

## Effect of Machining Settings and Tool Geometry on Surface Quality after Machining of Al/CFRP Sandwich Structures

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### ABSTRACT

The paper describes the effect of cutting parameters and tool geometry on the surface quality after machining of an Al/CFRP (aluminium alloy/ Carbon Fibre Reinforced Plastics) sandwich structure. A two-layer sandwich structure made of an EN AW 2024 aluminium alloy and Carbon Fibre Reinforced Plastics (CFRP) was examined. The experiment used the process of peripheral milling. The experiment investigated the effects of cutting speed ( $v_c$ ), feed per blade ( $f_z$ ) and helix angle ( $\lambda_s$ ) on surface quality as defined by differences in the height of materials. It was also analysed how the machining conditions described above affected the values of cutting force components. In the experimental stage of the study, uncoated, double-bit carbide mill cutters with working diameter  $D_c = 12$  mm and a variable helix angle ( $\lambda_s = 20^\circ$ ,  $\lambda_s = 35^\circ$ ,  $\lambda_s = 45^\circ$ ) were used. The results have shown that cutting parameters and tool geometry do affect the surface quality and cutting forces after milling of the sandwich structure. The lowest material height difference was achieved when machining with the helix angle  $\lambda_s = 45^\circ$ , cutting speed  $v_c = 300$  m/min and feed per blade  $f_z = 0.08$  mm/blade. The highest material height difference occurred after machining under the following conditions:  $v_c = 300$  m/min,  $f_z = 0.08$  mm/min,  $\lambda_s = 20^\circ$ . The minimum cutting force value was obtained for cutting parameters:  $v_c = 80$  m/min,  $f_z = 0.08$  mm/blade during milling with the helix angle  $\lambda_s = 45^\circ$ . The maximum cutting force was recorded during machining with the helix angle  $\lambda_s = 20^\circ$ , cutting speed  $v_c = 400$  m/min and feed per blade  $f_z = 0.08$  mm/blade.

**Keywords:** sandwich structure, milling, material height difference, cutting parameters, helix angle.

### INTRODUCTION

Continued efforts to use lighter designs and faster means of transport have prompted a quest for structures that would feature appropriate tensile qualities while enabling to reduce their weight. Sandwich composites are among such materials [1, 2]. Sandwich structures are composed of two basic elements: a thinner outer layer (skin) made of a more rigid material and a thicker and lighter inner layer (core) made of some other material. The properties of sandwich structures are dependent on the qualities of sandwich-forming materials and those of bonding elements. Advantages of sandwich composites include, above all, high strength and structural stiffness despite relatively low weight. Also the possibility to reduce or minimise the number

of stiffeners in large-sized building structures is considered to be a real asset of sandwich composites [3]. Drawbacks of sandwich structures primarily involve anisotropy and inhomogeneity. A disadvantage is also little manufacturing experience as compared to other engineering materials that are known. Compared to the machining of metal workpieces, subtractive manufacturing of hybrid sandwich composites is difficult due to their structural inhomogeneity and anisotropy. Sandwich structures are usually fabricated in their near-final shapes. Two of the most commonly used machining techniques for this type of structures are milling and drilling [4–6]. Machining of aluminium alloy/ Carbon Fibre Reinforced Plastics (Al/CFRP) sandwich structures is troublesome as the properties of each layer can vary greatly [7]. During machining of this type of material, the tool

encounters different cutting resistances, which results in flaws on the work surface. One of the reasons behind this phenomenon is the variability of cutting force components – higher values of cutting force components have a deteriorating effect on the quality of the work surface [8]. While aluminium alloys are usually easy for machining, CFRP is classified as being difficult to work with [9]. The anisotropy of composites has a positive effect on the tensile properties of materials, yet on the other hand, it makes subtractive machining difficult due to intensive wear of cutting tools, formation of various damage patterns following machining and problems in maintaining the dimensional and geometrical accuracy and the consistent quality of the work surface [10]. Increased cutting force caused by higher tool wear also leads to delamination and burr formation.

Machining of the hybrid structures using traditional cutting tools is difficult due to the poor machinability of the non-metallic materials [11]. Optimisation of cutting parameters is regarded to be the most effective way to improve the quality of the work surface. The choice of technological parameters depends on what materials a sandwich structure is made from. When selecting a tool, it is important to take into account that multiple layers that have different, sometimes extreme, properties will be machined at the same time. Ideally, the cutting parameters should be adjusted to the material the currently machined layer is made from. Unfortunately, this is not always possible, therefore the tool and its process specifications are usually matched to one of the materials the sandwich composite is made from. Such a solution produces differences in workmanship across the surfaces of individual layers. Although hybrid sandwich constructions are often used in many industries, the cutting conditions for these materials are not yet sufficiently defined. Most of the work focuses on the study of surface roughness of polymer composites [12], the drilling of sandwich materials [13], properties [2] or the review of current trends in the use of such materials [14, 15]. Only few works deal with the shape defects after milling of hybrid sandwich structures and the reasons for their formation. Denkena et al. [8, 16] distinguishes three types of shape deviations that can be used to assess the surface quality of sandwich constructions: material height deviation, transition deviation and surface roughness deviation. However, they did not investigate how the cutting conditions affect the values of

the described deviations. The focus was on the attempt to predict and explain shape deviations on the surface of sandwich composites after face milling. Hosokawa et al. [17] submitted the results of milling CFRP composite using tools with variable cutting edge diamond coating. They showed that the occurrence of the shape deviations on the surface of the workpiece depends on the cutting forces and the wear of the tool on the orientation of the fiber. In [18] it was found that the surface quality of CFRP composites after machining is influenced by the material and geometry of tool, but not by the radial depth of cut. Liu et al. [19] drew a similar conclusion. They also found that the increase in cutting speed led to a decrease in the surface roughness of the CFRP. Ghidossi et al. [20] have found that the burr formed during CFRP machining depends on the wear of the cutting tool. Chibane et al. [21] have demonstrated that an increase in feed per blade during machining of polymer matrix composites increases burr length, whereas an increase in cutting speed decreases it.

