UDC 621.923.42 DOI https://doi.org/10.35546/kntu2078-4481.2023.4.17

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DIGITAL TWIN OF SPINDLE UNITS. REVIEW

The Digital Twin technology of the spindle unit can realize the control of accuracy, quality of processing and other indicators that affect to the efficiency of the system. Many articles focus on Digital Twin, but there are no clear and systematic analysis of the process of creating Digital Twin. To address this gap, this study conducted an article analysis of the Digital Twin of the spindle unit (up to May 1, 2023).

In this article, we will consider the existing definitions of the concepts of digital twin and digital twin of metal-cutting machines. In addition to the articles themselves, we will consider other reviews of digital twins and attempts to systematize existing research. No review articles on the topic of digital twins of spindle assemblies were found.

For the search methodology, traditional methods of searching scientific sites and search engines were used, and the analysis of the obtained results is presented in graphs. The analysis included a total of 143 selected publications. After a detailed examination of which, it turned out that most of the articles, despite the presence of keywords, did not deal with the creation of digital twins, but only mentioned the possibility of creating digital twins. Some articles have ideas for creating a digital twin model for metal cutting machinery or spindle unit. As a result of the search, no domestic works in the given direction were found, most of the works are foreign, of which the lion's share is financed by the government of the People's Republic of China. It is expected that this will give an impetus to the in-depth study of the process of creating a digital twin of a spindle node. It can be useful in the post-war reconstruction of Ukraine, taking into account the problems of wear and tear of existing machine tools of machine-building enterprises. In addition, it is a possibility of adapting machines that were in use, which can be obtained in within the framework of international assistance to enterprises.

***Key words:** intelligent spindle, DT, industry 4.0, model of digital twins, metal cutting machinery.*

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ЦИФРОВІ ДВІЙНИКИ ШПИНДЕЛЬНИХ ВУЗЛІВ. ОГЛЯД

Технологія цифрового двійника шпиндельного вузла може реалізувати контроль точності, якості обробки та інших показників, що впливають на ефективність системи металообробки. Багато статей присвячено цифровим двійникам, але чіткого та систематичного аналізу процесу створення цифрового двійника немає. Щоб усунути цю прогалину, у цьому дослідженні було проведено аналіз статей по тематиці цифрового двійника шпиндельного вузла (до 1 травня 2023 р.).

В даній статті розглянемо наявні визначення поняття цифрового двійника та цифрового двійника металорізальних верстатів. Окрім самих статей розглянемо інші огляди на цифрові двійники та спроби систематизації наявних досліджень. Оглядових статей по тематиці цифрових двійників шпиндельних вузлів не виявлено.

За методологію пошуку було використано традиційні методи пошуку науковими сайтами, пошуковими системами і аналіз отриманих результатів представлено в графіках. Аналіз включає загалом 143 вибрані публікації. Після детального розгляду яких, виявилось що більшість статей попри наявність ключових слів

не займались створенням цифрових двійників, а лише згадували про таку ймовірність створення цифрових двійників. Деякі статті мають ідеї зі створення моделі цифрового двійника. Вітчизняних праць по заданому напрямку в результаті пошуку не виявлено, більшість праць зарубіжні, з яких левова частина профінансовані урядом Китайської народної республіки. Очікується, що це дасть поштовх до поглибленого вивчення процесу створення цифрового двійника шпиндельного вузла, що може принести користь в післявоєнній відбудові України з врахуванням проблем зносу діючих верстатів підприємств машинобудівної ланки, так і можливість адаптації верстатів, які були в використанні, які можуть бути отримані в рамках міжнародної допомоги підприємствам.
Ключові слова: *розумні шпинделя, ЦД, індустрія 4.0, модель цифрового двійника, металорізальні верстати.*

Formulation of the problem

Digital Twin is a popular topic in improving technological systems, but there are no clear and systematic analysis of the process of creating Digital Twin for spindle unit of metal cutting tool. To develop this area of the study need conducted an article analysis of the Digital Twin of the spindle unit.

