienia lub pęcznienia. Stosowana jest również obróbka epoksydu stosowanego jako spoiwo. Pył powstający podczas obróbki materiału kompozytowego może mieć negatywny wpływ na zdrowie i spowodować wybuch. Zapalenie skóry lub wdychanie toksycznej żywicy epoksydowej to tylko niektóre z przykładów. Powszechnym rozwiązaniem tego problemu jest odsysanie cząstek i oparów za pomocą maszyn wytwarzających podciśnienie. Usunięcie tych szkodliwych substancji z powietrza jest dość wymagające i kosztowne. Co więcej, stosowanie popularnych systemów ssących jest wielokrotnie mniej wydajne niż deklarowane przez producentów. W artykule przedstawiono nowy sposób walki z zanieczyszczeniami powodowanymi przez obróbkę kompozytową. Alternatywnym sposobem do obróbki kompozytów jest ścieranie strumieniem wody (AWJ). Ten sposób jest wydajny we wszystkich podstawowych procesach obróbki i powoduje powstawanie w powietrzu tylko około 1% niebezpiecznych zanieczyszczeń w porównaniu do klasycznych narzędzi. Przedstawiono postępy systemu obróbki AWJ opartego na robocie jako urządzeniu ruchowym i komentowano pierwsze wyniki. Główna uwaga skupiona jest na możliwościach obróbki strumieniem wody. Przedstawiono również inne współczesne badania koncentrujące się na zmniejszaniu tłumieniu zanieczyszczeń z procesu obróbki kompozytów.

Słowa kluczowe: *kompozyt, cięcie strumieniem wody, cięcie, toczenie, zanieczyszczenie*