All damage occurring during machining of composite materials makes the process more time-consuming as additional treatments have to be done. In [22] it has been shown that the cutting speed during machining of CFRP affects how chips are formed. It has also been demonstrated that increasing this parameter leads to a decrease in cutting forces and an extension of tool life. One way of obtaining high surface quality after machining is to reduce the cutting forces. This minimises the incidence of imperfections on the surface of the material, yet on the other hand brings about a decrease in the efficiency of the process. Higher cutting forces result in a poorer quality of the work surface [8]. So far, much attention has been given to the development of a cutting force model that could improve machining efficiency and reduce manufacturing costs by optimising machining conditions. Qi et al. [23] have elaborated a theoretical model for predicting cutting forces during CFRP machining. They have determined the threshold value of critical forces above which composite materials become destroyed (due to matrix cracking). The study [24] investigated cutting force components and surface roughness after CFRP milling. It was noticed that feed rate, cutting depth and chip size are factors that affect cutting force the most. On the other hand, it has been shown in [25] that the main factors affecting the cutting forces during

CFRP machining are carbon fibre orientation, cutting depth and helix angle. In [26], the focus was put on the possibility of detecting defects in composites by non-destructive testing through prediction of cutting force components.

Varying properties of sandwich composites decrease the efficiency of the process, causing problems in forming appropriate chip shapes and sizes and removing the chips. What is crucial is the thoughtful selection of the tool, its geometry and the technological parameters of the process. Considering the fact that most of the research focuses on the machining of FRP (Fiber Reinforced Plastics), it seems reasonable to carry out experimental research into the selection of tool geometry and technological parameters that would enable effective and efficient machining of hybrid sandwich structures.

## METHODOLOGY AND MATERIALS

The study explored the effects of technological parameters and tool geometry on the surface quality of sandwich structures after milling. Fig. 1 provides an overview of the experiment setup.

A two-layer sandwich structure was tested in the study. The sandwich structure was made from two materials: EN AW 2024 aluminium alloy [27] in the T3 state [28] and CFRP composite. The materials were selected due to their growing use in industry, especially in the aerospace sector. The aluminium alloy used is a copper-based material featuring low density and higher yield strength. As this alloy has low resistance to oxidation, it is not suited to solutions where corrosion could be a risk. The material is machinable, but not suitable for either anodising or welding. Among other applications, it is used in the aerospace industry for aircraft fuselages, wing tensioners, aircraft skin panels, bulkheads, guard rails and steering mechanisms. In addition, the material is used in the automotive, railway and construction industries. The second material used to create the sandwich structure was Carbon Fibre Reinforced Plastics. Thermosetting epoxy resin CP006 from C-M-P (Germany, Heinsberg) with a minimum viscosity index of 1050 mPas was used as the composite matrix. A fabric of the high-strength carbon fibres was used for reinforcement. Table 1 shows the specifications of the pre-preg used. The composite was manufactured under vacuum-pressure