Analysis of recent research and publication

One of the first digital twin (DT) was presented by Grieves [1] during the presentation of the product life cycle management technology (PLM). Initially, the Digital Twin served as an inexpensive tool for simulating various conditions for modeling NASA rockets, over time it advanced technologically and expanded the fields of use [2]. Definitions of the concept of DT from different authors are given in Table 1.

Table 1

Definition of digital twin

Author, year	Definition of digital twin
Grieves, 2014	“A virtual representation of what was created” [1].
R. Stark and others, 2017	“A digital representation of a unique asset that describes its properties, conditions, and behavior using models, data, and information” [3].
Söderberg and others, 2017	“A digital copy of a physical system for real-time optimization” [4].
Zhuang and others, 2018	“A virtual dynamic model that fully describes the physical essence of the system and can simulate the behavior, characteristics and properties of its physical analog in real-time” [5].
Qi and Tao, 2018	“Virtual models of physical systems are created digitally to simulate their behavior in a real environment” [6].
Y. Xu and others, 2019	“Records, simulates and improves the production process from design to system retirement, including the content of virtual space, physical space and the interaction between them”[7].
Kannan and Arunachalam, 2019	“A digital representation of physical assets that can communicate, coordinate and collaborate to improve productivity through knowledge sharing”[8].

Let’s take a closer look at digital twins of metal cutting machines. Definitions of digital twins of metal cutting machines and their authors are listed in Table 2.

Table 2

Definition of digital twin of metalcutting machine

Author, year	Definition of digital win of metalcutting machine
Wardandothers, 2021	The digital twin of metal cutting machine is a digital copy of the process in real time; the process receives real-time data, control digital model data, or makes changes to work based on information from a numerically controlled machining center (CNC)[9]
Liu and others, 2023	The digital twin of metal cutting machine is an intelligent processing system with a pair of physical objects and digital models, where the processing is analyzed, solved and controlled based on the digital model [10]
Fujita Tomoya, 2022	A digital twin of the machine is created in the virtual world, which has a controller model, a machine model and a process model, and receives real data during the machining process, which are used to identify the process models [11].

Literature reviews of digital twins of spindle units were not found on the Internet. At the literature search stage, literature reviews on metal cutting machines and literature reviews on other related topics were identified.

A review of digital twins based smart design and control of ultra-precision machining was made in [12]. Authors consider 64 papers up to July 2021 on thematic of precision machining and digital twin. In article was considered the design of various modules such as bearing, spindle-drive, stage system, servo, and clamping modules is examined. A review also includes an overview of control studies based on digital twins, which encompass voxel modeling, process planning, process monitoring, vibration control, and quality prediction.

Detail review of smart spindle was shown in [13]. Nonetheless, there is only idea to creation of digital twin of spindle unit. Article has 357 references. Authors describe 6 main potential functions and three key enabling technologies of intelligent spindles.

Paper [14] presents advancement and the current status of the digital Twin-driven smart manufacturing. The enabling technologies, core concept, application scenarios, reference model, and research issues of digital Twin-driven smart manufacturing was discussed. Overall article described 84 references for manufacturing developing digital twins.

In review of digital twin driving machining after analyzed 143 sources authors divided all articles in three analysis perspectives – point perspectives, line perspectives, face perspectives [10]. Point perspectives consist of DT models. Line perspectives consider connection between virtual and physical entity. Face perspectives consider feedback processes and repeated cycles.

