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EXPERIMENTAL STUDY OF THE PROCESS OF BORING MACHINE PARTS USING A CUTTER EQUIPPED WITH TENSOR SENSORS

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Abstract. The article presents a methodology for experimental investigation of the boring process of non-rigid helical machine parts. Based on an analysis of recent research in this field, requirements are established for the physicomechanical properties of the workpiece material, technological and design parameters of helical parts, and their manufacturing technologies. Experimental results are described, particularly focusing on boring forces. During the machining of holes with small internal diameters in non-rigid helical workpieces made of materials that form continuous chips, friction between the chips and the machined surface and chip jamming inside the hole are observed. Accordingly, the quality of the machined surface depends on the chip curling behavior. A special boring tool setup with strain gauge sensors was developed for precise cutting force measurement. A tool with a replaceable cubic boron nitride (CBN) insert was used to create different internal profiles and to study the influence of tool geometry on the boring process. To ensure measurement accuracy, the strain gauges were calibrated on a custom test rig using lever systems in a static position. The experimental study established and optimized recommended feed values relative to specified surface roughness and cutting depth parameters. The research also revealed that cutting speed must be maintained within certain limits; otherwise, the helical surface may deform or bend. Resulting graphs demonstrated patterns of boring parameters: cutting forces decrease with increasing cutting speed, while forces increase with higher feed rate, cutting depth, and spiral thickness.

Key words: cutting modes, boring, non-rigid helical parts, strain gauge sensor, deformation.

Introduction

The development of new designs for non-rigid screw workpieces in machines expands the scope of mechanisms utilizing screw devices and places increased demands on the technological and structural parameters of finished screw parts, as well as their manufacturing technology. This has led to their increasingly widespread application across various sectors of the economy. Their nomenclature and design features are determined by the specific operational requirements, which are driven by the performance of diverse technological operations, their combinations, and many other conditions.

Modeling of cutting processes depends on numerous factors: the material's physical and mechanical properties, feed rate, depth of cut, nature of loads, and so forth [1,2]. Since these factors are stochastic, it is necessary to conduct a comprehensive set of experimental studies to identify the dominant factors that significantly influence the boring process [3]. To perform a statistical analysis of the obtained results, empirical dependencies should be introduced into the selected mathematical model. These dependencies will illustrate the change in cutting force as a function of both depth of cut and feed rate.

Analysis of foreign and domestic research and publications

The development of novel designs for non-rigid machine workpieces broadens the applicability of mechanisms incorporating screw devices. This also imposes more stringent requirements on the technological and structural parameters of finished screw components, as well as their manufacturing processes. Consequently, these components are finding increasingly widespread use across various sectors of mechanical engineering. Their specific nomenclature and design characteristics are dictated by the unique operational demands, which arise from the execution of diverse technological operations, their combinations, and numerous other influencing factors.

Non-rigid screw workpieces are manufactured from alloy structural steels, plastics, and other materials. Typically, steels of grades СТ3 (Fe37-3FN – European Union analogue), 08 КП (DC04 – European Union analogue), and 10 КП (DC01 – European Union analogue) are used in their production. When necessary, their working surfaces are subjected to chromium plating, nickel plating, and the application of other electroplated coatings. Additionally, technological methods are often employed to increase the hardness of the screw helix's outer diameter. To understand the mechanism of interaction of the tool with coated parts, it is useful to study the response of functionally gradient ceramic [4,5,6,7] and chromium [8,9,10,11] coatings to local loading.

The specifics of forming and machining this type of workpiece are primarily determined by its geometric shape and manufacturing precision. Numerous methods for machining non-rigid screw workpieces are known [12]. These methods differ in terms of technological process characteristics, as well as the sequence and number of operations involved. During the boring of holes with small internal diameters in non-rigid screw workpieces made from materials that produce continuous chips, chip friction against the machined surface and chip jamming within the hole may occur.

