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A study of the relationship between cutting force and machined surface roughness with the feed per tooth when milling EuTroLoy 16604 material produced by the DMD method

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ABSTRACT

Introduction. Currently, a substantial proportion of the machine-building industry is made up of one-off products or products manufactured in small batches. In this regard, innovative approaches to obtaining such products are being actively applied in order to reduce the cost of special, expensive tooling of the blanking process. Such technologies include the *Direct Metal Deposition* (*DMD*) method, the essence of which is the deposition of metal particles from a gas-powder stream. This method has a lot of advantages, but one of the main drawbacks is that the products after growing have a rough surface and do not meet the accuracy requirements of the finished part drawing. Consequently, the parts require further machining by cutting. However, due to the novelty of the materials, there are no regime parameters for machining. In this regard, the aim of the work is to establish the functional relationship between the cutting force and roughness of the machined surface with the feed per tooth during end milling of *EuTroLoy 16604* material formed by *DMD*-method. In this paper an experimental study of cutting force and roughness of machined surface with varying the tooth feed during end milling is carried out. **The research method** is an experiment on milling of *EuTroLoy 16604* material obtained by *DMD*-method with measuring the output parameters of the process (cutting force and roughness of the machined surface). **Results and discussion**. The measured values of cutting force and roughness of the machined surface allowed establishing functional and graphical dependences of the output parameters of the milling process on the feed per tooth. It is found that using a cutter with a smaller clearance angle results in lower cutting forces and the surface has a lower height of microroughness. Thus, the developed functional relationships of cutting force and roughness of the machined surface with the feed per tooth allow predicting the output parameters of the cutting process and increasing the efficiency of machining operations by cutting. A promising direction for further work is seen in the study of relative machinability and evaluation of its quantitative value.

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Introduction

The fabrication of one-off products or small batches is a distinctive feature of the machine-building industry [1]. Innovative technologies are used to produce such products and the creation of complex-shaped parts is currently one of the most rapidly developing fabrication technologies [2]. Direct Metal Deposition (*DMD*), a method of local metal deposition, relates to these technologies. In this method, a laser beam generates a molten pool into which a metal powder is injected [3], resulting in the powder being melted with the substrate material to create a strong bond.

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DMD increases material utilization because the final product is manufactured by adding the desired amount of material rather than removing it from a solid workpiece; local deposition of material is possible. This method is widely used for coating and the restoration of worn surfaces with powders [4–6].

However, *DMD* is associated with producing surfaces that do not fully meet the functional requirements [7–10]. Thus, subsequent machining is required. Since *DMD* is not used in mass production, there are no references for cutting modes for its processing. Most companies machine grown items, selecting suitable cutting modes and cutting tools by trial and error. However, such processing is not effective due to material consumption. Theoretical and experimental testing is required to establish the relationship between the operating parameters and output parameters of the cut. Research data enables the development of a base of recommendations for assigning rational modes of machining *DMD*-materials.

A large number of studies report the characteristics of machining new materials [11-13] and show that the mechanical engineering industry is interested in these materials for the production of parts with the necessary properties. An experimental study of the machinability of *Al*/*SiC*-*MMC* was conducted in [14]. The influence of cutting depth, feed, and cutting speed on the roughness of the machined surface and the cutting force were analyzed. The data established the relationships between these factors, and showed its influence on cutting tool wear. The results enable the selection of suitable values for the feed, cutting speed, and the depth of cut to meet the functional requirements.

Eun-Jung Kim et al. [10] conducted an experimental study on the machining of *304L* stainless steel. Numerical values of the cutting force and surface roughness were determined to establish the machinability of the material. An experimental model of the relationship between machined surface roughness and cutting modes (spindle speed and feed rate) in turning *DMD*-produced *VT6* titanium alloy was developed in [15]. The milling of *IN718* material samples produced using additive technologies are presented in [16–18]. Thus, cutting force, cutting tool wear, surface roughness, and residual stresses under different technological conditions were analyzed.

Machinability and the machining process of deposited materials were studied to form a regulatory base for cutting modes. Such data will improve the efficiency of machining operations, which is relevant to the mechanical engineering industry.

The purpose of this study is to identify the functional relationship between the cutting force and machined-surface roughness and the feed per tooth during the end milling of *DMD*-produced *EuTroLoy 16604* to improve the efficiency of machining operations.

