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RESEARCH OF THE MILLING PROCESS OF A CYLINDRICAL SURFACE BY AN ORIENTED INSTRUMENT

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Abstract. The object of this study is the milling process of a cylindrical surface using a tool whose axis intersects the axis of the workpiece. During the research, generalized modular three-dimensional models were applied to describe the tool surface, material removal, and the formation of the cylindrical surface. These models are based on three unified modules: the tool module, the surface-forming module, and the orientation module. In addition, computer simulation methods were employed to construct a three-dimensional model of the milling process of a cylindrical surface using an oriented cutting tool. A graphical representation of the oriented milling process for a cylindrical surface was developed. A cylindrical surface-forming module of the tool was designed, described by the product of displacement matrices along the corresponding coordinate axes, as well as a model of the machined surface represented by the product of the tool radius vector and its orientation module within the shaft coordinate system. A distribution curve of the specific productivity of the milling process along the tooth profile of the tool was obtained for machining under intersecting axes of the cutter and the workpiece. Analysis of this curve demonstrated that milling with an oriented tool improves the accuracy of surface formation due to more uniform tool wear. The angle between the axes of the cylindrical surface and the tool was determined based on the condition of achieving maximum material removal while ensuring uniform loading of the end part of the milling cutter. For this purpose, a three-dimensional model of the milling process with intersecting axes of the tool and the workpiece was developed, in which rough milling is performed by the end face of the cutter, while

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finishing is carried out by its peripheral part. The study showed that during finishing milling, the rotation angle of the cutter should be selected to ensure full engagement of the peripheral cutting edges. An increase in machining efficiency is achieved through the intersection of the tool and workpiece axes, which enables programmable control of the intersection point and ensures uniform tool wear, thereby improving the quality of the machined surface. Additionally, the application of high-speed milling is considered a promising approach for further increasing process productivity.

Keywords: intersecting-axis milling, oriented milling cutter, modular three-dimensional modeling, intersection angle, cylindrical workpiece.

Annotatsiya. Mazkur tadqiqotning obyekti asbob o‘qi ishlov berilayotgan detal o‘qi bilan kesishadigan sharoitda silindrik sirtni frezalash jarayonidir. Tadqiqot davomida asbob sirtini, qo‘shimcha qatlamni olib tashlash jarayonini va silindrik sirtni shakllantirishni tavsiflash uchun umumlashtirilgan modulli uch o‘lchamli modellar qo‘llanildi. Ushbu modellar uchta unifikatsiyalangan modulga asoslangan: asbob moduli, shakllantirish moduli va orientatsiya moduli. Bundan tashqari, yo‘naltirilgan kesuvchi asbob yordamida silindrik sirtni frezalash jarayonining uch o‘lchamli modelini qurish uchun kompyuter modellashtirish usullaridan foydalanildi. Yo‘naltirilgan freza bilan silindrik sirtni frezalash jarayonining grafik sxemasi ishlab chiqildi. Asbobning silindrik sirtini shakllantirish moduli mos koordinata o‘qlari bo‘ylab siljish matritsalarining ko‘paytmasi orqali tavsiflandi, shuningdek, ishlov berilgan sirt modeli asbob radius-vektori va uning val koordinatalar tizimidagi orientatsiya modulining ko‘paytmasi sifatida ifodalandi. Freza va detal o‘qlari kesishgan holatda ishlov berishda frezalash jarayonining xususiy unumdorligining asbob tishi profili bo‘ylab taqsimlanish grafigi olindi. Ushbu grafik tahlili shuni ko‘rsatdiki, yo‘naltirilgan asbobdan foydalanish asbobning bir tekis yeyilishi hisobiga shakllantirish aniqligini oshirish imkonini beradi. Silindrik sirt va asbob o‘qlari orasidagi burchak frezaning uch qismi bir tekis yuklanishini ta’minlagan holda maksimal materialni olib tashlash sharti asosida aniqlandi. Shu maqsadda asbob va detal o‘qlari kesishgan holatda frezalash jarayonining uch o‘lchamli modeli ishlab chiqildi, bunda qo‘pol ishlov frezaning uch qismi orqali, yakuniy ishlov esa uning periferik qismi orqali amalga oshiriladi. Tadqiqot natijalariga ko‘ra, yakuniy frezalashda frezaning burilish burchagi uning periferik kesuvchi qirralari to‘liq yuklanishini ta’minlashi lozim. Ishlov berish samaradorligining oshishi asbob va detal o‘qlarining kesishishi hisobiga erishiladi, bu esa ularning kesishish nuqtasini dasturlash imkonini beradi hamda frezaning bir tekis yeyilishini ta’minlab, ishlov berilgan sirt sifatini yaxshilaydi. Bundan tashqari, yuqori tezlikda frezalash