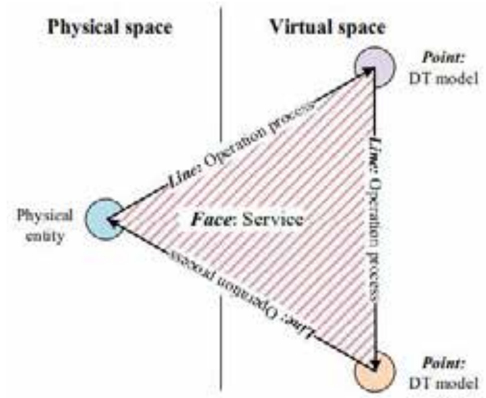


Fig. 1. Sketch of DT machining system [10]

Review of digital twin for smart manufacturing described in [15]. Article describes experience big company such as Tasla, Siemens, Airbus, ABB, Rolls-Royce from open source about work under implementation of digital twins in manufacturing

All described articles not included literature review of digital twin of spindle unit, therefore, further research on this issue is necessary.

Presenting main material

<u>Methodology of the research</u>

"Traditional" research methods were used to write this article – literature review, search for information on search engines and specialized scientific sites. When searching for information, the following languages were used: Ukrainian, Russian and English. To generate results, the query was limited to recent data, namely, information up to 2018 was excluded as outdated.

For relevance, the search was performed on the following scientific sites – [16–21]. The following phrases and designations were used for the search: "Digital twin", "digital twin for machining", "Digital twin machine tool", "Digital twin, spindle", "Digital twin metal cutting", "Digital twin for spindle", "DT", "Spindle knots" etc.

The obtained results were checked using VOSviewer for relevance to the topic of research by keywords, and data that did not relate to digital twins were discarded. An example of the analysis is shown in Figure 2.

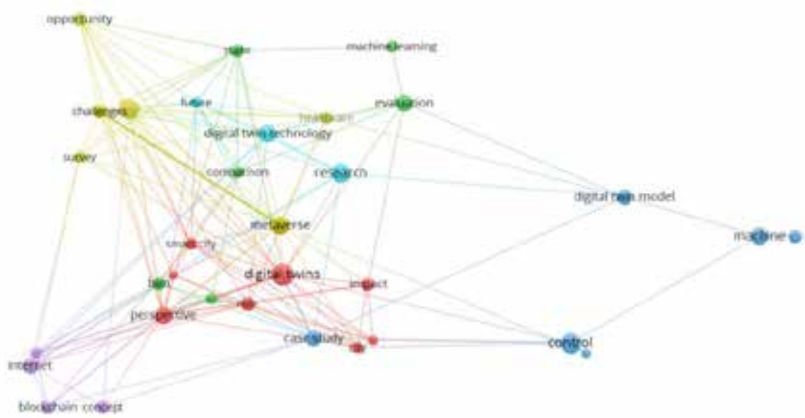


Fig. 2. The result of the analysis by keywords on the example of the website https://www.scopus.com/ for the request «Digital twin» in the VOSviewer software

We will divide the entire search spectrum into 3 conditional phases: the phase of searching for information on digital twins, the phase of searching for information on digital twins of metal-cutting machines, the phase of searching for literature in the direction of digital twins of spindle units.

The next stage of the research was the filtering of the results – the results of research on the practical implementation of digital twins in areas unrelated to production and mechanical engineering were excluded.

Based on the obtained results, the main definitions of the concept of a digital twins were considered. After filtering the results by topic, the question of what a digital twins of metal-cutting machines is. The results of the analysis are shown in the second section.