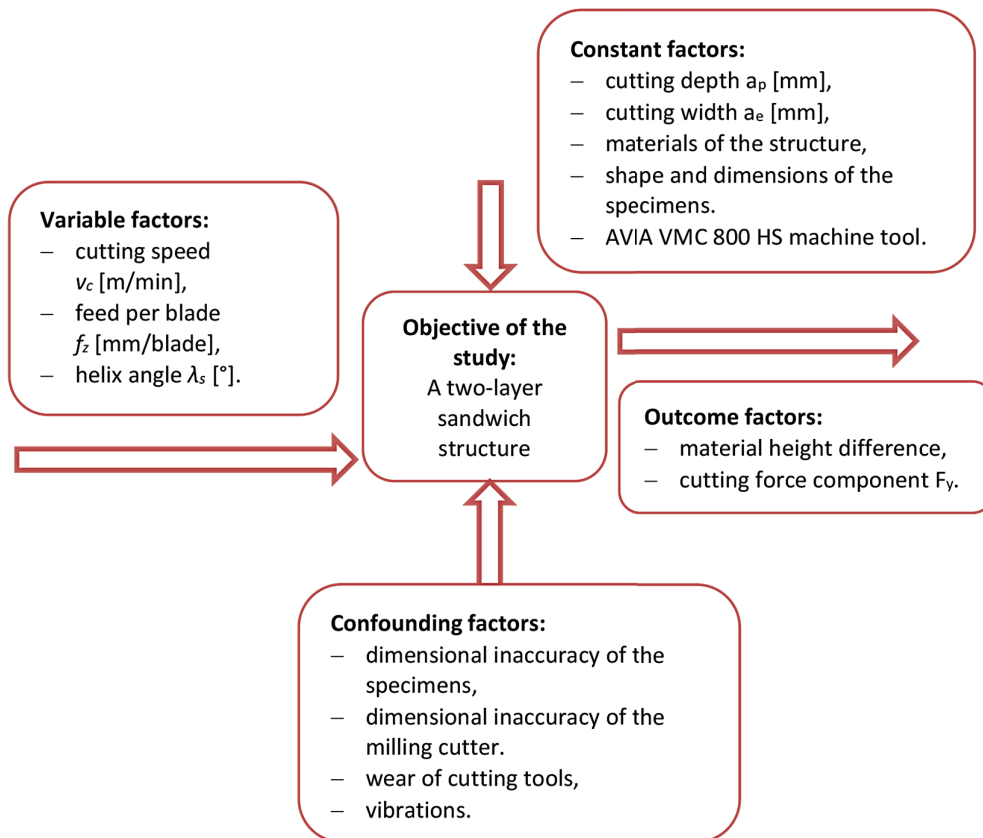


Fig. 1. Experimental design

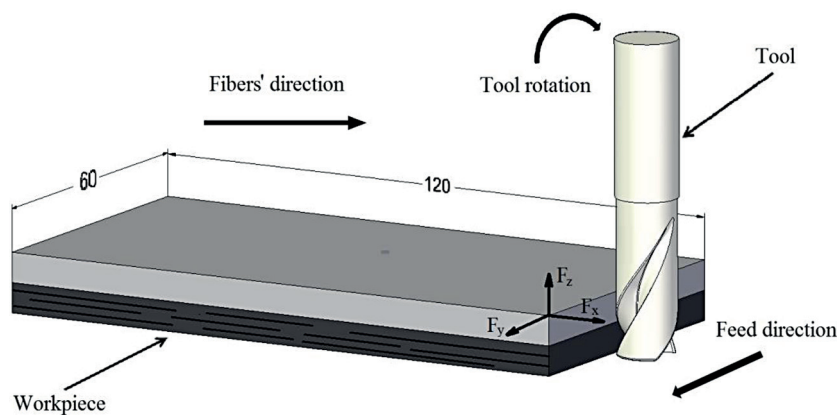
**Table 1.** Reinforcement features of the composite material [29]

Fibre weight [g/m <sup>2</sup> ]	20
Resin content [%]	90
Pre-preg weight [g/m <sup>2</sup> ]	245
Width [mm]	1
Twill weave	2/2

impregnation. The volume share of the carbon fibres in the cured composite was approximately 60%. The materials were bonded using Scotch-Weld EC-9323 B/A structural epoxy adhesive from 3M. Specimens measuring 120 × 60 × 6 mm were used for testing (Fig. 2). Because of the small value of the adhesive layer (0.1 mm), the thickness of this layer was not taken into account when determining the total thickness of the structure. The study used specimens with geometries representing a simplification of real structures used in industry. Sandwich structures used in industry usually consist of an thin layer of outer facing and a thicker core made from another material. Such a solution helps obtain a high stiffness of the structure without overloading it. In the study, a constant layer thickness of 6 mm was adopted due to research constraints.

A peripheral down milling was chosen for machining the test specimen. An AVIA VMC 800 HS vertical machining centre was used for this purpose. The shorter edge (60 mm) of each specimen was subjected to machining. The workpiece was clamped in a machine vice. The machining of hybrid sandwich structures should combine the properties of machining metal and composite materials. It is very important to select optimal cutting parameters and tool geometry for effective cutting of sandwich materials. The study focused

on determining the optimal cutting parameters and cutter geometry to achieve the lowest possible material height difference. Currently, there is a trend to dedicate the tool to a particular material or group of materials. This is a disadvantage when processing sandwich structures. Therefore, an attempt was made to evaluate the surface quality of the Al/CFRP structure after the use of the universal tools. An uncoated double-bit shank milling cutter manufactured by the Hoffman Group with working diameter  $D_c = 12$  mm, rake angle  $\gamma = 16^\circ$ , corner radius of  $45^\circ$  and corner chamfer width of 0.12 mm was used for the milling. The tool was made of fine-grained sintered carbide K10F (90% WC, 10% Co). The tool was designed for machining cast aluminium alloys, aluminium alloys used in plastic moulding and polymer matrix composites [30]. Three comparable milling cutters with variable helix angles  $\lambda_s$  were used for the machining. Helix angle affected periodic changes in the cross-section of the machined layer [31]. Furthermore, higher helix angle improves evacuate chips from the cutting zone, reduce cutting forces and improve the surface quality of workpieces. Higher helix angles of milling cutters are of particular importance when machining polymer composites, which tend to clog chip grooves. The angle also determines the shape of chips. For aluminium alloys, the recommended range of helix angles is  $25^\circ$ – $45^\circ$  and for polymer composites  $5^\circ$ – $40^\circ$  [32]. Keeping in mind this range, experiments were conducted that used three milling cutters featuring helix angles  $\lambda_s = 20^\circ$ ,  $\lambda_s = 35^\circ$  and  $\lambda_s = 45^\circ$ . The geometries of the tools were freely accessible and were selected based on the manufacturer’s tool catalog. In the experimental part, the effects of cutting speed  $v_c$  [m/min] and feed per blade  $f_z$  [mm/blade] upon the surface quality after



**Fig. 2.** Test specimen

milling of the sandwich structure were also investigated. For each of the parameters under study, five values were adopted (Table 2). When selecting the parameter values, the manufacturer’s recommended values were taken into account, i. e. the maximum and minimum values of the parameters for cutting aluminium alloys, the maximum and minimum values of the parameters for cutting polymer composites and the intermediate value for both materials. The machining was carried out with a constant axial depth of cut  $a_p = 12$  mm and a constant radial depth of cut  $a_e = 4$  mm. The value of the  $a_p$  parameter has been selected to allow simultaneous processing of the structure layers. The value of the  $a_e$  parameter was selected based on the recommendation of the manufacturer of the cutting tools used.