Consequently, the quality of the machined surface depends on the nature of chip curling [13]. Also, screw surfaces are cut in the hole of the steel nipple of a fiberglass sucker rod with an adhesive-press connection [14]. Their geometric parameters and accuracy significantly affect the strength of the connection [14].

Therefore, it is necessary to propose measures to reduce the chip curl radius (*Rc*) to satisfy condition: $R_c<R_h$, where R_h is the radius of the hole being machined. Experimental studies on boring holes in these workpieces have enabled a more accurate understanding of the chip curling characteristics. The proposed theory refines existing theories [15] by considering the specific features of the cutting process for boring this type of workpiece.

The boring process of the internal (basic) surface of a non-rigid screw workpiece is characterized by intermittent cutting accompanied by significant dynamic loads. These loads arise within the structural elements of the machine tool, the tool holder, the cutting tool, and the workpiece itself [16]. The presence of such dynamic loads significantly deteriorates the machining process, reduces the quality and accuracy of the internal surface, and negatively affects tool wear resistance.

To achieve a high-quality surface finish on non-rigid workpieces during the cutting process, it is essential to ensure stable movement of both the workpiece and the tool along the theoretically calculated trajectory. In practice, however, various dynamic phenomena arise during the machining of non-rigid screw workpieces. These phenomena significantly affect both the process of geometric form generation and the physical progress of the machining operation [17]. Vibrations occurring within the technological machining system [18] during cutting substantially reduce machining productivity and tool wear resistance. They also negatively impact the quality of the machined surface by decreasing dimensional accuracy and increasing surface roughness.

Utilizing the developed and implemented equipment, we performed boring operations on non-rigid screw workpieces under a wide range of parameter variations. This enabled us to more precisely identify the patterns and specific characteristics of the cutting and boring processes in non-rigid workpieces.

Purpose of the work and justification for its implementation

The aim of this study is to investigate the specific features of the boring process for non-rigid workpieces and to determine the optimal cutting parameters for such them. This study covers a wide range of tasks, including the following: to plot graphs for analyzing the dependence of cutting force on feed rate and cutting depth based on the results of experimental studies; to plot a graph representing the optimization parameter – i.e., the dependence of cutting force on the variation of one input factor while maintaining the other two factors constant. Another objective is to examine the stability condition of non-rigid screw workpieces during machining. Finally, the study seeks to experimentally determine the influence of force parameters on the processes of form generation and boring for this type of workpiece.

Presentation of the main material

The experimental research methodology included both static and dynamic studies, along with the measurement of technological, force-related, and structural parameters during the boring of non-rigid screw machine parts. Testing was conducted under both laboratory and production conditions to ensure compliance with required indicators of accuracy, reliability, and operational technical specifications.

Using the developed and implemented equipment, boring operations on non-rigid screw parts were carried out across a wide range of parameter variations. This enabled a more precise determination of the patterns and specific characteristics of the cutting and boring processes for non-rigid screw parts [19].

Experimental studies of the boring process aimed to establish the relationships between forces, moments, and the design parameters of non-rigid screw machine parts and boring bars under various boring setups. Based on these studies, zone of plastic deformation was also identified.

The technological process for manufacturing high-precision non-rigid screw parts includes operations of turning the outer diameter and boring the inner diameter. This improves the surface quality of both the outer and inner helical edges of the non-rigid screw workpiece and enhances the operational characteristics of the finished screw parts.

The boring process of non-rigid screw parts (Fig. 1) was investigated using parts with the following parameters: material – 08КП steel (DC04 – European Union analogue); outer diameter range – 40–250 mm; helix thickness – 1–4.5 mm.