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texnologiyasidan foydalanish jarayon unumdorligini oshirishning istiqbolli yo‘nalishi sifatida ko‘rib chiqiladi.

Kalit so‘zlar: o‘qlari kesishgan holda frezalash, yo‘naltirilgan freza, modulli uch o‘lchamli modellashtirish, kesishish burchagi, silindrik detal.

Аннотация. Объектом данного исследования является процесс фрезерования цилиндрической поверхности с использованием инструмента, ось которого пересекается с осью обрабатываемой детали. В ходе исследования применялись обобщённые модульные трёхмерные модели для описания поверхности инструмента, процессов снятия припуска и формообразования цилиндрической поверхности. Указанные модели основаны на трёх унифицированных модулях: инструментальном, модуле формообразования и модуле ориентации. Кроме того, использовались методы компьютерного моделирования для построения трёхмерной модели процесса фрезерования цилиндрической поверхности ориентированным инструментом. Разработана графическая схема процесса фрезерования цилиндрической поверхности ориентированной фрезой. Создан модуль формообразования цилиндрической поверхности инструмента, описываемый произведением матриц перемещений вдоль соответствующих координатных осей, а также модель обработанной поверхности, представленная произведением радиус-вектора инструмента и модуля его ориентации в системе координат вала. Получена кривая распределения удельной производительности процесса фрезерования вдоль профиля зуба инструмента при обработке со скрещёнными осями фрезы и детали. Анализ данной зависимости показал, что применение ориентированного инструмента способствует повышению точности формообразования за счёт более равномерного износа инструмента. Определён угол между осями цилиндрической поверхности и инструмента, который выбирается из условия обеспечения максимального съёма материала при равномерной нагрузке торцевой части фрезы. С этой целью разработана трёхмерная модель процесса фрезерования со скрещёнными осями инструмента и детали, при котором черновая обработка осуществляется торцевой частью фрезы, а чистовая — её периферийной частью. Установлено, что при чистовом фрезеровании угол поворота фрезы должен обеспечивать полное нагружение периферийных режущих кромок. Повышение эффективности обработки достигается за счёт скрещивания осей инструмента и детали, что позволяет программно задавать точку их пересечения, а также за счёт равномерного износа фрезы, повышающего качество обработанной поверхности. Дополнительно отмечено, что

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применение высокоскоростного фрезерования является перспективным направлением для увеличения производительности процесса.

Ключевые слова: фрезерование со скрещёнными осями, ориентированная фреза, модульное трёхмерное моделирование, угол скрещивания, цилиндрическая деталь.

1. INTRODUCTION

Cylindrical components represent one of the most widespread categories of parts manufactured in mechanical engineering industries. For such components to meet technical specifications, their functionally significant surfaces must comply with strict requirements related to dimensional accuracy and surface quality. Milling is considered an efficient and highly productive machining method for the processing of cylindrical parts.

Investigating the milling process of cylindrical surfaces enables an increase in machining productivity while preserving the required accuracy and surface integrity. For instance, study [1] presents the results of machining cylindrical surfaces using a system of disk-type milling cutters. In work [2], a method for machining large-diameter cylindrical parts is proposed, in which two end mills with axes intersecting the axis of the workpiece are applied, combined with longitudinal feed motion along the workpiece axis. The characteristics of milling with intersecting axes between cylindrical parts and cutting tools were analyzed in [3]. Moreover, studies [4, 5] focused on various aspects of cylindrical surface milling processes.

