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## **THERMOMECHANICAL AND TRIBOLOGICAL ASPECTS OF CUTTING MULTILAYER CFRP-TITANIUM ALLOY STACKS**

*Drilling of CFRP-titanium alloy stacks is a complex technological task due to significant differences in the physical, mechanical, and thermophysical properties of carbon fiber and titanium alloy. This article presents a review of modern scientific research describing the physics of the cutting process separately for each layer of the package and comprehensively for transient processes in the contact zone of carbon fiber and titanium alloy, respectively. The features of the fracture mechanisms in the cutting zone for each of the stack materials are analyzed, and a classification of factors affecting the wear conditions and growth during the drilling process is performed. It was determined that the combination of the abrasive effect of carbon fibers significantly worsens the microgeometry and microrelief of the cutting edge, creating favorable conditions for the adhesion of titanium alloy particles to the tool surface. The combination of adhesive and abrasive wear processes significantly reduces the tool life, complicating the possibility of a thorough study of this phenomenon.*

*Keywords:* CFRP, titanium alloy, drilling, cutting, wear, build-up edge.

*Fig.: 2. Tables: 2. References: 61.*

**Relevance of the research.** Despite the significant amount of publications, the focus of existing studies on hole quality parameters, delamination and burr formation prevails. The mechanisms of wear and build-up edge formation under conditions where the tool transitions between CFRP and Ti layers are often covered fragmentarily. This limits the possibility of forming generalized, physically based ideas about the features of build-up edge formation, specifically when machining carbon fiber-reinforced plastic (CFRP)–titanium alloy stacks. Generalization of existing research will aid in understanding the direction of feature research for developing techniques to ensure the tool life of carbide twist drills when drilling holes in CFRP-Titanium alloy stacks.

**Target setting.** Currently, the problem of ensuring hole accuracy and quality when drilling CFRP-Ti alloy stacks is in the focus of research in industrial and academic societies. Physical aspects, such as the effect of cutting parameters on thrust force, torque, and hole accuracy, are studied in various aspects. However, authors suggest that there is still a lack of solid research on the topic of the effect of cutting parameters on wear and built-up edge formation. The current paper presents an analytical review of the state-of-the-art in this field to gain a more comprehensive understanding of the current state of this problem.

**Actual scientific researches and issues analysis.** In scientific publications, the issue of machining carbon fiber-reinforced plastic (CFRP) is considered a distinct area that emerged at the intersection of cutting theory and fracture mechanics of anisotropic materials. Generalized information on the machinability of composites, the nature of chip formation and typical defects is given in review and reference works (Jinyang et al., 2023). Approaches to technological support for manufacturing products from composites, as well as the role of mechanical processing in forming end joints, are separately outlined (Franz et al., 2022).

Research on drilling CFRP is primarily focused on analyzing delamination as the dominant defect and determining the influence of cutting modes on the area of delamination propagation, which is estimated using appropriate criteria (Jinyang et al., 2022). Experimentally validated approaches have been proposed to reduce delamination, including optimization of feed, cutting speed, and drill geometry (Chen et al., 2023). It has been demonstrated that tool design features, including specialized cutting-edge profiles and multi-edge drills, can modify the loading condi-

tions of the reinforcing fiber layers (Jia, 2020). A separate area of research is devoted to the influence of drill geometry on axial force, chip formation, and hole quality in CFRP (Wang, 2021). One of the factors affecting the mechanics of the cutting process is the apex angle and cutting edge configuration (Peterka & Pokorny, 2014), which has been more thoroughly investigated for specialized drill designs aimed at increasing the stability of the cutting process and improving chip evacuation (Yuanxiao et al., 2024). It was found that the use of drills with multi-blade auxiliary cutting edges reduces damage to the composite layer (Shu et al., 2021).

General trends and the current state of the CFRP drilling problem for aerospace components are systematized in a review (Aamir et al., 2019). The challenges of burr formation during the processing of packages in a composite material composition and methods for their evaluation were also separately outlined (Poor et al., 2021). Currently, in the aspects of machining the CFRP layer, issues related to hole accuracy, geometric deviations, and ensuring the specified surface condition of the holes remain (Prisco et al., 2019; Soori & Arezoo, 2023).