Experiments were conducted on a 1A616 lathe. Cutting forces were measured using strain gauge tensometry. Strain gauges were affixed to the cutting tool on both the upper and lower sur-

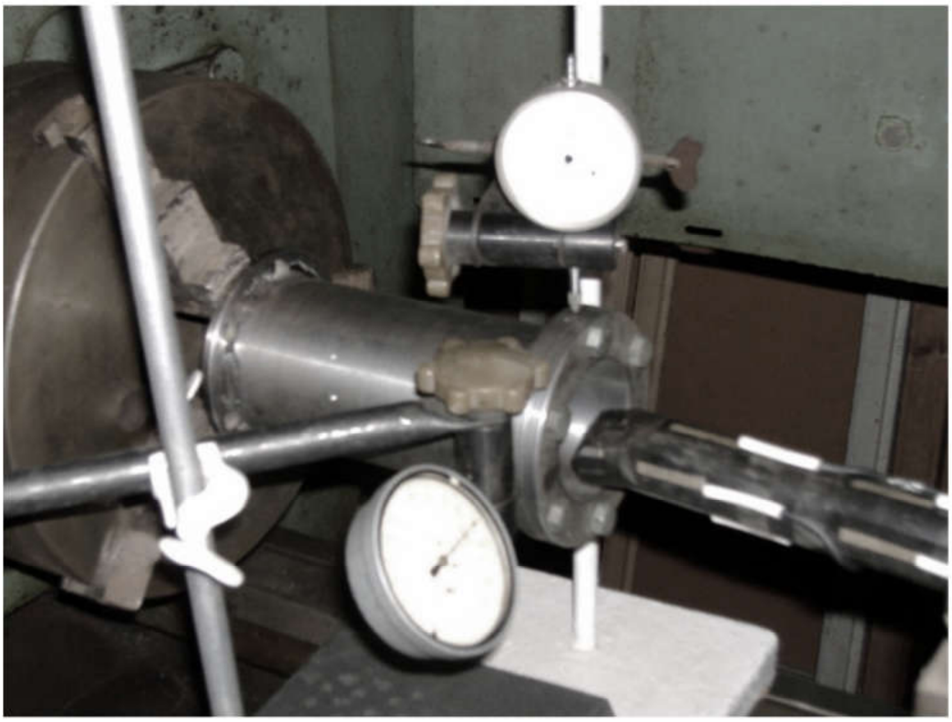
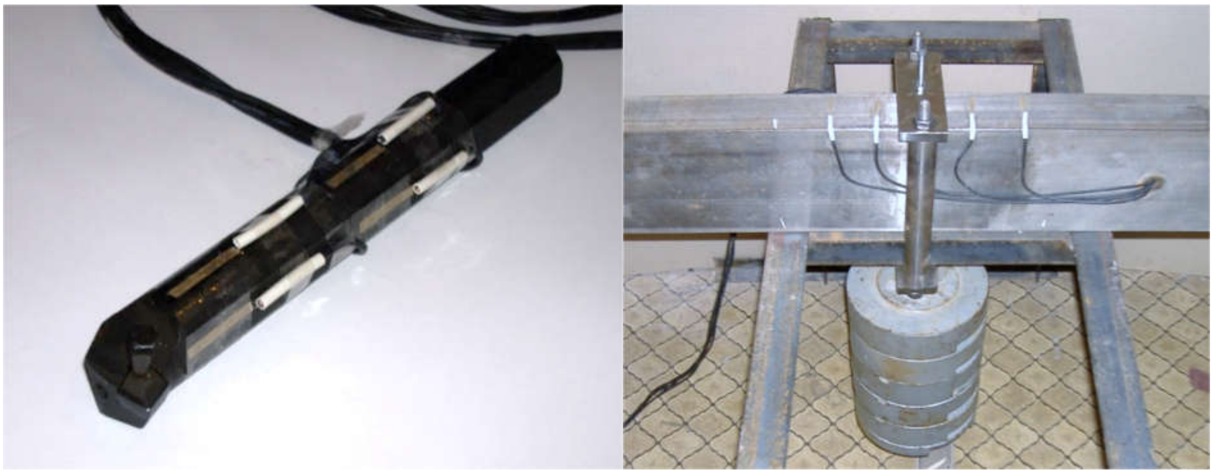


Figure 1 – Investigation of the boring process



a) *b)*

Figure 2 – a) Cutting tool with strain gauges; b) Sensor calibration in a static state

faces, at the beginning and middle of the insert, using a half-bridge circuit. Boring force signals were recorded using an amplifier and a recording device.