In the furtherance of this goal two steps were taken.

– an experimental study of the machinability of milling *EuTroLoy 16604* by end mills at different cutting angles, measuring the cutting force and the roughness of the machined surface, was conducted.

– mathematical models of the relationship between cutting force and machined surface roughness and feed per tooth were constructed.

Research Methodology

The sample for the study is a layer of *EuTroLoy 16604* powder deposited on a steel plate using *DMD* (Fig. 1). The layer was deposited in the research laboratory of mechanics, laser processes, and digital production technologies at the South Ural State University using the *FL-Clad-R-4* laser cladding complex [19]. The substrate is a plate of structural fine carbon *Steel 45* (0.45% C).

Deposition modes: laser power – 1,600 W; laser scanning speed – 10 mm/s; powder flow rate – 10.5 g/min; scan step – 1.4 mm.

The chemical composition and the size of the powder main fraction are given in Table 1.

A microstructural examination of the deposited layer was performed using a *JEOL JSM 7001-F* scanning electron microscope with an *X-Max-80 Oxford Instruments* X-ray fluorescence energy dispersive analyzer. Thee indentations of the sample were made to measure the microhardness in the depth of the deposited layer using a *HV-1000* microhardness tester.

Fig. 1. A sample of deposited material

Table 1

Chemical composition and the size of the powder main fraction

Chemical element				The powder main fraction size, μm
Fe	*Co*	*Cr*	*Mo*	
Concentration, at. %				
68	15	15	2	40 – 120

The machining was out on a *CNC* milling machine model *GF2171S5*. For milling the sample, end mills with a diameter of 8 mm made of *R6M5* (*HSS-G*) material were used. The cutters with 13º and 19º clearance angles in the end section were used to compare the output parameters of the cutting process. Structurally, in most cases, end mills are made with clearance angles, the value of which varies from 13º to 19º. The boundary values of the angles were selected for the experimental study. Guided by the regulatory reference book for the processing of stainless steels [20], the corresponding technological parameters of the milling process were selected. The technological parameters of the experiment, including the characteristics of the cutting tool, are presented in Table 2.

To measure the cutting force, a *Kistler 9257B* dynamometer was used, on which a plate with a deposited material was installed and fixed with screws. The processing of experimental data was carried out using *DynoWare* software. The machined surface roughness was measured by a contact profilometer model 130 with an accuracy degree 1 according to GOST 19300 – 86. Single-factor regression analysis was used to develop mathematical models of the relationship between the machined surface roughness and the cutting force with the feed per tooth.

Table 2

Technological parameters

Feed per tooth S_z, mm/tooth	Spindle speed *n*, rpm	Cutting depth *t*, mm	Cutting tool diameter *D*, mm	Cutting tool material
0.01	1,000	0.5	8	*HSS M2*
0.02				
0.03				
0.04				

Results and discussion

Properties of the deposited layer

The thickness of the deposited layer was determined using a *JEOL JSM 7001-F* scanning electron microscope and an *X-Max-80 Oxford Instruments* X-ray fluorescence energy dispersive analyzer (Figure 2).

Thickness of the deposited layer varies from 1.36 mm to 1.51 mm and a homogeneous structure with insignificant nonmetallic inclusions in the substrate is observed.

The homogeneity of the deposited layer is proven by changes in the microhardness at different depths. The results of microhardness measurements are provided in Figure 3.

Cutting force component

The operating values of the cutting force were recorded with a signal frequency of 0.1 second. The data were converted in *DynoWare* and the array of the numerical values of the cutting force was processed in *MS Excel*. Graphs of the cutting force component F_{yz} were drawn using built-in functions.