In parallel, research on the machining of titanium alloys is developing, with thermal stress of the process and the instability of the contact interaction between the tool and the workpiece material being key considerations. Titanium alloys are widely used in aircraft structures, which improves their manufacturing technologies, particularly relevant (Martin & Evans, 2000). The cutting processes of titanium alloys are characterized by high temperatures in the contact zone and significant contact stresses, which determine the intensity of tool wear (Wong, 2008). A separate layer of work considers the influence of tool geometry on the stability and quality of holes in Ti alloys (Astakhov, 2024).

Of significant interest are studies on the mechanical processing of hybrid packages, particularly those involving CFRP/Ti. Classical works show that when drilling “composite–titanium” stacks, a complex set of defects in the composite layer and significant technological difficulties in the metal layer arise (Xu et al., 2020). Approaches to optimizing the drilling process of graphite/bismaleimide–titanium stacks are considered (Kim & Ramulu, 2004). It is also demonstrated that technological recommendations for multilayer systems necessitate a separate generalization and cannot always be applied directly from the case of homogeneous materials (Benezech et al., 2012). The state of the problem of drilling hybrid FRP/Ti-stacks is systematized in a specialized review (Xu et al., 2016). The works present an analysis of the mechanisms of material removal, the characteristics of subsurface layer damage, and the relationship between cutting modes and hole quality parameters (Xu et al., 2018). Based on orthogonal cutting, an interpretation of the material removal modes and the conditions for the formation of subsurface damage in CFRP/Ti6Al4V is proposed (Vijayathithan & Anil, 2025). The influence of cooling and lubrication methods on the process parameters and hole quality indicators in CFRP/Ti packages is also studied (Rodriguez et al., 2024).

A significant portion of the work focuses on evaluating the quality indicators of holes in CFRP/Ti packages. Geometric deviations, dimensional errors and surface condition during drilling are studied. The relationship between thermal phenomena and geometric accuracy of the hole is shown (Kolesnyk, 2020). The characteristics of the holes and the integrity of the surface layer are considered with alternative methods of obtaining holes in Ti6Al4V/CFRP hybrid systems (Li et al., 2019).

A separate area of research is devoted to the formation of burrs and interlayer defects in stacked materials. In particular, the regularities of burr formation in the interlayer region under the influence of technological conditions were described (Abdelhafeez et al., 2015). It has been demonstrated that the presence of a gap between the layers creates conditions for the growth of the interlayer burr, and the compressive force exerted by the layers affects both its height and the thickness of the burrs (Poor et al., 2021). Generalized approaches to analyzing burrs and methods for their reduction are presented in a review (Hassan et al., 2020).

The issue of tool wear when drilling CFRP/Ti stacks is considered a key factor in determining process stability. Currently, mathematical models exist, and the wear mechanisms of carbide drills during drilling CFRP/TiAl6V4 without the use of lubricating and cooling have been described. A comparative study of tool wear on a CFRP/Ti stack and on individual layers was conducted. It has been demonstrated that the wear mechanisms and their intensity vary depending on whether the material is processed as a monolithic layer or as part of a stack (Jinyang et al., 2023).

Within the framework of CFRP research, information on the use of tungsten carbides and polycrystalline diamond as tool materials for working in abrasive wear conditions has also been systematized. For the production conditions of aerospace assembly, approaches to using PCD tools when drilling critical structures are presented (An et al., 2020). Separate works compare the performance of carbide tools when drilling CFRP and CFRP/Ti stacks (Beal et al., 2011). In this context, the issue of technological selection and tool design to improve the quality of holes in multilayer systems is also highlighted (Jia, 2020).