Three-dimensional modeling approaches for different milling techniques were investigated in [6, 7], highlighting the effectiveness of spatial simulation in machining analysis. Consequently, the investigation of cylindrical surface milling using an oriented cutting tool remains a relevant and important research task. Therefore, the object of this study is the milling process involving intersecting axes of the cylindrical surface and the cutting tool. The aim of the research is to develop a three-dimensional model of cylindrical surface milling that employs both the end and peripheral parts of the cutter under conditions of crossed axes between the tool and the workpiece.

2. METHODS OF RESEARCH

The research methodology is based on the theoretical and practical findings presented in studies [8, 9]. A schematic representation of the milling process with intersecting axes between the milling cutter (1) and the shaft (2) is shown in Fig. 1.

To construct a three-dimensional model of the cutting tool surface, it is necessary to define a cylindrical surface-forming module. This module accounts for variations in the coordinate position along the cutting edge profile of the tool

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tooth, as well as changes in the tool rotation angle φ. The shaping module enables an accurate description of the spatial position of the tool surface during the milling process and forms the basis for further modeling of material removal and surface formation mechanisms.

$$\vec{R}_t = M^C_{Z_t,\alpha,R_t} \cdot \vec{e}_4, \quad (1)$$

where $\vec{R}_t$ is the radius vector corresponding to the points of the tool surface, $M^C_{Z_t,\alpha,R_t}$ denotes the cylindrical surface-forming module, and $\vec{e}_4$ represents the radius vector of the initial reference coordinate system coordinate [8].

The cylindrical surface-forming module of the cutting tool is expressed as a product of displacement matrices $M2$ and $M3$ acting along the Y_t and Z_t axes, together with the rotation matrix $M6$ describing rotation about the OZ_t axis:

$$M^C_{Z_t,\alpha,R_t} = M3(Z_t)\, M6(\alpha)\, M2(R_t). \quad (2)$$

Here, $Z_t = 0 \ldots H$ is the linear coordinate measured along the periphery of the tool tooth and varies from zero to the cutter width H, R_t is the outer radius of the cutting tool, and $\alpha = 0 \ldots 360°$ is the angular coordinate defined along the tool profile.

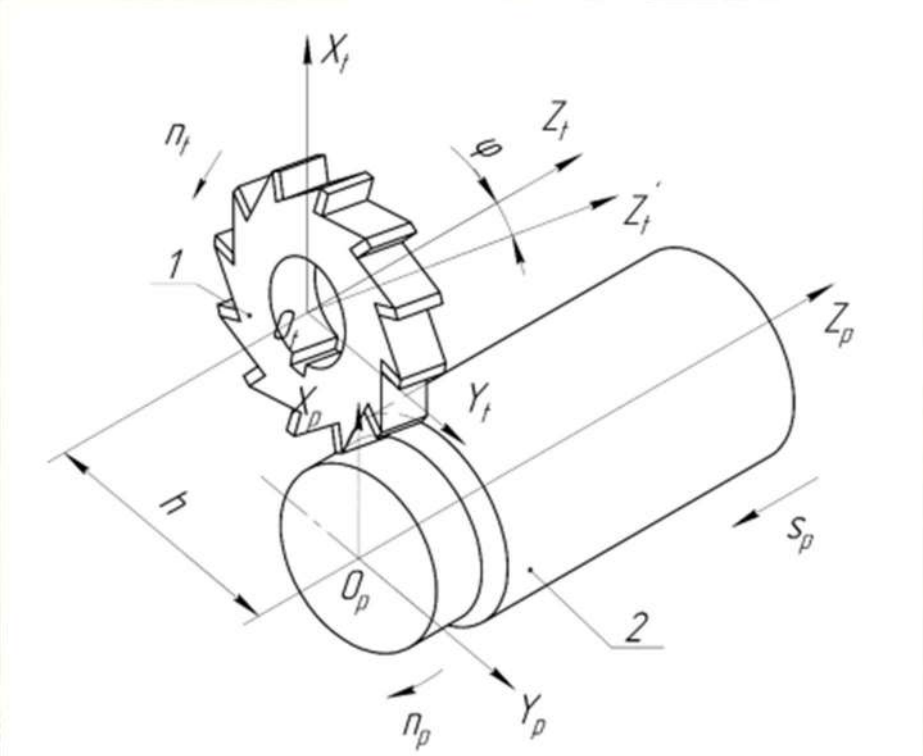


Fig. 1. Scheme of milling a cylindrical surface with an oriented tool: 1 – mill; 2 – shaft