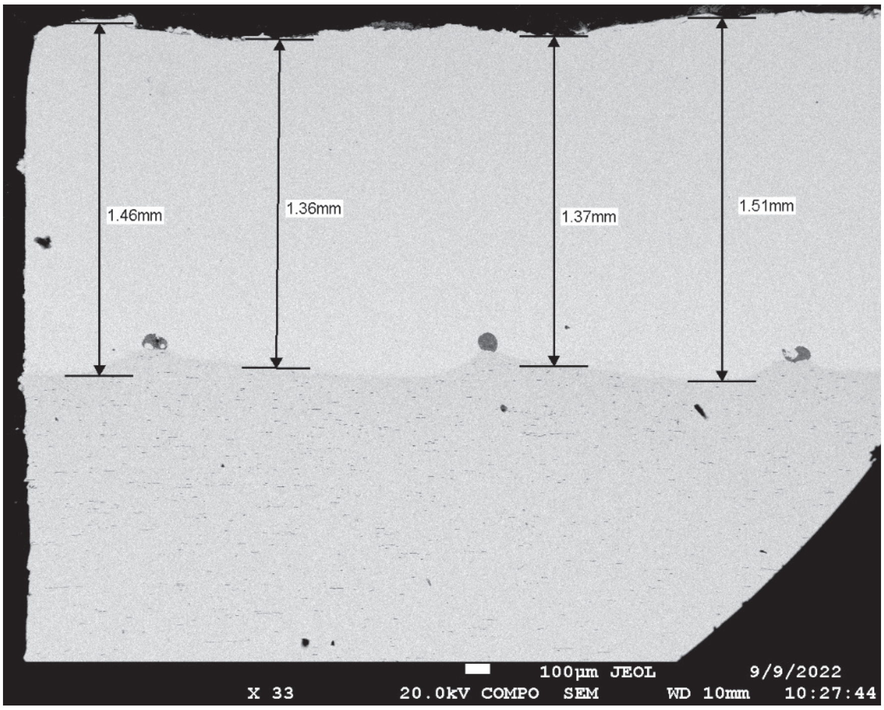

Fig. 2. Thickness of the deposited layer

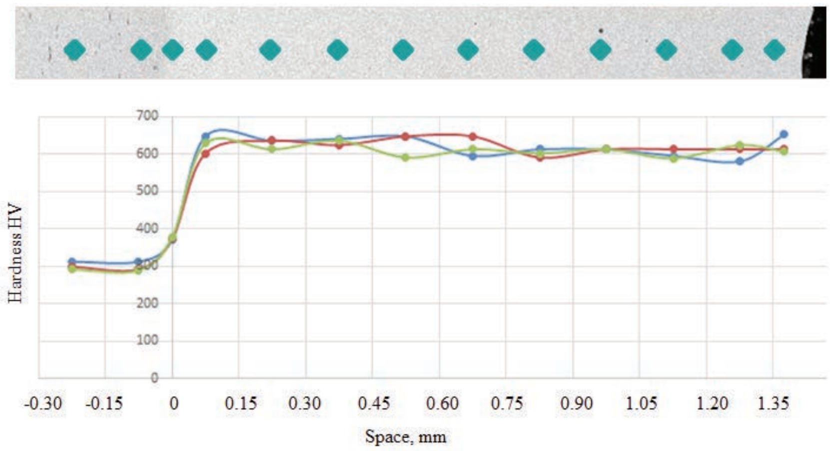

Fig. 3. Microhardness of the deposited layer

Figures 4–7 show graphs of the cutting force component F_{yz} for feeds (S_z) of 0.01 – 0.04, respectively, used in the bending analysis of the cutter. F_{yz} was calculated from the F_y and F_z components.

Cutting was done perpendicular to the laser scanning direction to determine the maximum values of the cutting force arising from blows, i.e., the most unfavorable conditions were chosen for the study. As a consequence, peaks and valleys in the cutting force values are observed in the graphs. The cutting force peaks are in the middle of the weld bead, and the valleys correspond to the positions between the weld beads. To avoid differences in the cutting force results and to give a homogeneous change, machining should be done in the scanning direction. The graphs also show that an increase in the feed leads to an increase in cutting force. Similar results were obtained in [21].

A regression analysis was performed to establish the functional dependence of the cutting force component and the feed per tooth. For this purpose, the five maximum values were selected for each feed. The values of the cutting force component are presented in Table 3.