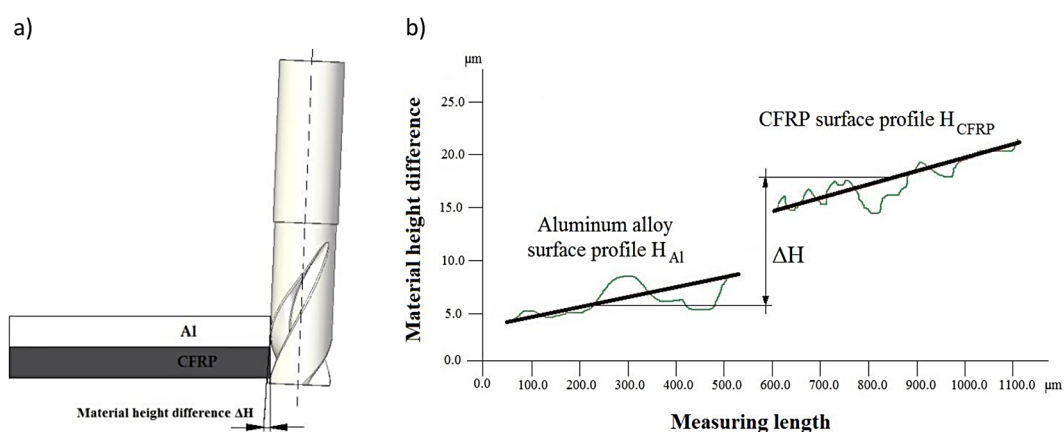
A material height difference was used to evaluate the surface quality after milling of the sandwich structure. It is a result of the cutter shaping the workpiece by its feed motion. As each layer of the structure has different properties, the tool meets different cutting resistances during machining. In Fig. 3a it can be observed the different elastic deformation of the materials forming the considering sandwich structure, which are the cause of the material height difference. During milling of the facings, the tool is pushed away from the workpiece. At the same time, the tool machines the core, which has a lower density compared to the

facings, causing a sudden change in cutting resistance and pulling the tool deeper into the workpiece (Fig. 3a). As a consequence, defects develop on the surface of the structure, adversely affecting its further use. The criterion for evaluating the most favourable milling conditions was to keep material height differences as low as possible. The criterion was adopted because sandwich structures are widely used in aviation as structural elements and aircraft equipment. One of the requirements in the aerospace industry is high quality components associated with tight tolerance ranges.

Measurements of the material height differences were made using a Keyence VHX-500 digital microscope (500x magnification). The measurements were performed on separate measuring sections positioned in the middle of each test specimen. Three measurement points were singled out within the measuring section. The distance between these points was 125µm. The resulting material height difference in each specimen was the mean of the readings taken at the three measurement points. Each material height difference value reported was the mean of the three measurements. The material height difference was defined as the difference between the mean surface profiles of sandwich structure components (Fig. 3b). At each measurement point, the surface profile of the sandwich structure was mapped (Fig. 3b – lines in green colour). Subsequently, the average surface profiles

**Table 2.** Experiment setup

Factor	Level				
$v_c$ [mm/min]	80	200	300	400	500
$f_z$ [mm/blade]	0.04	0.06	0.08	0.10	0.12
$\lambda_s$ [°]	20°		35°		45°



**Fig. 3.** Material height difference: a) formation, b) measurements

of the aluminium alloy ( $H_{Al}$ ) and the CFRP ( $H_{CFRP}$ ) were calculated (Fig. 3b – lines in black colour) and the distance between them was measured. The material height difference ( $\Delta H$ ) at any given measurement point was the difference between the mean surface profile of the aluminium alloy and of the CFRP after milling. One of the milling strategies for sandwich structures is to diminish cutting force components. So the incidence of typical damage of this type of structures (delamination, fibre pull-out, matrix cracking, etc.) is reduced, also causing lower machining efficiency, e.g. due to lower feed rates. In this study, an attempt was made to compare the maximum values of the cutting force components recorded during machining of the sandwich structure. The cutting force components were captured using a Kistler 9257B dynamometer connected to a 5017B amplifier. The axes of the dynamometer overlapped with the axes of the tool and the CNC controlled axes. The cutting force components were measured using specialised software and a data acquisition card. The sampling frequency was 5kHz. As maximum values were observed for the feed ( $F_y$ ) component, only the results for this component were analysed. The adopted values represented the arithmetic mean of the readings from three specimens, and the reading within each specimen was the arithmetic mean of 30 highest dynamometer indications.

## RESULTS AND DISCUSSION

Fig. 4 shows areas with variations in the average material height difference obtained, depending on the process parameters and tool geometry applied. The highest material height difference (32.83  $\mu\text{m}$ ) after machining with the helix angle  $\lambda_s = 20^\circ$  was obtained with  $v_c = 300$  m/min and  $f_z = 0.08$  mm/blade, and the lowest one (4.13  $\mu\text{m}$ ) after machining with cutting speed  $v_c = 300$  m/min and feed per blade  $f_z = 0.06$  mm/blade (Fig. 4a).