Despite the significant volume of publications, existing studies are predominantly oriented towards the parameters of hole quality, delamination, and burr formation. The mechanisms of wear and build-up formation in the conditions of the tool transition between layers of CFRP and titanium alloy are often covered fragmentarily. This limits the possibility of forming generalized physically based ideas about the features of build-up edge formation specifically when machining CFRP/Ti alloy stacks.

#### **The statement of basic materials. Physics of CFRP cutting**

The machining of CFRP is characterized by the complex physics of the cutting process, which is due to the anisotropic structure of the material and the presence of reinforcing fibers, whose properties differ significantly from those of the polymer matrix. CFRP is a multiphase composite material in which the load-bearing function is mainly implemented by reinforcing fibers, while the matrix acts as a binding medium. The physical mechanisms of material failure during the cutting of CFRP differ significantly from those characteristic of isotropic metals. Plastic deformation of the material in the cutting zone is practically absent, and material removal occurs primarily through the brittle fracture of the fibers and local displacement of the polymer matrix. Depending on the fiber orientation relative to the cutting direction, various mechanisms for cutting, breaking, or pulling out the fibers can be implemented (Hassan et al., 2022). This aspect is one of the determining factors affecting the nature of the force interaction between the tool and the material. When cutting along the fibers, increased process stability is observed, while cutting at an angle or across the fibers is accompanied by uneven destruction and increased fluctuations in cutting forces, which is due to the complex nature of the cutting edge loading and the instability of the contact interaction (Alvarez-Alcon et al., 2020).

An essential feature of the physics of the cutting CFRP is the intense abrasive effect of reinforcing fibers on the cutting tool. Carbon fibers have a high specific hardness and can cause micro-cutting of the contact surfaces of the tool. As a result, abrasive wear becomes the dominant mechanism of cutting-edge degradation already at the initial stages of drilling (Zhang, 2022). Abrasive wear is accompanied by a change in the microgeometry of the cutting edge, in particular, an increase in its cutting edge radius. This leads to a change in the conditions of tool entry into the material, a redistribution of contact stresses, and an increase in specific cutting forces. These phenomena are especially evident when machining multilayer laminates, where the cutting edge sequentially interacts with fibers of different orientations (Balan et al., 2021).

Thermal processes during the cutting of carbon fiber composites have a specific nature. The low thermal conductivity of the polymer matrix and the absence of intense plastic deformation result in limited heat release in the cutting zone compared to metals. At the same time,

a local increase in temperature can lead to thermal softening or degradation of the matrix. Such phenomena negatively affect the surface quality of the holes and can contribute to the formation of defects in the surface layers (Poor et al., 2021).

Cutting parameters have a significant impact on the nature of physical processes during the machining of CFRP. Increasing the cutting speed, as a rule, helps to reduce cutting forces, but can lead to an increase in temperature in the plastic deformation zone. The feed directly affects the intensity of the load on the laminate layers and the conditions under which they are destroyed. In this regard, optimizing cutting modes is a key area for ensuring process stability (John et al., 2022).

The geometry of the cutting tool has a significant impact on the physics of the CFRP cutting process. Cutting tool angles, the shape of the cutting edge and the configuration of the chip removal grooves determine the nature of the contact with the fibers and the conditions for chip removal (Jia et al., 2020). Specialized tool geometries can partially reduce the intensity of abrasive wear and improve the quality of the machined surfaces (Priarone, 2017).

Given the numerous factors and aspects that influence the mechanics of the cutting process, it is advisable to summarize the leading research in this area (Table 1).

*Table 1 – The analysis of the cutting process aspect of the mechanics of CFRP destruction*