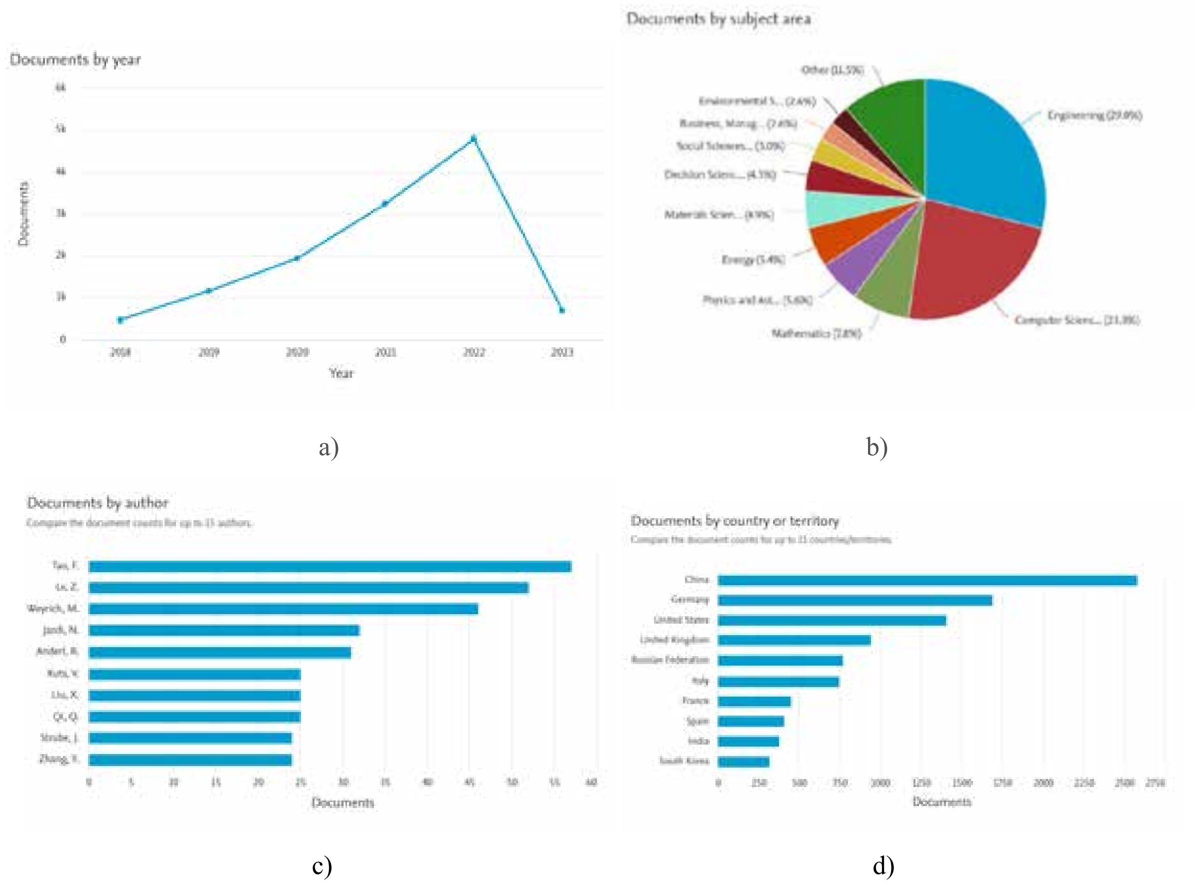


Fig. 3. An example of analysis on the request of "digital +twin" on the website https://www.scopus.com/

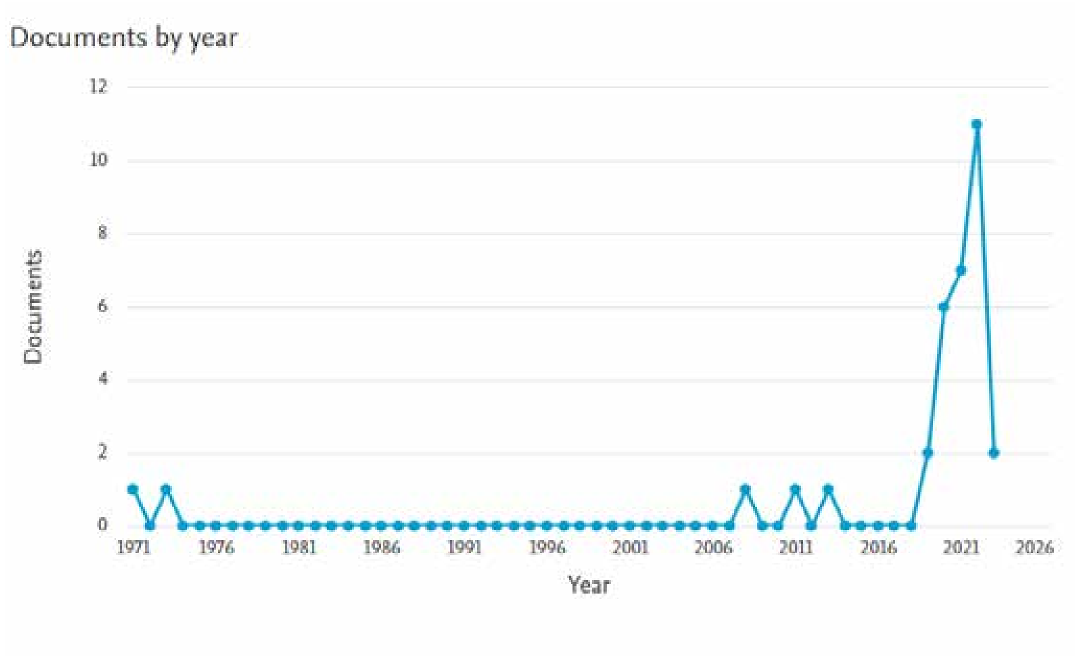
a) – publications by year; b) – publications by subject area; c) – publications by authors; d) – publications by country