For a milling cutter with the angle  $\lambda_s = 35^\circ$ , the highest material height difference (22.90  $\mu\text{m}$ ) was observed for  $v_c = 300$  m/min and  $f_z = 0.12$  mm/blade, while the lowest one (3.27  $\mu\text{m}$ ) was recorded after machining with cutting speed  $v_c = 300$  m/min and feed per blade  $f_z = 0.06$  mm/blade (Fig. 4b). Milling with the helix angle  $\lambda_s = 45^\circ$  resulted in obtaining the highest material height difference (18.87  $\mu\text{m}$ ) for  $v_c = 300$  m/min and  $f_z = 0.12$  mm/blade and the lowest one (1.60  $\mu\text{m}$ ) for  $v_c = 300$  m/min and  $f_z = 0.08$  mm/blade (Fig. 4c). Fig. 5 and Fig. 6 show the effects of the cutting parameters and tool geometry on the material height difference obtained after machining. Analysis of the effects of cutting speed on material height difference (Fig. 5) showed that after machining with the angles  $\lambda_s = 20^\circ$  and  $\lambda_s = 35^\circ$ , the similar material height differences were obtained depending

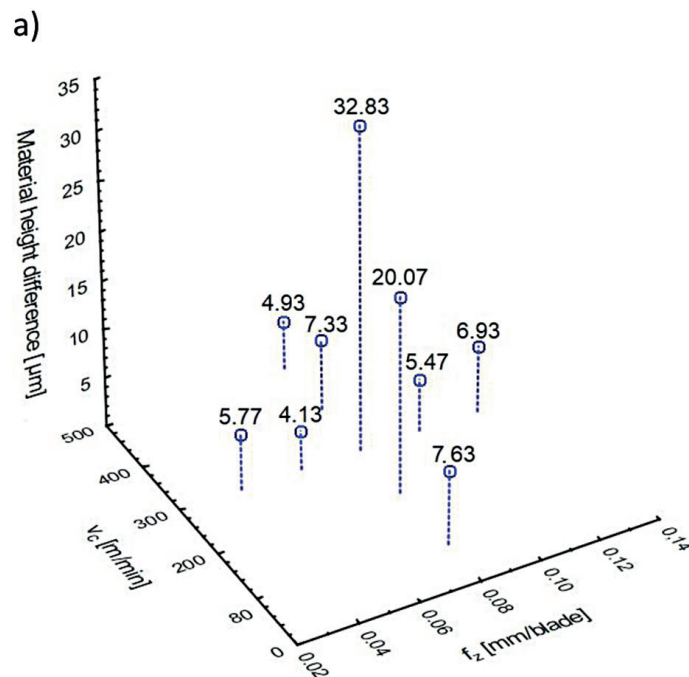
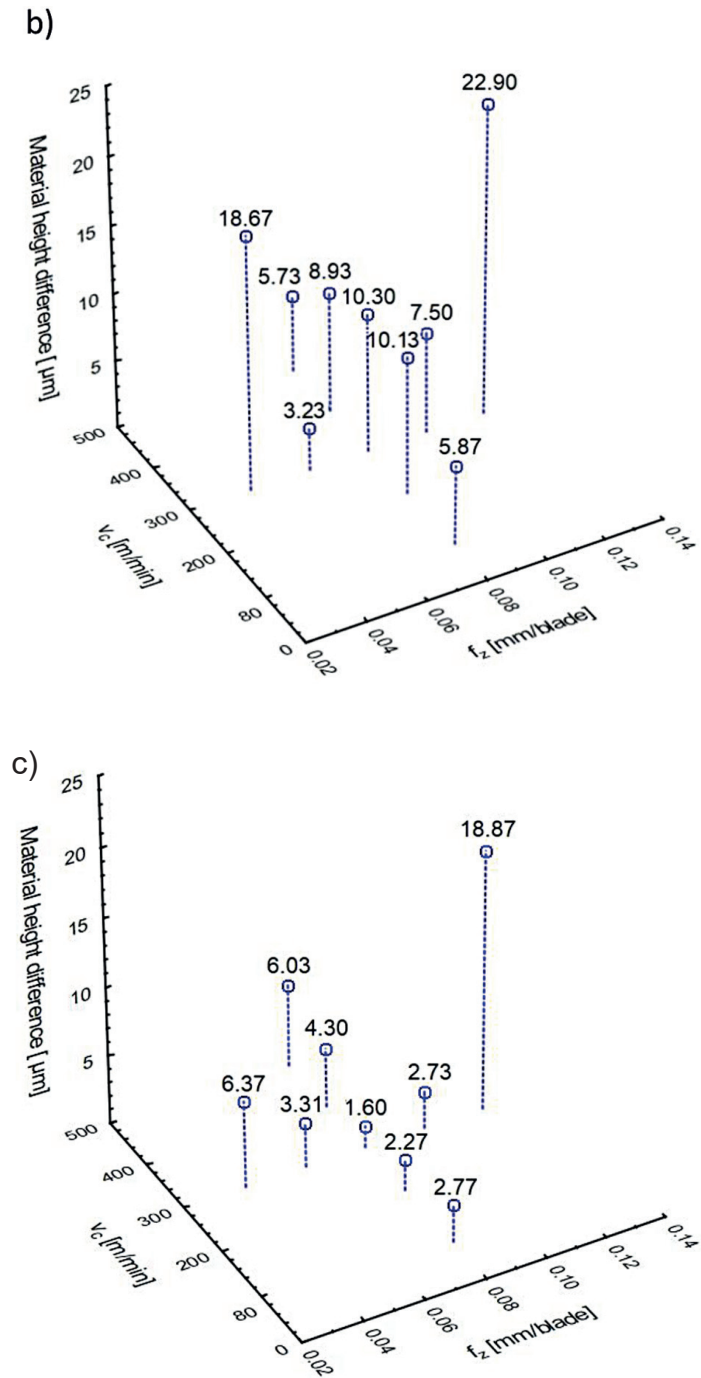