Reference	Topic	Conclusions
(Yu et al., 2023)	Thermomechanical damage during drilling of CFRP. The influence of the cutting-edge condition on the mechanism of carbon fiber fracture during CFRP drilling.	It was found that the heat distribution from the cutting zone is uneven, leading to heat accumulation, reduced fiber-matrix adhesion, and brittle fracture of the carbon fibers. The increase in tool wear exacerbates the abrasive-brittle nature of fiber fracture, intensifying the damage to carbon fibers.
(Arjun et al., 2022)	The mechanism of material removal during milling of unidirectional carbon fiber, taking into account fiber orientation and heat release.	The destruction of carbon fiber occurs through brittle fracture of the fibers. Effective cooling and lubrication reduce friction, lower the temperature, and improve the quality of the machined surface.
(Chaosheng et al., 2024)	The effect of spiral drilling on the force and thermal characteristics of cutting carbon fiber. The effect of step drill geometry and cyclic drilling on the failure mechanism of CFRP in stacks.	Cutting against the direction of the fibers is accompanied by increased forces and more intense defect formation; the optimal strategy is to reduce temperature and damage. The use of step drills helps to reduce axial force and reduce delamination in CFRP.
(Shariar et al., 2025)	Contact stresses and thermal effects in the tool–CFRP interface. Systematization of the physical mechanisms of cutting CFRP in stacks with metals	Excessive cutting temperature leads to “glassing” of the polymer matrix, changes the contact mechanics, and increases the risk of delamination, thereby deteriorating the quality of the holes. A combination of brittle fracture of the fibers, thermal destruction of the matrix, and contact stresses in the zone of connection between the carbon fiber layer and the metal determines the physics of cutting CFRP in stacks.
(Chealvan et al., 2022)	Numerical modeling of the effect of temperature on damage to carbon fiber in multilayer stacks	Heat accumulation in carbon fiber accelerates thermal degradation of the matrix and promotes the spread of delamination of the lower layers of CFRP.

Summarizing the research results in this chapter, it can be concluded that the physics of the carbon fiber cutting process is determined by a combination of a brittle fracture mechanism of the material and an intense abrasive interaction between the reinforcing fibers and the cutting tool. It is these features that shape the state of the cutting edge after passing through the composite layer, which is of fundamental importance for the subsequent interaction of the tool with the titanium alloy in multilayer stacks.

**Physics of Ti alloy cutting**

Machining of titanium alloys is characterized by high process complexity, which is due to the combination of high material strength, low thermal conductivity and increased chemical activity of titanium. This combination of properties leads to the formation of a stress-strain state with localization of plastic deformation in a narrow shear zone (Geng et al., 2020). During the cutting of titanium alloys, the majority of the mechanical energy is converted into heat in the tool-workpiece contact zone. Due to the low thermal conductivity of titanium, heat removal into the material volume is limited, which contributes to an increase in temperature in the cutting zone (Kolesnyk, 2020). Increased temperatures significantly impact contact processes and the wear intensity of the cutting tool (Wang & Jia, 2021).

When cutting titanium alloys, the formation of segmental or chipping chips is usually observed (Fu et al., 2022). The nature of chip formation is due to the cyclic accumulation of plastic deformation, followed by local rupture (John et al., 2022). As a result, fluctuations in cutting forces and process instability are observed, which negatively affect the quality of the machined surfaces.

High contact stresses and temperatures in the cutting zone create favorable conditions for adhesive interaction between the titanium alloy and the tool material. Particles of the machined material stick to the cutting edge, forming a build-up edge. The formation of the build-up changes the geometry of the cutting wedge, friction conditions and the direction of chip convergence (Chowdhury et al., 2017). The build-up edge formation process is unstable and is accompanied by its periodic destruction. The detachment of parts of the build-up can lead to microcracks of the cutting edge and additional intensification of tool wear. As a result, the condition of the cutting tool gradually deteriorates and the stability of the cutting process decreases (Astakhov & Shvets, 2020).

Tool wear during cutting of titanium alloys is complex. Along with adhesive wear, diffusion processes and thermal softening of the tool material occur in the contact zone. The combined effect of these mechanisms determines the wear intensity and tool life (Beal et al., 2011).

The geometry of the cutting tool has a significant impact on the physics of the cutting process for titanium alloys. The leading and trailing angles, as well as the leading angle and the helix angle, have a significant impact, determining the conditions for chip formation and the nature of the contact interaction (Astakhov, 2024). Geometry optimization enables the reduction of temperature load and partial stabilization of the cutting process (Li et al., 2023).