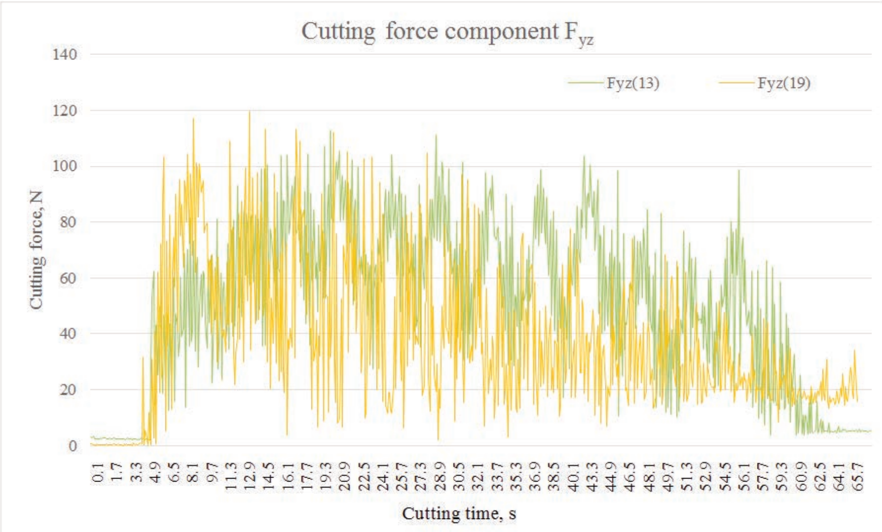

Fig. 4. Graphs of the cutting force component (S_z = 0.01 mm/tooth)

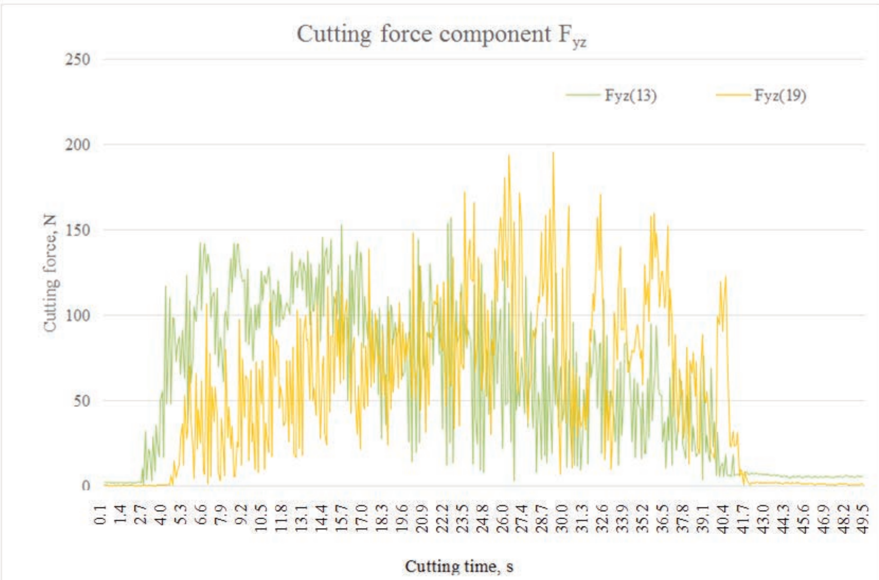

Fig. 5. Graphs of the cutting force component (S_z = 0.02 mm/tooth)

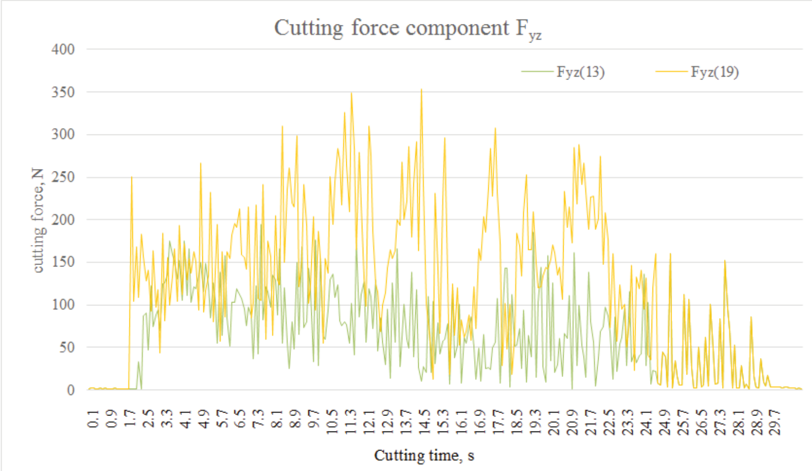

Fig. 6. Graphs of the cutting force component (S_z = 0.03 mm/tooth)