Fig. 4. Area with variations in material height difference after milling with helix angles: a)  $\lambda_s = 20^\circ$ , b)  $\lambda_s = 35^\circ$ , c)  $\lambda_s = 45^\circ$



**Fig. 4b & 4c. Cont.** Area with variations in material height difference after milling with helix angles: a)  $\lambda_s = 20^\circ$ , b)  $\lambda_s = 35^\circ$ , c)  $\lambda_s = 45^\circ$

on the cutting speed applied. With  $v_c$  growing, an increase in material height difference could be seen within range  $v_c = 80 - 300$  m/min for these tools. For higher values ( $v_c = 400$  m/min and  $v_c = 500$  m/min), the material height differences decreased with increasing cutting speed. This may be indicative of High-Speed Machining (HSM) [33]. The results obtained during milling with the helix angle  $\lambda_s = 45^\circ$  showed an inverse trend – for the first

three cutting speeds, the material height differences decreased while  $v_c$  was growing and then increased for  $v_c = 400$  m/min and  $v_c = 500$  m/min.

For the effect of  $f_z$  parameter on the material height differences (Fig. 6), it was difficult to determine a conclusive trend. For the milling cutters with the helix angles  $\lambda_s = 20^\circ$  and  $\lambda_s = 35^\circ$ , the material height difference alternates between increasing and decreasing with changes in feed rates. The impact of feed per blade on material

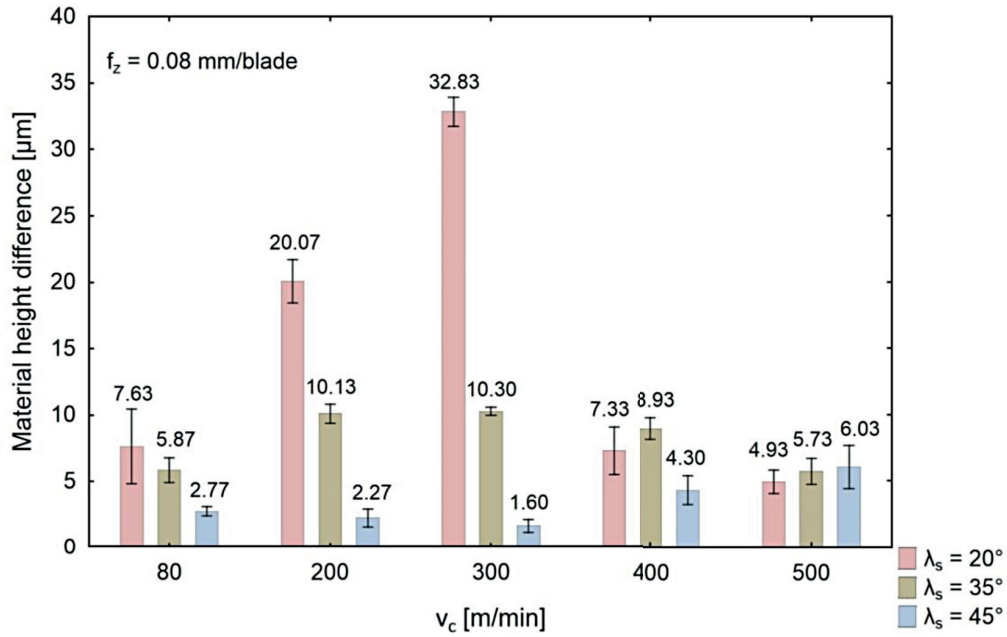


Fig. 5. Effects of cutting speed and helix angle on material height differences

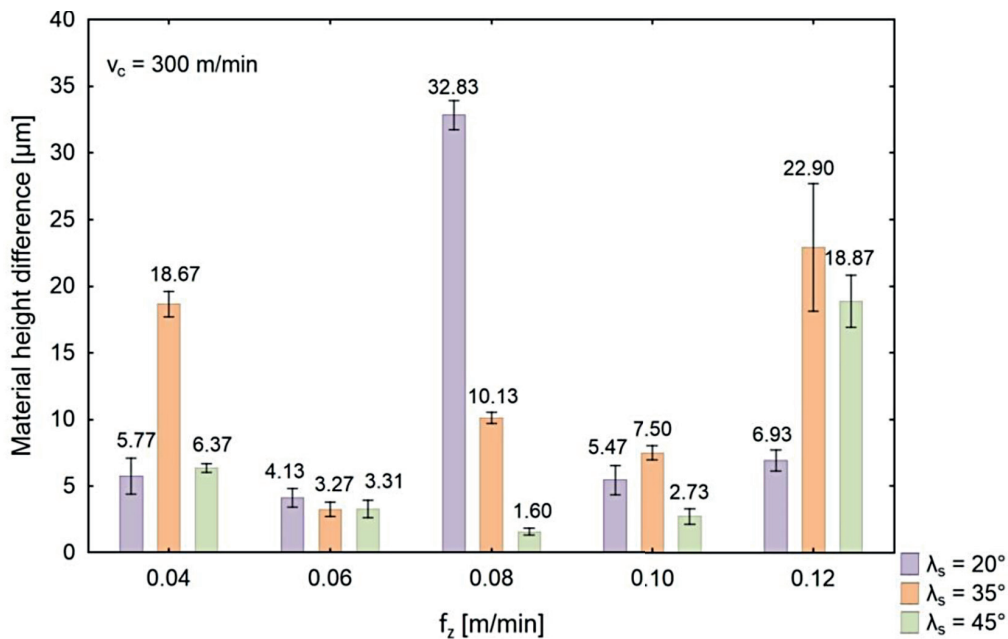


Fig. 6. Effects of feed per blade and helix angle on material height differences

height differences for these tool geometries was different from that of cutting speed [34]. The material height differences measured during the machining with the helix angle  $\lambda_s = 45^\circ$  decreased within range  $f_z = 0.04 - 0.08$  mm/blade and increased for  $f_z = 0.10$  mm/blade and  $f_z = 0.12$  mm/blade. The material height differences are mainly attributable to the different properties of the materials sandwich composites are made from. It is also result from discrepancies