Cutting parameters also play a crucial role in determining the cutting conditions of titanium alloys. Increasing the cutting speed typically increases temperature in the contact zone, whereas increasing the feed rate affects the magnitude of the contact stresses. The choice of cutting modes is a compromise between process performance and cutting tool stability (An et al., 2020).

Summarizing the research results, it is notable that the physics of the cutting process of titanium alloys is determined by the interaction of thermomechanical and adhesive factors (Table 2).

*Table 2 – Analysis of key research in machining Ti alloy*

Reference	Topic addressed	Key conclusions
1	2	3
(Hiremath et al., 2025)	The influence of thermal and adhesive phenomena on chip formation, cutting forces and surface quality during drilling and helical milling.	Lower axial force values are associated with helical milling due to its kinematics and significantly lower temperatures in the cutting zone, which reduces the risk of thermal damage and decreases the intensity of wear/adhesion. The machining process can be accompanied by riveting of the machined surface and is characterized by the formation of short, fragmented chips, which contribute to process stability and quality.

*End of the table 2*

1	2	3
(Zhu et al., 2025)	Influence of the use of minimal lubrication (MQL) techniques on cutting temperature, wear, adhesion and process stability during drilling of titanium alloy	The increase in cutting-edge temperature is a key factor in the intensification of wear and adhesion phenomena during the drilling of titanium alloys. MQL reduces the thermal load, resulting in slower degradation of the cutting edge compared to cutting without coolant. The results highlight the crucial role of heat removal from the cutting zone in determining tool life during the machining of titanium alloys.
(Yang et al., 2025)	The effect of cryogenic cooling technique on cutting temperature, cutting forces, and thermomechanical damage of the surface layer of holes in titanium alloys.	Cryogenic cooling changes the thermomechanical balance of the cutting process of titanium alloys. As a result of the differences in cutting forces, conditions for the formation of residual stresses and hardening are created. It is shown that the state of the machined surface for titanium is a function of the temperature in the cutting zone.
(Shixiong et al., 2025)	Systematization of cause-and-effect relationships between heat generation, adhesion/build-up, wear, plastic deformation and quality indicators of the machined surface when cutting titanium alloys.	The review summarizes that the low thermal conductivity and chemical activity of titanium enhance the influence of local heat generation and adhesion, which leads to build-up formation and accelerated wear of the cutting tool. These phenomena directly affect the roughness, depth of the defect layer and residual stresses. It is demonstrated that optimizing surface quality indicators requires simultaneous control of the contact interaction between the tool and the workpiece, as well as the thermal cooling mode.
(Debard et al., 2025)	Burr formation mechanisms when drilling Ti-6Al-4V under the influence of thermomechanical conditions and the state of the cutting edge.	Burr formation in Ti-6Al-4V is a result of a combination of plastic deformation at the exit, high cutting temperature, and cutting edge wear.

The formation of a built-up edge is a key manifestation of this interaction, significantly affecting the stability of the process and tool wear. These features are of particular importance in the machining of multilayer stacks, where the previous interaction with the composite material layer additionally determines the state of the cutting edge.

**Physics of cutting CFRP/titanium alloy stacks**

Fundamentally more complex cutting conditions characterize the machining of multilayer CFRP/titanium alloy stacks compared to machining homogeneous materials. This is due to the sequential interaction of the cutting tool with layers that differ significantly in mechanical, thermophysical, and tribological properties (Franz et al., 2022; Xu et al., 2023). During the cutting process, the tool initially interacts with the composite layer, which is characterized by a brittle fracture mechanism and the intense abrasive action of the reinforcing fibers. As a result, the cutting edge becomes blunt and its microgeometry changes. The state of the cutting edge directly affects the subsequent interaction of the tool with the titanium layer (Chowdhury et al., 2017). A sharp change in cutting conditions occurs as the cutting tool transitions through the material boundary. The change in the mechanism of material destruction, the nature of contact interaction and heat generation creates unstable operating conditions for the tool. At the layer boundary, the superposition of abrasive and adhesive wear mechanisms is observed (Alonso et al., 2019). In the titanium layer, cutting occurs under conditions of increased contact stresses and temperatures, which are formed by considering the previous abrasive wear of the cutting edge. Blunting of the tool after cutting carbon fiber plastic results in an increase in the contact area and intensification of the adhesive interaction between the tool and the titanium alloy, creating favorable conditions for growth (Alvarez et al., 2011). A feature of package cutting is that the formation of growth does not occur under the “classical” conditions characteristic of cutting solid titanium alloys. The initial state of the cutting edge, changed by the abrasive action