A boring bar of type S32T-SCLCR12 with an indexable carbide insert (CBN) was used as the cutting tool (Fig. 2a) [20]. Five strain gauges were mounted on the tool – both on the top surface and on the side – in order to measure cutting forces and force distribution at various points along the tool [21]. The tool with the indexable insert was used to form different internal workpiece profiles and to study the influence of tool geometry on the boring process.

Calibration of the strain gauges was carried out using levers in a static setup (Fig. 2b).

During the experimental investigations, recommended feed rates for boring were determined and optimized relative to specified surface roughness parameters and depth of cut. The recommended feed rate values are presented in Table 1.

The cutting speed V is determined by the formula:

$$V = 230/(T^{0,15} \cdot S^{0,25} \cdot t^{0,15})K_v; \quad (1)$$

$$K_v = K_b \cdot K_f \cdot K_m,$$

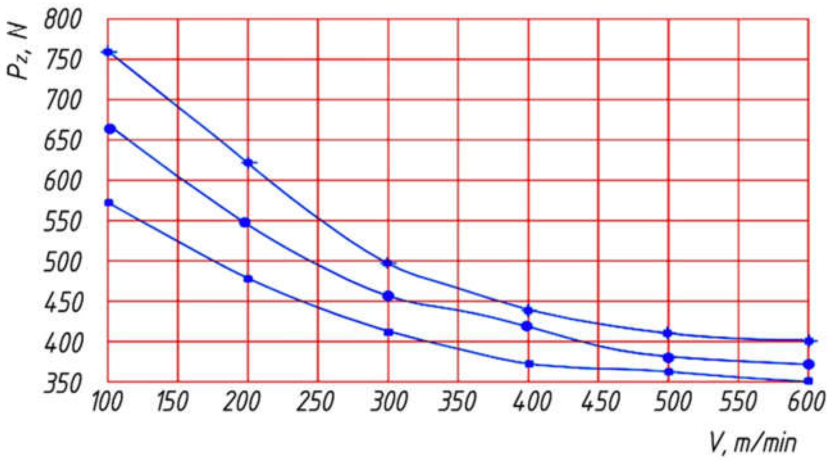
where K_b – coefficient accounting for screw blade thickness, K_b=*h/2,5*; K_f – coefficient accounting for tool shape; K_m – coefficient accounting for workpiece material, for St3 steel K_m = 0,9; for 08KP steel K_m= 1.

Table 1 – Recommended feed rates (mm/min)

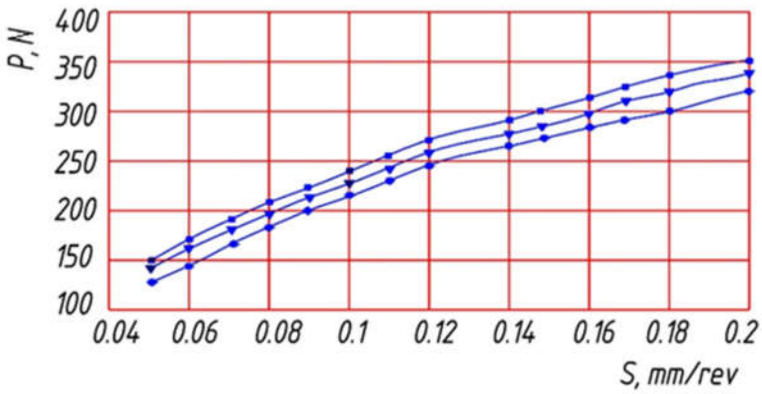
Roughness parameter R_a, µm	Depth of cut, mm	Helix thickness at the inner edge, mm					
		0.5	1.0	1.5	2.0	2.5	3.0
0.63	0.5	0.02	0.03	0.035	0.04	0.045	0.05
1.6	1.0	0.09	0.13	0.15	0.18	0.2	0.23
3.2	1.5	0.25	0.37	0.41	0.5	0.55	0.63
6.3	1.5	0.65	0.98	1.21	1.39	1.55	1.7