in the longitudinal rigidity of the facings and the core. The material height differences were also caused by the different elasticity of the materials – the elastic deformation of the composite material was higher than that of the aluminium alloy. It caused the composite to bend more strongly during machining. The research conducted has shown that the cutting parameters affected the surface quality of the material – depending on the adopted machining settings, different material



height differences could be recorded [35, 36]. The results were also affected by the tool geometry [18]. A comparison of how the helix angle affected the material height difference values obtained during machining with variable parameters  $v_c$  and  $f_z$  shows that in most cases the lowest material height difference values were recorded when using a milling cutter with the highest value of the angle  $\lambda_s$ . This can be explained by the effects of the helix angle on the speed with which chips are evacuated from the cutting zone and the direction in which they flow. For low values of the angle  $\lambda_s$  chips flow axially, whereas when  $\lambda_s$  is higher the direction of chip flow is radial [32]. The considered cutting parameters and tool geometry affected the material height differences to varying degrees. This allows the conclusion that one should not concentrate on just one cutting parameter when selecting machining conditions for Al/CFRP structures, but rather look for an optimal machining setup that takes into account specific criteria. Fig. 7 and Fig. 8 show plots of maximum cutting force component  $F_y$  obtained depending on the adopted cutting parameters and tool geometry.

Analysis of the data in Fig. 7 revealed that, for all the tool geometries, the  $F_y$  component increases for cutting speeds  $v_c = 80 - 400$  m/min, while it decreases for  $v_c = 500$  m/min. In most cases, the highest  $F_y$  values were obtained during milling with the helix angle  $\lambda_s = 20^\circ$ , while the lowest ones were recorded during milling

with the helix angle  $\lambda_s = 45^\circ$ . The maximum  $F_y$  (382N) was reached during machining with cutting speed  $v_c = 400$  m/min using a tool with the helix angle  $\lambda_s = 20^\circ$ . The lowest value (42N) was measured when machining with the cutting speed  $v_c = 80$  m/min and the helix angle  $\lambda_s = 45^\circ$ . A comparison of the effects of the cutting speed on the material height difference and cutting force component  $F_y$  (Fig. 5 and Fig. 7) revealed that, for the angles  $\lambda_s = 20^\circ$  and  $\lambda_s = 35^\circ$  within range  $v_c = 80 - 300$  m/min, the material height difference and the  $F_y$  component had similar patterns. The difference occurs for  $v_c = 400$  m/min, where the material height difference decreases while the cutting force component increases. For  $v_c = 500$  m/min, the material height difference and the  $F_y$  component decrease. For the helix angle  $\lambda_s = 45^\circ$ , the material height differences exhibit a trend opposite to that of the  $F_y$  component.

Based on Fig. 8, it can be concluded that the  $F_y$  component grew with increasing feed rates for all the tool geometries examined [22]. As was the case with cutting speed, the highest  $F_y$  cutting force component was recorded during machining with the helix angle  $\lambda_s = 20^\circ$ , and the lowest one with the helix angle  $\lambda_s = 45^\circ$ . The maximum  $F_y$  component (338N) was obtained when machining with  $f_z = 0.12$  mm/blade using the tool with the angle  $\lambda_s = 20^\circ$ . The lowest value (69N) was recorded when machining with the lowest feed rate using a milling cutter with the angle  $\lambda_s = 45^\circ$ . By comparing

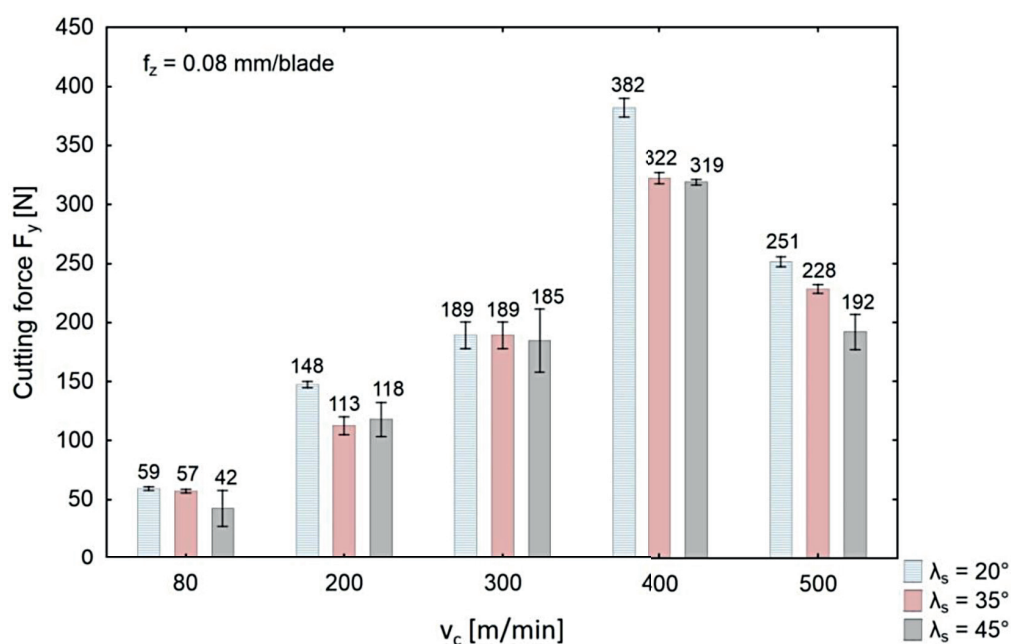


Fig. 7. Effects of cutting speed and helix angle on maximum cutting force component  $F_y$