Only some works consider separately the creation of the DT of spindle units and mention it in the titles of the articles, however, quite a lot of works on the creation of a system of a digital twin of a metal cutting machine touch on the topic of creating and researching issues related to the DT of a spindle unit. For a wider disclosure of the issue and systematization of materials, we systematize materials according to the system of a digital twin of a metal-cutting machine. And on the basis of the described stages of the creation of the DT of spindle, will analyzed which works pay more attention to the creation of the DT of the spindle, and which individual articles are at which stage of the DT.

At the initial stage, more than 40,000 articles mentioning a digital twin were found on scientific websites. In the course of the analysis, articles not related to engineering and mechanical engineering were excluded, after removing duplicated articles on the sites, only 43 articles remained in the direction of digital twins of metal-cutting machines.

After analyzing all the articles by direction, articles dealing with issues of digital twins of the spindle node were singled out – 31 articles. Despite this, not all articles that appear as keywords – spindle node and digital twin have information on the topic, only 16 articles have an actual mention of the DT and spindle in the article, but none of the articles developed a digital twin of the spindle assembly.

Most of the articles in the direction of creating digital twins of metal-cutting machines are tangentially related to the process of creating a digital twine of a spindle in a digital twin of a metal-cutting machine.



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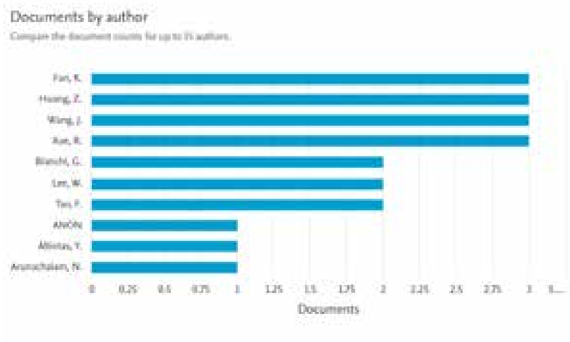

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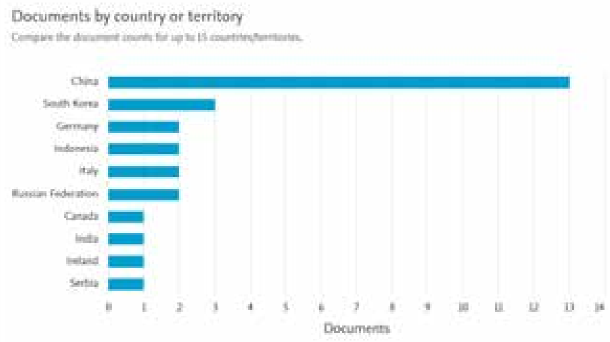

c)

Fig. 4. An example of the analysis by request "digital + twin+spindle" on the website https://www.scopus.com/

a) – publications by year; b) – publications by authors; c) – publications by country

<u>Stages of creating a digital twin</u>

In [23], the author breaks down the process of creating a DT into specific stages:

– creating the idea of a digital twin;

– a prototype of a digital twin – designing what a DT should look like;

– creation of an instance of a digital twin – accumulation and analysis of the work of an instance will contribute to the creation of a working product;

– creation of a digital twin product;

– creation of a digital twin environment.