Table 2 – Recommended values of coefficient K_v

Rib thickness of the coil of the thin-strip workpiece h, mm	K_v
0.5–1.0	1.5
1.0–1.5	1.38
1.5–3.0	1.2
3.0–6.0	1.0



■ – *S = 0.05 mm/rev*; ● – *S = 0,15 mm/rev*; ✸ – *S = 0,25 mm/rev*
Figure 3 – Dependence of cutting force P_z on cutting speed V



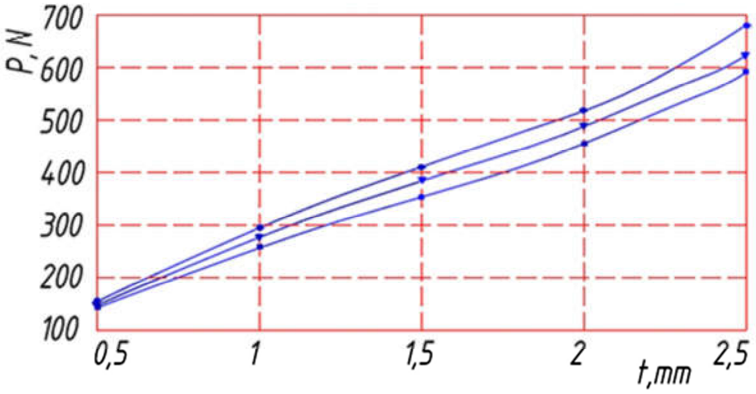
✵ – *V = 500 m/min*; ▼ – *V = 300 m/min*; ■ – *V = 250 m/min*
Figure 4 – Dependence of cutting force *P* on feed rate *S*

Then we get:

$V = 92/(T^{0,15} \cdot S^{0,25} \cdot t^{0,15}) \cdot h \cdot K_f \cdot K_m.$ (2)

During the experiment, optimal values of K_v were determined depending on the workpiece's helix thickness (Table 2).

An analysis of the research results on the boring process of non-rigid screw workpieces at the inner diameter revealed that increasing the cutting speed leads to a reduction in cutting force (Fig. 3). Conversely, the cutting force increases with higher feed rates (Fig. 4) and greater depths of cut (Fig. 5).



■ – *V* = *250 m/min*; ▼ – *V* = *300 m/min*; ✸ – *V* = *500 m/min*

Figure 5 – Dependence of cutting force *P* on depth of cut *t*

Table 3 – Cutting modes

No.	Parameters of workpieces, mm	Rotational speed, rpm	Depth of cut, mm	Feed rate, mm/rev
1	95 x 55 x 3	120.0	0.5	6.0
2	95 x 55 x 3	150.0	0.4	6.0
3	95 x 55 x 3	180.0	0.3	6.0

t=1,0 mm; S=0,4 m/min; V=150 m/min; P_z*=400 N*

Figure 6 – Oscillogram of the non-rigid screw parts boring process

The research results can be used for developing technological processes for manufacturing non-rigid screw machine parts.

Cutting modes for boring processes using the 1A616 machine tool are presented in Table 3.

Experimental studies indicate that cutting speed must fall within specific ranges; otherwise, the helical surface may deform or bend. The optimal range of cutting speeds was determined empirically. For instance, to achieve a surface quality of R_a = 20–65 µm and a precision of 7–9 quality grades, if the helical surface thickness increases by more than 0.5 mm, the cutting speed can be reduced to 240–280 m/min. However, this reduction will result in a one to two order decrease in machining quality. The time-dependent behavior of the cutting force is pulsating, with a period $T = 60/n$ (where n is the number of helix revolutions per minute). This is clearly evident in the oscillograms (Fig. 6).

The obtained graphs enabled the identification of patterns in the variation of boring parameters: as the cutting speed increases, cutting forces decrease, whereas they increase with higher feed rates, greater depths of cut, and increased helix thickness.