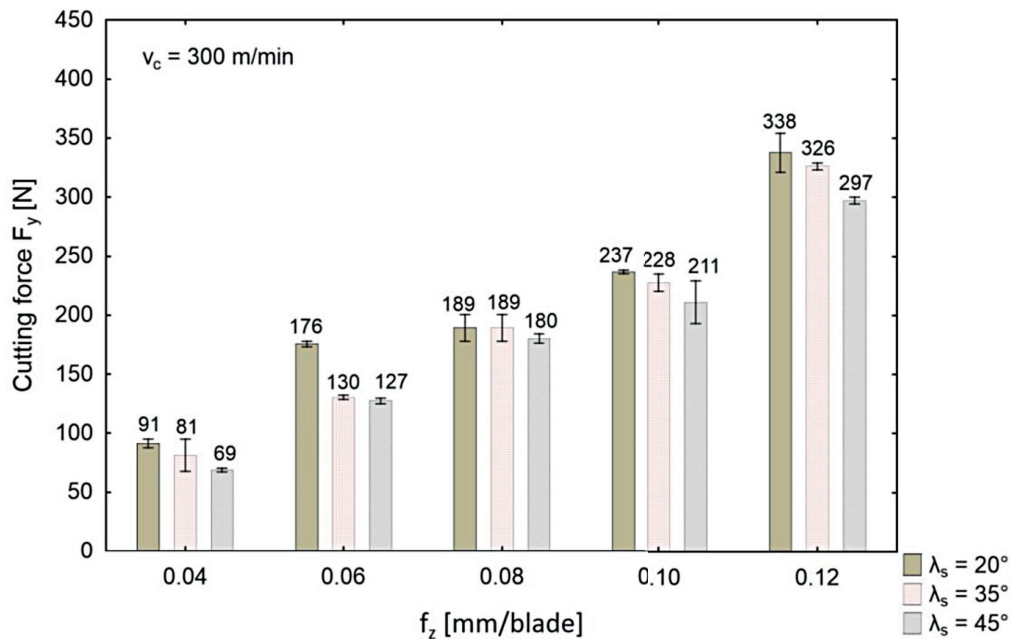


Fig. 8. Effects of feed per blade and helix angle on maximum cutting force component  $F_y$ .

Fig. 6 and Fig. 7, it can be realised that feed per blade does not affect the material height differences as much as the cutting force. In most cases, the higher values of the  $F_y$  component, for both variables, were obtained by using the tool with the helix angle  $\lambda_s = 20^\circ$ . Milling with a tool with angle  $\lambda_s = 45^\circ$  led to lower values of the  $F_y$  component [32].

## CONCLUSIONS

Hybrid sandwich structures are considered to be poorly machinable [43]. Effective machining of Al/CFRP structures should combine the features of metal and polymer composite machining. In practice, machining settings are selected based on the material one of the layers is made of (usually the composite layer), which may be inappropriate for the other materials. Based on the obtained results, the following conclusions were presented. Milling of the sandwich structures produces differences in material heights along the border of the bonded materials, which adversely affects the surface quality of such structures. The cutting parameters ( $v_c$  and  $f_z$ ) can influence the material height differences. Considering the effects of cutting speed on the material height differences recorded depending on tool geometry, it could be observed that, for the angles  $\lambda_s = 20^\circ$  and  $\lambda_s = 35^\circ$ , similar results were obtained. For the angle  $\lambda_s = 45^\circ$ , an opposite trend could be observed. Analysis of the effects of  $f_z$  parameter upon surface quality after

machining shows that the material height differences obtained for the angles  $\lambda_s = 20^\circ$  and  $\lambda_s = 35^\circ$  have a similar irregular pattern. As was the case with  $v_c$  for this tool geometry, feed per blade when milling with the helix angle  $\lambda_s = 45^\circ$  resulted in a decrease in material height differences for the first three  $f_z$  values and an increase for the last two. The lowest material height difference values were obtained for the following machining conditions:  $v_c = 300$  m/min,  $f_z = 0.08$  mm/blade and  $\lambda_s = 45^\circ$ . The highest material height difference was recorded using the same values of  $v_c$  and  $f_z$ , but for  $\lambda_s = 20^\circ$ .

The maximum cutting forces were obtained for the  $F_y$  component, i.e. for the feed direction. A change in the helix angle affected the  $F_y$  component: the highest values of cutting force component  $F_y$  were obtained when machining with the helix angle  $\lambda_s = 20^\circ$ , and the lowest ones with the helix angle  $\lambda_s = 45^\circ$ . The maximum value of the  $F_y$  component was obtained during machining with cutting speed  $v_c = 400$  m/min, feed per blade  $f_z = 0.08$  mm/blade and helix angle  $\lambda_s = 20^\circ$ . The minimum value of the  $F_y$  component was recorded for the following machining conditions:  $v_c = 80$  m/min,  $f_z = 0.08$  mm/blade and  $\lambda_s = 45^\circ$ .

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