The product of the radius vector of the tool and its orientation module in the shaft coordinate system, as well as the part shaping module, have a machined part surface:

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$$\bar{R}_p = M^C_{Z_p,\beta_p,h} \cdot M^S_{\alpha,\beta} \cdot \bar{R}_t = M3(Z_p)M6(\beta_p)M2(h)M4(\varphi)M5(\psi), \quad (3)$$

Where $M^C_{Z_p,\beta_p,h} = M3(Z_p)\, M6(\beta_p)\, M2(h)$ is the cylindrical module describing the relative motion of the cutting tool with respect to the workpiece; Z_p denotes the feed of the part along the axis OZ_p; β_p is the rotation angle of the workpiece; h represents the center distance between the tool and the shaft. The spherical orientation module of the tool in the coordinate system of the workpiece is defined as $M^S_{\alpha,\beta} = M4(\varphi)\, M5(\psi)$, where φ is the intersection angle between the axes of the cutter and the workpiece, and ψ is the rotation angle of the tool in the coordinate system of the shaft [8, 9].

Using equation (1) and (2), the cylindrical surface obtained during machining with an oriented cutting tool can be described by the following relation:

$$\bar{R}_p = M^C_{Z_p,\beta_p,h} \cdot M^S_{\alpha,\beta} \cdot M^C_{Z_t,\alpha,R_t} \cdot \vec{e}_4. \quad (4)$$

The condition of contact between the cutter profile and the workpiece surface at various time [3] is applied to determine the profile of the machined shaft. A modular three-dimensional representation of the tool surface $\bar{R}_t$ (equation (1)) is further employed to evaluate the specific processing productivity Q:

$$Q = \int_{\alpha_1}^{\alpha_2} V_n \cdot R_t \, d\alpha. \quad (5)$$

where V_n denotes the projection of the relative velocity vector of the milling cutter onto the direction normal to its surface; α_{t1} and α_{t2} are the angular coordinates measured along the profile of the cutting tool. The distribution of the specific processing productivity Q along the cutter tooth profile during machining with an oriented tool is illustrated in Fig. 2. n the diagram (Fig. 2), the interval from i_{end} to i_{st} corresponds to the end part of the milling cutter, where i_{st} begins at the peripheral section of the tool. In this zone, the removal of the rough allowance is performed by the end face of the cutter tooth, whereas the finishing allowance is removed by the peripheral cutting edges. It is observed that the value of the specific processing productivity Q decreases in the direction from i_{end} to i_{st} and then remains at relatively low levels. Consequently, milling a cylindrical surface with an oriented tool ensures high forming accuracy due to reduced wear of the peripheral sections of the cutter teeth during finishing operations. Accordingly, rough machining of cylindrical surfaces using an oriented milling cutter is advisable to carry out with the end face of the tool, while finishing should be performed by the peripheral part. This machining strategy guarantees the required surface quality and dimensional accuracy of the processed parts. To achieve the maximum possible material removal while maintaining uniform loading of the end

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face of the cutter during rough milling of a cylindrical surface, the tool must be rotated relative to the workpiece by an angle φ, which is defined as follows:

$$\varphi = 2s_p \sqrt{\frac{(R_p + r_z)^2}{4(r_z + m)^2 R_p^2 - \left[2r_z(R_p - m) - m^2\right]^2}}, \quad (6)$$

where m is the machining allowance [9]; s_p denotes the longitudinal feed of the workpiece; r_z is the radius of the workpiece. During finishing operations, the milling cutter must be oriented relative to the workpiece at such an angle that the terminal point i_{end} of the curvature radius r of the cutter tooth is positioned on the radius r_z of the workpiece (Fig. 3).

