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Optimisation of the bore reaming process in hybrid stacks made of carbon fibre and metal alloys

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Abstract. The present work aims to improve the existing technology of reaming bores in hybrid stacks containing a composite material interlayered with titanium and aluminium alloys. The study was conducted using statistical approaches at the stages of experimental design and data processing in the Statistica 6 and Microsoft Excel 2010 software. The bore roughness was measured using a Taylor Hobson Form Talysurf i200 contact profilometer. The height of the tool build-up edge was investigated using a Bruker ContourGT-K1 optical profilometer. Bore diameters were determined using a Carl Zeiss Contura G2 coordinate measuring machine. An experimental study was carried out using an Atlas Copco PFD-1500 automatic feed drilling unit and a 14 mm MAPAL reamer with a replaceable head. A methodology for a comprehensive experimental study of boring and reaming processes in the "OT4 titanium alloy - VT6 titanium alloy - polymeric composite materials - VT6 titanium alloy - 1933 aluminium alloy" hybrid stack was developed and implemented. It was found that the most significant factors affecting the parameters of bore accuracy, in particular, the deviation from the true bore longitudinal section profile, include the cutting speed in the first and the second degree, as well as the feed. The optimum cutting modes are a cutting speed of 7.24 m/min, a feed of 0.27 mm/rev and a machining allowance of 0.5 mm. As a result, the time of reaming one bore is reduced by 4.6 times. The optimum cooling method, ensuring the increased accuracy and reduced roughness of the bore in the aluminium alloy layer, is cooling by carbon dioxide at a temperature of -56.5°C. As a result of experimental works, basic laws governing the boring and reaming processes in multicomponent hybrid stacks composed by carbon-fibre-reinforced plastics with titanium and aluminium alloys were investigated.

Keywords: reaming, reamer, carbon fiber, hybrid stack, titanium alloy, ANOVA
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МАШИНОСТРОЕНИЕ И МАШИНОВЕДЕНИЕ

Научная статья
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Оптимизация процесса чистовой обработки отверстий в многокомпонентных пакетах из углепластиков и металлических сплавов

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Резюме. Цель – оптимизация технологии обработки отверстий в смешанных пакетах, содержащих слои композиционного материала, титанового и алюминиевого сплавов. Исследование проводилось с помощью статистических подходов к планированию экспериментов и обработке результатов в программе Statistica 6, а также в приложении Microsoft Excel 2010. Измерение шероховатости отверстий производилось на контактном профилометре Taylor Hobson Form Talysurf i200. Высота нароста на режущей кромке инструмента исследовалась с помощью оптического профилометра Bruker ContourGT-K1, снятие параметров диаметров отверстий – на координатно-измерительной машине Carl Zeiss CONTURA G2. Экспериментальное исследование производилось с помощью сверлильной машины с автоматической подачей Atlas Copco PFD-1500 и сборной развертки MAPAL диаметром 14 мм. Разработана и реализована методика комплексного экспериментального исследования процесса получения отверстий в СП структуры «титановый сплав ОТ4 – титановый сплав ВТ6 – полимерные композиционные материалы – титановый сплав ВТ6 – алюминиевый сплав 1933». Установлено, что наиболее значимыми факторами среди исследованных, влияющих на параметры точности отверстия, в частности на отклонение профиля продольного сечения отверстия, являются скорость резания в первой и второй степени, а также подача. Оптимальными режимами резания для поставленной цели являются скорость резания – 7,24 м/мин, подача – 0,27 мм/об и припуск на обработку – 0,5 мм. Таким образом, время обработки одного отверстия на операции развертывания снижено в 4,6 раза. Показано, что оптимальным способом охлаждения, обеспечивающим повышение точности и снижение шероховатости поверхности отверстия в слое из алюминиевого сплава, является охлаждение углекислым газом с температурой -56,5°С. Таким образом, в результате выполнения экспериментальных работ были исследованы основные закономерности процесса обработки точных отверстий в многокомпонентных смешанных пакетах из углепластиков, титановых и алюминиевых сплавов, реализуемого в технологической последовательности «сверление – развертывание».