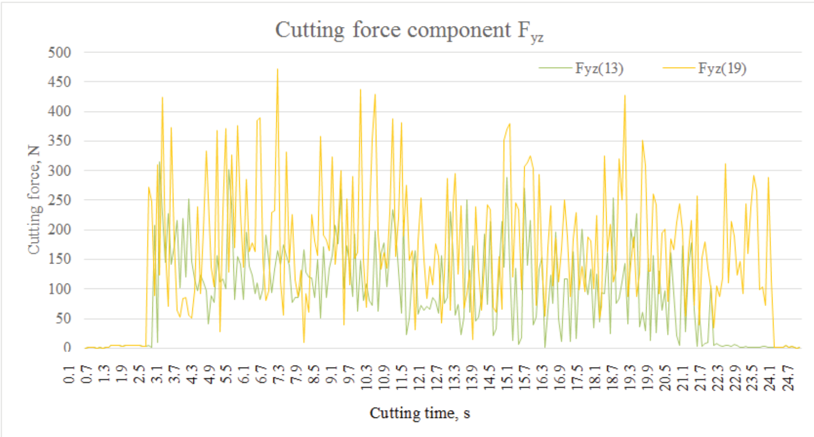

Fig. 7. Graphs of the cutting force component (S_z = 0.04 mm/tooth)

Table 3

Maximum values of the cutting force component

Cutting tool with a 13º clearance angle					
Feed per tooth S_z, mm/tooth	Cutting force component F_{yz}, N				
	Point No.				
	1	2	3	4	5
0.01	113.06	111.27	104.05	107.25	104.55
0.02	153	144.75	154.15	157.56	145.94
0.03	194.89	176.16	174.54	184.99	174.6
0.04	315.98	302.59	269.06	289.36	270.28
Cutting tool with a 19º clearance angle					
Feed per tooth S_z, mm/tooth	Cutting force component F_{yz}, N				
	Point No.				
	1	2	3	4	5
0.01	117.13	119.47	112.35	113.37	113.29
0.02	193.84	196.16	181.03	172.08	172.18
0.03	325.85	348.92	353.08	309.75	309.92
0.04	423.67	471.75	437.13	428.62	427.28

The results of regression analysis provided us with graphical dependences (Fig. 8) and power functional dependences of the cutting force component F_{yz} on the feed per tooth S_z for the tool with clearance angles of 13º and 19º, respectively:

$$F_{yz} = 2037.49 S_z^{0.65}, \tag{1}$$

$$F_{yz} = 9820.20 S_z^{0.98}. \tag{2}$$

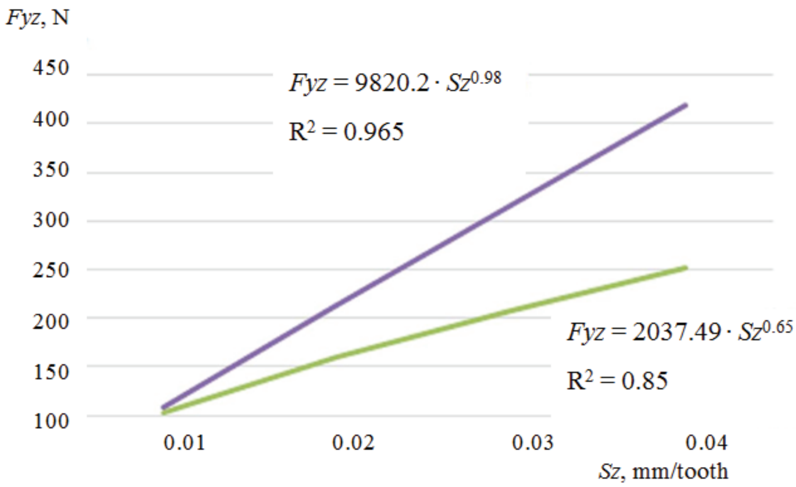

Fig. 8. Dependences of the cutting force component F_{yz} on the feed per tooth S_z

Machined surface roughness

Measurements of the machined surface roughness were made five times for each feed; the results are presented in Table 4. From the data, it can be seen that an increase in the feed per tooth leads to an increase in roughness. The machined surface roughness is higher at small feeds for the tool with a large clearance angle.