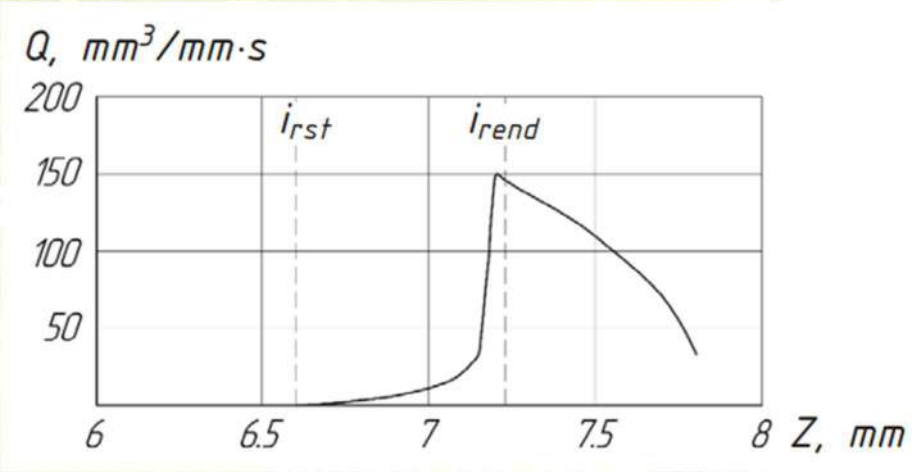


Fig. 2. Distribution of specific processing productivity along the tooth profile of the tool

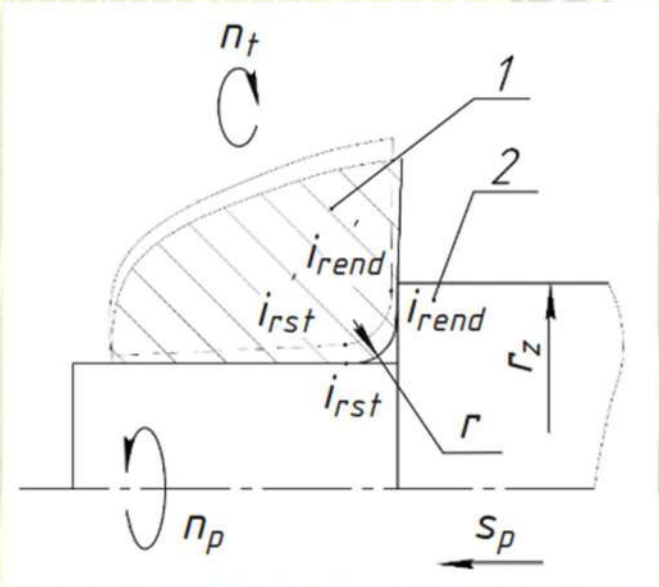


Fig. 3. The scheme for determining the orientation angle of the tool relative to the part: 1 – mill; 2 – workpiece

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This placement of the tool will provide the condition for a full load of the peripheral section of the cutter during finishing of parts. This will contribute to an even distribution of forces and wear of the cutter teeth.

3. RESEARCH RESULTS AND DISCUSSION

Using the results of studies in [10], a three-dimensional model of the process of milling a cylindrical surface 2 (Fig. 4) with an oriented tooth of a mill 1 in the form of a tetrahedral plate is created. The universal software ABAQUS is used to create this model. The finite element mesh is applied using the Mesh module. The shape of the elements is chosen hexahedral. The resulting stress distribution model makes it possible to analyze the state of the surface layer of the part in the process of milling with an oriented tool. So, according to Fig. 4, the highest stress values (4390 MPa) fall on the insertion zone of the cutting insert into the part, and when approaching the periphery of the tool they decrease (295 MPa).