Ключевые слова: развертывание, развертка, углепластик, смешанный пакет, титановый сплав, дисперсионный анализ

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INTRODUCTION

In modern mechanical engineering, existing materials begin to approach the limit of design possibilities. Therefore, it is important to search for and introduce materials with higher mechanical properties. In this study, we investigate polymeric composite materials (PCM) [1, 2]. The application of PCM allows the weight of the finished product to be reduced, which subsequently decrease the product operational costs. It is practically impossible to completely abandon classical materials in highly loaded assemblies; therefore, metal alloys are used for such purposes. The so-called hybrid stack (HS) is formed at the points of connecting dissimilar materials. HS represents a combination of composite materials with metal alloys. Bolted joints are typically used to connect dissimilar materials [3–5]. Since the reliability of such joints depends on the bore quality [6–8], the achievement of accurate bores [9–11] in dissimilar materials appears to be a priority.

MATERIALS AND METHODS

The object of the study was a five-layer HS (fig. 1) containing a composite material interlayered with titanium and aluminium alloys.

The HS machining [12, 13] was carried out from the OT4 side, which is determined by the presence of one-sided approach to the stack in the real product. Bore requirements: a diameter of 14 mm; a diameter allowance of IT9; the upper roughness allowance limit (Ra) for metal alloy and PCM layers of 1.6 and 6.3 μm, respectively [14–17].

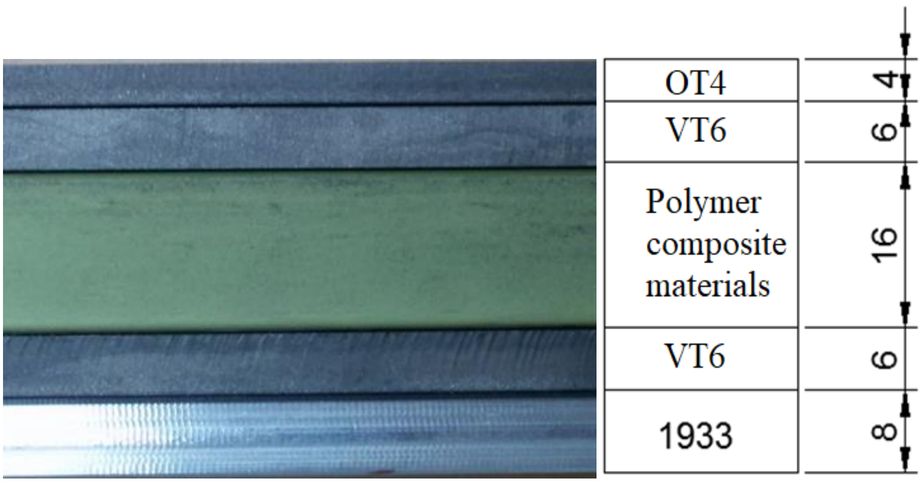

Fig. 1. Hybrid stack
Рис. 1. Смешанный пакет

Study tool. The cutting tool [18–20] used in the study was a 14 mm replaceable-head MAPAL reamer. The cutting part of the replaceable head consists of six brazed carbide tips. The cooling channel is directed to the front surface of each tip. The cutting tool is shown in fig. 2.

The use of a replaceable-head reamer is justified by the reduction in tool costs, as well as the need to remove the tool for investigating the built-up formation at the cutting edge. This design ensures quick installation and deinstallation and reduces the installation error.

***Measurement equipment*.** In order to study the diameters of the reamed bores, a Carl Zeiss contura G2 coordinate measuring machine was used. The bore roughness was measured by a Taylor Hobson Form Talysurf i200 contact profilometer. A FLIR SC7000 thermal camera was applied for recording the temperature in the cutting area.

***Testing procedure*.** In order to determine cutting modes ensuring the highest reaming performance and required quality indicators of bores, multicriteria optimisation was applied to establish the degree of the effect caused by technological factors on the parameters of the bore in the considered HS. These factors include cutting modes, allowance, cooling method, and hybrid stack composition.

The study was conducted using the three-level composite design with two main and one block factor. The main factors involve machining modes of feed and cutting speed with the reaming allowance selected in terms of a block factor. The choice of these factors is justified by their influence on the bore parameters, which is confirmed by the work performed in a related field.

The composite design is non-full factorial, which means using fewer experiments than necessary for testing all the studied modes. This approach appears to be relevant for machining studies, since an increase in the number of work cycles leads to an increase in the cutting tool wear, thus affecting the obtained results.

The allowance levels of the main factors in the regression model describing the effect of the cutting process parameters on the bore quality are provided in tab. 1.

Table 1. Allowance levels of the main factors
Таблица 1. Уровни варьирования главных факторов

Factor	Level -1	Level 0	Level +1
Cutting speed, V, m/min	6.1	11.8	17.5
Feed, S, mm/rev	0.16	0.27	0.38

The block factor characterises the reaming allowance Z. The values of the block factor are given in tab. 2.