of the composite layer, determines the morphology of the growth and the nature of its interaction with the tool (Luo et al., 2019).

A vital zone from the point of view of process physics is the boundary between the composite and metal layers. It is here that the maximum instability of cutting forces and an increase in cutting temperature are observed. Fluctuations in forces and temperature negatively impact the state of the cutting edge, contributing to the intensification of tool wear (Chen et al., 2025). The physics of cutting stacks is also influenced by the technological parameters of the process, specifically cutting speed, feed and cooling conditions. These factors affect the processes in the composite and titanium layers differently. Optimal modes for one material do not always ensure process stability when processing a package in a different material. This complicates the choice of technological parameters and requires compromise solutions (Fig. 1, Fig. 2) (Xu et al., 2023).

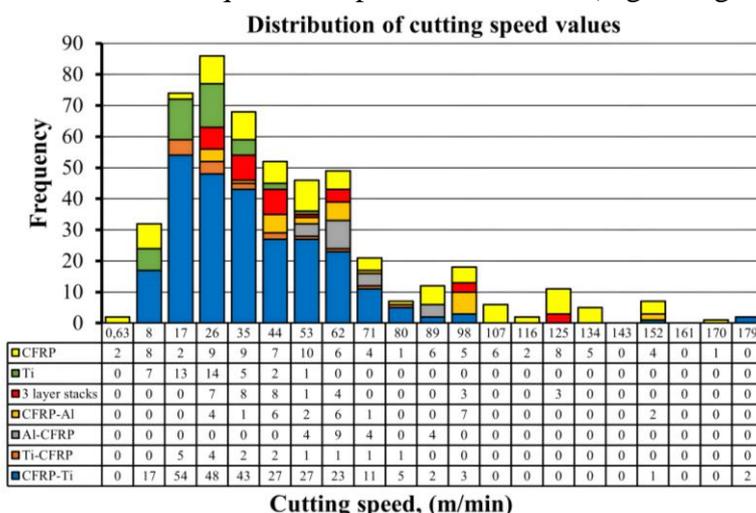


Fig. 1. Cutting speed distribution diagram depending on the stacks sequence (Xu et al., 2023)

The cutting direction and the sequence of layers have a significant impact on the physics of the cutting process. In the case of drilling, when the tool sequentially processes the composite material and then the titanium alloy, the effect of preliminary wear of the cutting edge is most pronounced. These features must be considered when analyzing the wear and build-up processes (An et al., 2020).