To establish the dependence of the machined surface roughness on the tooth feed, a regression analysis was carried out, which made it possible to obtained graphic (Fig. 9) and power functional dependences of the machined surface roughness R_a on the feed S_z for the tool with clearance angles of 13º and 19º, respectively:

$$Ra = 93.94 S_z^{1.019}, \tag{3}$$

$$Ra = 41.85 S_z^{0.75}. \tag{4}$$

The use of the dependencies enables to predict the output parameters of the machining process when varying the feed per tooth.

Conclusions

The obtained mathematical models of the relationship between the cutting force (1), (2) and the roughness of the machined surface (3), (4) with the feed per tooth have the form of power-law dependence. The use of these models enables to predict the machined surface roughness and the cutting force while cutting the *DMD*-produced material under the given conditions.

Table 4

Roughness of the machined surface

Cutting tool with a 13º clearance angle					
Feed per tooth S_z, mm/tooth	Roughness of the machined surface Ra, µm				
	Point No.				
	1	2	3	4	5
0.01	0.91	0.92	0.89	0.98	0.89
0.02	1.58	1.44	1.76	1.53	1.79
0.03	2.42	2.35	2.42	2.23	2.32
0.04	4.01	3.98	4.11	4.13	3.94
Cutting tool with a 19º clearance angle					
Feed per tooth S_z, mm/tooth	Roughness of the machined surface Ra, µm				
	Point No.				
	1	2	3	4	5
0.01	1.44	1.43	1.45	1.46	1.40
0.02	1.75	1.78	1.74	1.80	1.74
0.03	3.11	3.33	3.12	3.14	3.21
0.04	3.93	4.11	3.85	3.95	3.81

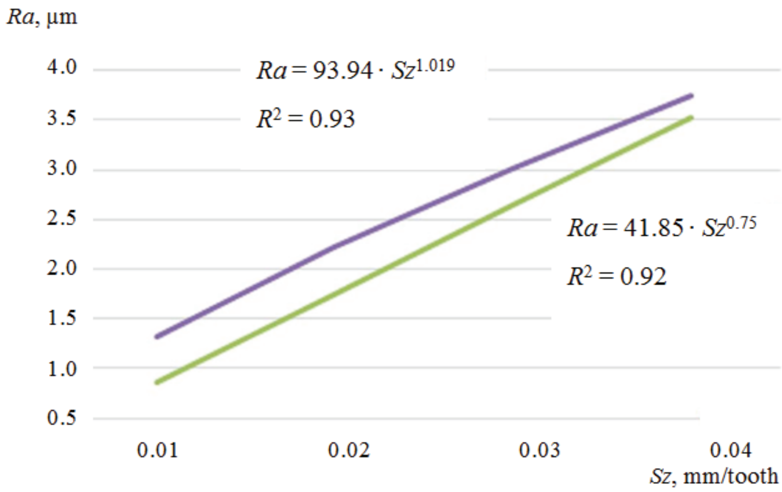

Fig. 9. Dependences of the machined surface roughness *Ra* on the feed per tooth *Sz*

The measured cutting forces allowed to establish that the maximum values of cutting force range from 113.16 to 315.98 N and from 119.47 to 471.75 N for cutting with clearance angles of 13° and 19° when changing feed from 0.01 to 0.04 mm/tooth respectively; machined surface roughness ranges from 0.89 to 4.13 µm and from 1.4 to 4.11 µm for the first and second tool respectively.

At low feed rates, there is a noticeable difference in the machined surface roughness; hence, it can be assumed that cutters with a smaller clearance angle should be used at the finishing stage of machining.

Further research on different factors of the cutting process is planned. The base formed as a result of this and future studies will allow the rational assignment of cutting modes in the machining of deposited materials, which will increase the efficiency of technological operation design.

The design of mechanical operations takes into account such basic criteria of machining quality as accuracy, which is influenced by cutting force, and roughness. As a consequence, it is necessary to build up a theoretical base on machinability of *DMD*-produced materials.

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Conflicts of Interest

The authors declare no conflict of interest.