Table 2. Allowance levels of the block factor
Таблица 2. Уровни варьирования блокового фактора

Block	Level 1	Level 2
Block: reaming allowance, Z, mm	0.1	0.5

Fig. 2. MAPAL replacebale-head reamer (Ø14 mm)
Рис. 2. Режущий инструмент MAPAL (Ø14 мм)

In order to investigate the influence of the cutting area cooling method and the composition of adjacent layers in the hybrid stack on the parameters of the bore in the aluminium alloy layer during reaming, a full Box-Behnken factorial design with two main factors was selected. In terms of these factors, discrete variables, represented by the method of cooling the cutting area and the hybrid stack composition, were used.

The allowance levels of the factors in the 3-level full Box-Behnken factorial design are provided in tab. 3.

Table 3. Factor allowance levels
Таблица 3. Уровни варьирования факторов

Factor	Level -1	Level 0	Level +1
Cutting area cooling method	no cooling	air cooling	-56.5°C carbon dioxide cooling
Composition of the studied object	Ti/Al	PCM/Al	Al

RESULTS

Let us consider the expression for optimising the process of reaming the HS of the "OT4 titanium alloy – VT6 titanium alloy – PCM – VT6 titanium alloy – 1933 aluminium alloy" structure.

The optimisation task of the reaming process in terms of performance consists in the minimisation of the cutting time. The cutting time is calculated by the formula:

$$T_C = \frac{(l + l_p + l_o)\pi d}{1000sv},$$

where *l* – the thickness of the object, where the through bore is formed; $l_p + l_o$ – the tool penetration length and overtravel at the end of cutting; *d* – the tool diameter; *s* – the feed; *v* – the cutting speed. In this study, the sum of the penetration length and overtravel is assumed to be 5 mm.

In this regard, it is necessary to select the advanced cutting modes providing the surface roughness within the range of allowed values. In order to solve this problem, let us determine the most efficient cutting modes by establishing the desirability levels of response functions. For the optimisation in terms of performance, the desirability for the lower and average values of the studied parameters is taken equal to one, while the upper value desirability is zero (except for the "cutting time" parameter describing the process performance). Therefore, the desirability values linearly decreasing with the increase in the cutting time are selected. Using this method, the cutting modes both ensuring the optimum values of the bore accuracy and having high performance were determined.

The highest desirability value was established corresponding to the values of the V = 7.24 m/min cutting speed, S = 0.27 mm/rev feed, and the reaming allowance of z = 0.5 mm. In the above modes, the correspondence of maximum performance (1.01 min cutting time) with the required parameters of the bore accuracy is achieved: the IT9 deviation of diameters from 14 mm is in the limits of 43 μm, the roughness of the bore surface for metallic material layers is under 1.6 μm, Ra = 6.3 is used for the composite material layers.

In order to increase the requirements for the parameters of the bore surface roughness, let us take the desirability equal to 0.5 for the average value levels. Since the optimisation in this case is aimed at improving the quality, the "cutting time" parameter is the exception and the desirability is set the same at all levels.

The highest desirability value was established corresponding to the values of the V = 6.1 m/min cutting speed, S = 0.22 mm/rev feed, and the reaming allowance of z = 0.5 mm.

In these modes, the maximum bore quality is achieved, while the response value of roughness and deviation from the true longitudinal section profile are decreased (tab. 4). However, the performance decreases due to the increased to 1.5 min cutting time of the reaming operation.

During the optimisation of the cutting area cooling methods and the composition of the hybrid stack in terms of surface quality and bore reaming accuracy, the desirability of a response at the upper, average, and lower levels was set equal to 1, 0.5 and 0, respectively, for obtaining maximum accuracy. The maximum desirability corresponds to the lower levels of response values.

The greatest desirability value corresponds both to the method of cooling (cooling by carbon dioxide with the temperature of -56.5°C) and the PCM/1933 composition of the hybrid stack. Although the use of these machined material combinations is not always possible, they should be preferred in the case of possible changes in the product design.

Tab. 4 represents factor combinations ensuring the maximum quality of machined bores.

Fig. 3 shows a histogram of the desirability function.