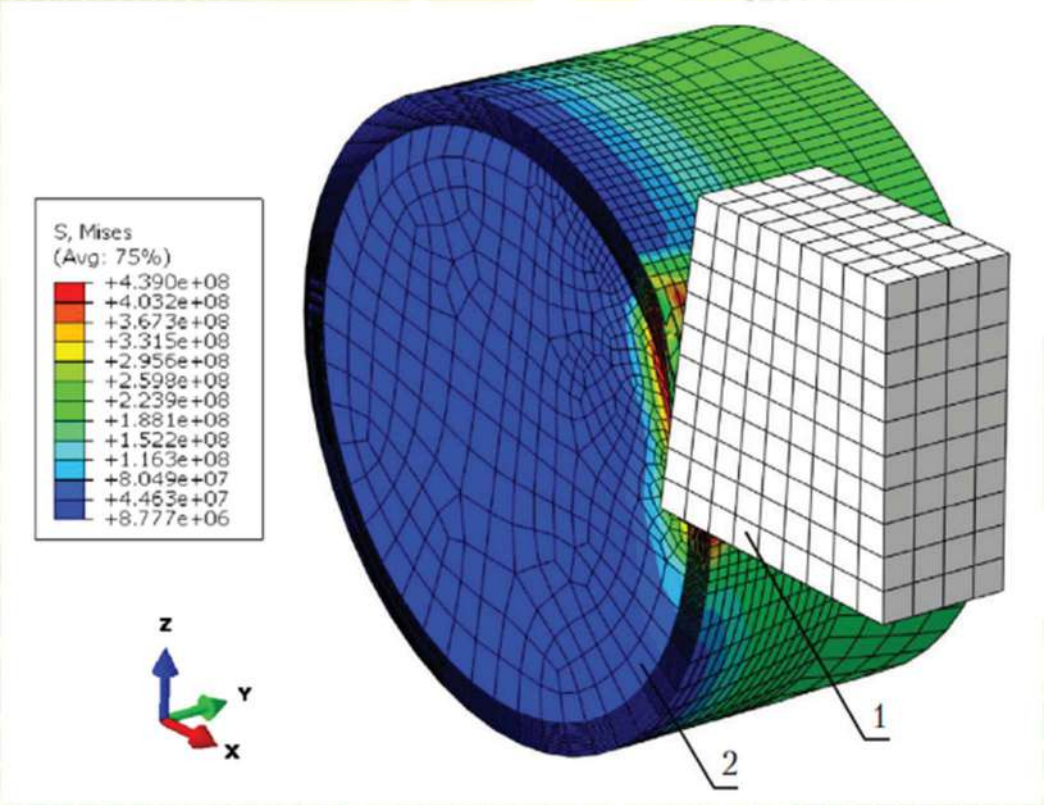


Fig. 4. Three-dimensional model of the process of milling a cylindrical surface with an oriented tool: 1 – oriented mill tooth; 2 – processed shaft

During the milling of a cylindrical surface under conditions of intersecting tool axes, the end face of the cutter tooth is used to remove the rough machining allowance, whereas the peripheral cutting edges perform the removal of the finishing allowance and ensure the final formation of the workpiece surface. Such a functional separation of the stock removal process leads to improved machining productivity and enhanced forming accuracy, which is achieved as a result of uniform and minimal wear of the finishing section of the cutting tool (Fig. 2). The

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efficiency of the oriented milling process is influenced by factors such as the cutter width, the number of cutting inserts, and the material from which these inserts are manufactured. In this machining scheme, rough milling is performed using a cutter orientation angle determined by equation (6), which guarantees uniform loading of the end face of the tool and allows the maximum material allowance to be removed. Finishing milling, in turn, is carried out at a tool rotation angle that ensures full engagement of the peripheral cutting edges, thereby providing the required conditions for high-quality surface formation (Fig. 3).

4. CONCLUSIONS

A three-dimensional model of the milling process has been created, enabling a detailed investigation of both material allowance removal and surface formation mechanisms of the machined part. The proposed approach enhances machining productivity by utilizing the intersection of the tool and workpiece axes, while the accuracy of surface shaping is improved through the ability to program the intersection point between the cutter axis and the cylindrical workpiece. The application of end-face machining for roughing operations combined with peripheral cutting during finishing ensures uniform tool wear. For efficient rough milling, the cutter rotation angle is selected based on the conditions of uniform loading and maximum material removal by the end face of the tool. During finishing operations, the rotation angle is chosen to guarantee full engagement of the peripheral cutting edges. In addition, the developed stress distribution model allows for the evaluation of the surface layer condition of the workpiece during the milling process using an oriented cutting tool.

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