The cutting force values were determined using the following formula:

$$P_z = V \cdot {C_{pz}}^{0,38} \cdot S^{0,4} \cdot t^{0,75} \cdot K_z, \qquad (3)$$

where C_{pz} – coefficient depending on the width of the strip material; C_{pz} = 3800–4500; V – cutting speed, m/min; S – feed per revolution, mm/rev; t – depth of cut, mm; K_z – coefficient dependent on the helix thickness of the workpiece at the outer edge, $K_z=(h/2,5)K_d \cdot K_w$, K_d – coefficient dependent on the feed direction of the cutting tool (for boring along the helical path K_d = 1,1; in the case of boring in the direction opposite to the helical path K_d = 0,9); K_w – wear-dependent coefficient, K_w = 0,8–1.

Considering these coefficients, we can write the formula for determining cutting force as:

$$P_z = 0{,}374 \cdot h \cdot C_{pz} \cdot V^{0{,}38} \cdot S^{0{,}4} \cdot t^{0{,}75} . \quad (4)$$

The obtained graphs allowed us to identify patterns in the variation of boring parameters: cutting forces decrease with increasing cutting speed, while they increase with higher feed rates, greater depths of cut, and increased helix thickness.

Conclusions

The proposed method for thread cutting in non-rigid workpieces and parts, along with the device for its implementation, ensures a reliable and high-quality threading process for non-rigid screw workpieces. This contributes to increased productivity and operational reliability, while also expanding technological capabilities.

As a result of theoretical investigations, patterns governing intermittent boring processes in non-rigid screw workpieces have been identified. The obtained optimal solutions made it possible to determine the fundamental characteristics of boring non-rigid workpieces, understand the nature of transient processes in tool–workpiece interaction, and analyze the influence of machining parameters on cutting forces.

Gratitudes
None.

Conflict of interest
None.

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ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ПРОЦЕСУ РОЗТОЧУВАННЯ ДЕТАЛЕЙ МАШИН ЗА ДОПОМОГОЮ РІЗЦЯ, ОСНАЩЕНОГО ТЕНЗОРНИМИ ДАВАЧАМИ

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Анотація. У статті визначено методику експериментальних досліджень процесу розточування гвинтових нежорстких деталей машин. На основі проведеного аналізу останніх досліджень за даною тематикою встановлено вимоги до фізико-механічних властивостей матеріалу заготовки, технологічних і конструктивних параметрів гвинтових деталей, технології їх виготовлення. Описані результати експериментальних досліджень, зокрема зусиль проточування. В процесі оброблення отворів з невеликим внутрішнім діаметром у нежорстких гвинтових заготовках із матеріалів, які утворюють зливну стружку, спостерігається тертя стружки до обробленої поверхні та заклинювання її в отворі. Відповідно, якість обробленої поверхні залежить від характеру закручування стружки. Розроблено спеціальне оснащення розточного різця тензометричними давачами для точного визначення сил різання. Різець з змінною твердосплавною пластиною (CBN) використовувався для утворення різного типу профілю внутрішньої частини заготовки та для дослідження впливу форми різця на процес розточування. Для досягнення точності вимірювання проведено тарування тензометричних давачів на розробленому стенді, яке проводилось за допомогою важелів у статичному положенні. Під час проведення експериментальних досліджень було встановлено та оптимізовано рекомендовані значення подач при розточуванні відносно заданих параметрів шорсткості та глибини різання. Завдяки цим дослідженням також встановлено, що швидкість різання повинна мати певні значення, інакше гвинтова поверхня може деформуватись та згинатись. Одержані графіки дозволили встановити закономірності зміни параметрів розточування, відповідно з підвищенням швидкості різання зусилля зменшуються, а із зростанням подачі, глибини різання та товщини спіралі зусилля підвищуються.

Ключові слова: режими різання; розточування; нежорсткі гвинтові деталі; тензорний давач; деформація.