Table 4. Combination of factors ensuring the maximum quality of machined bores
Таблица 4. Сочетание факторов, обеспечивающих максимум по качеству обработанных отверстий

Desirability	Factors and levels	Response	Response value
0.57	Cooling method: carbon dioxide (-56.5°C) Hybrid stack composition: PCM/1933	shape accuracy	10.47 μm
		Ra in 1933 layer	0.64 μm
		Rz in 1933 layer	3.42 μm
		Temperature	-15°C

Fig. 3 shows that the minimum level of desirability corresponds to the VT6/1933 combination during the machining both with and without air cooling. Therefore, this material combination should be avoided in the product design. When other material combinations are impossible, preference should be given to the selection of the most effective method of cooling the cutting area, i.e., the carbon dioxide cooling at a temperature of -56.5°C. The PCM/1933 combinations have desirability values insignificantly differing from those provided by cutting area cooling methods. A similar situation is observed during machining of the aluminium alloy layer only.

CONCLUSION

As a result of experimental works, basic laws governing the process of precise boring and reaming in multicomponent hybrid stacks made of carbon-fibre-reinforced plastics with titanium and aluminium alloys were investigated. The following theoretical conclusions and practical results were obtained:

1. A methodology for a comprehensive experimental study of the boring process in the HS of the “OT4 titanium alloy – VT6 titanium alloy – PCM – VT6 titanium alloy – 1933 aluminium alloy” structure was developed and implemented. The developed methodology is aimed at elucidating the technological possibilities of the reaming operation.

2. In order to determine the optimum combination of technological parameters of the bore reaming in HS, including cutting modes and machining allowance ensuring the required values of the roughness and bore accuracy, a methodology for investigating the process using the probabilistic method was applied on the basis of design experiment and multifactorial variance analysis.

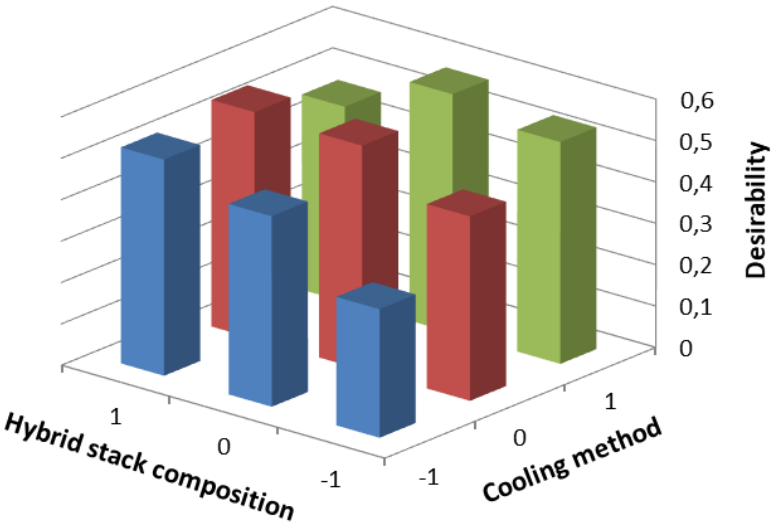

Fig. 3. Desirability function histogram (see tab. 4).
Рис. 3. Гистограмма функции желательности (см. табл. 4)

3. According to the obtained results, the task of increasing the performance, surface quality and bore accuracy in the studied stacks was solved by selecting the optimum cutting modes during reaming. The most significant factors, affecting the parameters of the bore accuracy, in particular the deviation of the bore longitudinal section profile, include the cutting speed in the first and the second degree, as well as the feed. The optimum cutting modes are a cutting speed of 7.24 m/min, a feed of 0.27 mm/rev, and a machining allowance of 0.5 mm. Thus, the time of reaming one bore is reduced by 4.6 times.

4. During the process of reaming the studied HS, the major technological problems arise during the machining of the aluminium alloy layer. These problems are related to the effect of the HS composition and the cooling method. These factors were investigated using the full factorial Box-Behnken design. The dependence of the roughness and accuracy of bores in the aluminium alloy layer on cutting area cooling methods and the HS composition was determined.

5. On the basis of the obtained results, the task of optimising the surface quality and accuracy of bores in the aluminium alloy layer was solved by selecting the optimum methods of cooling the cutting area and HS composition. The best cooling method improving the accuracy and reducing the surface roughness of the bores in the aluminium alloy layer was established to be the cooling with carbon dioxide at a temperature of -56.5°C.

6. Recommendations are formulated for the design of hybrid stacks, containing carbon-fibre-reinforced plastics interlayered with aluminium and titanium alloys. In order to achieve optimal parameters of the obtained bores in terms of accuracy and surface roughness, the aluminium alloy layer should be located after the carbon-fibre-reinforced plastic layer (in the machining direction) and the location of this layer after the titanium layer should be avoided.

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The author performed the research, made a generalization on the basis of the results obtained and prepared the copyright for publication.

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