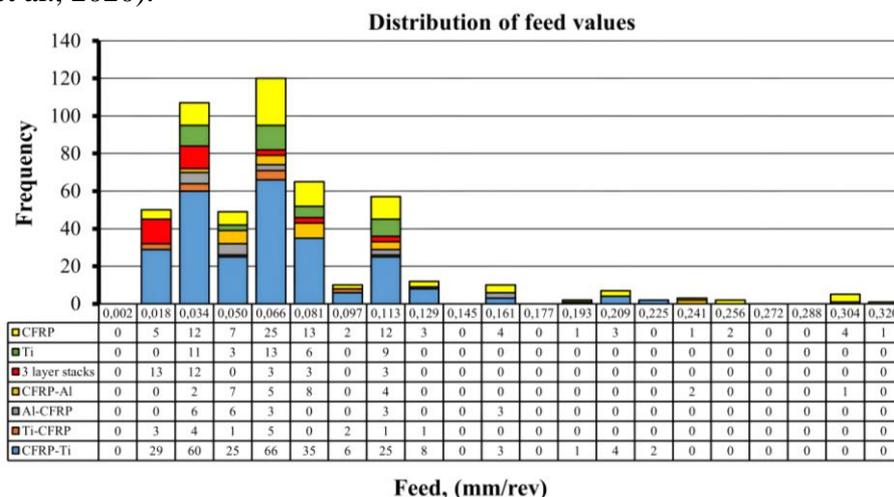


Fig. 2. Feed rate diagram depending on stack sequence (Xu et al., 2023)

Summarizing the results presented, it can be noted that the physics of cutting the “carbon fiber-titanium alloy” packages is determined by the combined action of abrasive and adhesive mechanisms, as well as the instability of thermomechanical conditions in the material interface zone. Such conditions form a specific nature of the cutting tool wear and create prerequisites for the features of build-up edge formation that differ from the processes characteristic of cutting homogeneous materials.

#### **Wear mechanics and build-up edge formation**

The wear of the cutting tool during the mechanical processing of a CFRP/titanium alloy stack is complex and multifactorial, due to the sequential interaction of the tool with layers of materials that differ significantly in mechanical and tribological properties. In the composite layer, the dominant mechanism influencing the cutting edge is abrasive wear caused by the action of rigid reinforcing fibers. The abrasive action of the fibers leads to a gradual blunting of the cutting edge and a change in its microgeometry. The change in the microgeometry of the cutting tool will manifest itself in an increase in the radius of the cutting edge, which quickly and significantly alters the conditions of interaction between the tool and the processed material. Thus, the cutting of the titanium layer of the package occurs with a tool that is already somewhat blunted, initially forming more unfavorable conditions for cutting the titanium alloy (Aydin & Nalbant, 2020). Two primary wear mechanisms accompany the machining of titanium alloys. Adhesive and thermomechanical wear are dominant, which are caused by high contact stresses on the cutting edge due to the high strength of the titanium alloy and increased cutting temperature, contributing to the adhesion of particles of the processed material to the cutting edge (Sharma et al., 2025).

A characteristic consequence of the combination of high contact stresses, low thermal conductivity, and high chemical activity in the cutting zone when drilling carbon fiber-titanium alloy packages is the formation of growth on the cutting edge of the drill (Chowdhury et al., 2017; Zhu et al., 2025). The combination of the conditions described above, in particular high cutting temperature and low thermal conductivity, leads to the fact that a significant part of the energy in the zone of plastic deformation is converted into heat, which, in combination with the chemical activity of the titanium alloy, leads to the adhesive transfer of its particles to the cutting edge of the tool. The unstable nature of the growth as a phenomenon leads to a cyclic process of growth formation and detachment, which significantly worsens the microgeometry of the drill for the next drilling cycle (Oliaei & Karpal, 2017; Salguero et al., 2011).

In addition to the conditions directly in the cutting zone, the formation of growth is influenced by the conditions of the strip removal from the cutting zone, as it worsens the thermodynamic conditions of the drilling process. Thus, preventing the formation of growth is an essential technological task in the processing of packages consisting of carbon fiber-titanium alloy. To date, two main directions for preventing growth using minimal lubrication (MQL) and cryogenic technologies have emerged (Yang et al., 2025; Zhu et al., 2025). The use of combined cooling schemes, which combine LCO<sub>2</sub> and MQL cooling, improves chip removal and reduces the intensity of adhesive transfer in titanium alloys (Rodriguez et al., 2024).

The mechanics of wear and built-up edge formation during the machining CFRP/Ti alloy stacks are attributed to the combined effects of the abrasive action of carbon fibers, high cutting temperatures, and the high chemical activity of the titanium alloy under conditions of high contact loads. The consensus in scientific publications regarding the problematic nature of studying the impact of growth on the drilling process due to the abrasive effect of carbon fiber makes this aspect of the physics of cutting composite materials a relatively understudied area. Thus, further research aimed at a systematic analysis of wear mechanisms and build-up edge formation during drilling of CFRP/Ti alloy stacks is advisable.

### Conclusions.

1. Machining CFRP/ Ti alloy stacks is characterized by more complex cutting conditions compared to the machining of homogeneous materials, due to significant differences in the physical, mechanical, and thermophysical properties of the layers of the stacks.

2. The physics of the cutting process of carbon fiber is characterized by a combination of brittle fracture of the fiber-matrix bond material and intense abrasive action of the fibers, which intensifies the wear process of the cutting edge of the drill due to the deterioration of its micro-geometry.

3. The physics of the cutting process of titanium alloys is characterized by a combination of thermomechanical and thermochemical factors that contribute to the built-up edge formation and can cause detachment of sections of the cutting edge during its separation, which significantly worsens the operating conditions of the tool and reduces its tool life.

4. It was determined that the mechanics of cutting tool wear during package processing is complex and cannot be reduced to the sum of wear mechanism factors typical for cutting carbon fiber and titanium alloys, since it has a stochastic, non-linear nature.

5. The generalization of the review results showed insufficient research into the processes of build-up formation during drilling of CFRP/ Ti alloy stack, which limits the possibilities of creating physically based models of tool wear and substantiating rational technological parameters.

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### Statement on the use of generative AI and AI-based technologies in the process of writing the text of the article

During the writing of this material, the authors used ChatGPT to check English grammar and to write an extended annotation. After using this tool/service, the authors reviewed and edited the content and take full responsibility for the content of the publication.

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## **ТЕРМОМЕХАНІЧНІ ТА ТРИБОЛОГІЧНІ АСПЕКТИ РІЗАННЯ БАГАТОШАРОВИХ ПАКЕТІВ «ВУГЛЕПЛАСТИК–ТИТАНОВИЙ СПЛАВ»**

Механічне оброблення багатошарових пакетів «вуглепластик–титановий сплав» є однією з найбільш складних і науково актуальних задач сучасного авіабудування. Поєднання матеріалів із принципово різними фізико-механічними властивостями зумовлює істотну неоднорідність термомеханічних і трибологічних умов у зоні різання. Таке поєднання ускладнює керування процесом та забезпечення якості оброблення. У статті виконано аналітичний огляд сучасних наукових досліджень, присвячених фізиці процесу різання вуглепластиків, титанових сплавів та їх пакетів.

Розглянуто основні механізми руйнування вуглепластиків, зокрема крихкий злам волокон, деградацію полімерної матриці та розширення. Окремо приділено увагу особливостям різання титанових сплавів. Зокрема, приділено увагу впливу високих контактних напружень, високої температури різання та адгезійної взаємодії інструмента на процес формування стружки та якість обробленої поверхні. Визначено, що особливістю фізики різання пакетів «вуглепластик–титановий сплав», є взаємний вплив шарів на механіку формування стружки, пов'язаний з послідовністю оброблення шарів, силовими та температурними навантаженнями інструменту.

Проаналізовано механізми зношення інструмента та формування наросту під впливом температури різання, тертя на контактних поверхнях, матеріалу і покриття інструмента, а також методів охолодження та змащення. На основі огляду літературних джерел визначено, що, попри значну кількість досліджень, питання формування наросту при свердлінні отворів у пакетах «вуглепластик – титановий сплав» залишаються недостатньо вивченими, особливо з урахуванням міжшарової взаємодії та змінного характеру процесу різання при переході інструменту з шару вуглепластика у шар титанового сплаву. Отримані узагальнення можуть бути використані як наукове підґрунтя для подальших досліджень і вдосконалення технологій механічного оброблення багатошарових з'єднань з використанням полімерних композиційних матеріалів, титанових та алюмінієвих сплавів.

**Ключові слова:** вуглепластик, титановий сплав, багатошарові пакети, механічне оброблення, фізика різання, зношування інструменту, нарост.

Рис.: 2. Табл. 2. Бібл.: 61.