In [24], the author pays considerable attention to disposal and the process of decommissioning digital twin and separates it as a separate stage of the existence of a digital twin.

In [2], the author systematizes the phases of the DT life cycle and divides it into 5 stages, each of which separately breaks down the tasks assigned to each of the stages, the authors of works on each of the directions are given in parentheses:

1. Development stage – integration of design and production based on DT, description of DT tools, service innovations, analysis and verification of DT.

2. Production stage – digitization of production, modeling strategies, production optimization, individual manufacturing, situational adjustment with DT support, production process monitoring.

3. Implementation stage – robot-human cooperation, database management, optimization of data transfer.

4. The stage of use – repeated application and evaluation of knowledge, improvement of the work process, improvement of production, digitization of process management and all production, improvement of energy and resource efficiency, DT management of the product life cycle.

5. The decommissioning stage.

For a simpler understanding of the creation process, let's break down the process of creating a DT of spindle unit into 4 stages: idea, modeling of a DT, experimental product and implementation.

Literature review of digital twins of spindle units

On the basis of the considered articles, we will single out those articles that consider in more detail the very issues related to the creation of spindle units with digital twins. We will break down all the found articles by the stages of creating digital twins of spindle units and present them in the form of Table 3.

Table 3

Works about DT of spindle unit according to stages of creation DT

Stages of creation a digital twin	References
1. Idea	13, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38
2. Model	-
3. Experimental sample	-
4. Existing DT	-

In the work [13], the authors describe the concept of creating intelligent spindle, which can serve as a basis for creating a DT of spindle units. The prototype of the intelligent spindle from the authors is shown in Fig. 5. The authors substantiate the perspective of creating intelligent spindle as independent components of machines. The article presents the expected functions of intelligent spindles and the goals that should be pursued by such functions. The advancement of technology for intelligent spindles is reviewed in great detail based on the stated goals and functions that a spindle assembly must perform. The authors consider many options, what should be monitored in the work process and how to do it. However, the authors in this article are not engaged in the creation of a model DT for spindle.

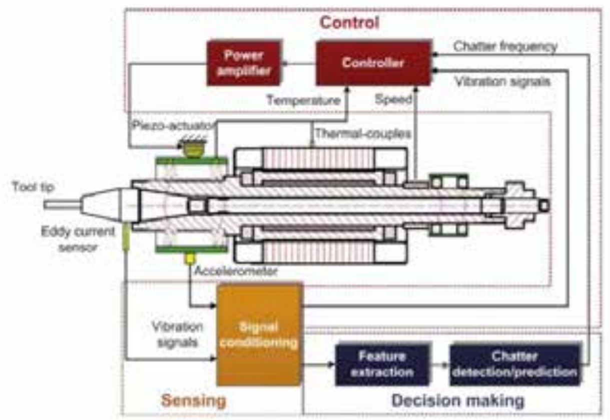

Fig. 5. Prototype of an intelligent spindle [13]

The prospect of creating a DT of spindle units is discussed in works [13, 25]. In the works [25–26], the main attention is focused on the architecture and functional capabilities, compatibility and confidentiality of the integrated system of local collection, unification, processing, presentation and transmission of data to the DT. This is how the authors consider the 4 main functions of the DT of spindle:

– data collection from sensors installed on the vehicle;
– processing of received signals;
– implementation of executive mechanisms;
– a presentation, as a connection of the spindle with the shop, the database and the manufacturer.

However, the authors are not directly involved in the creation of a model or an experimental sample.

In [27], a dynamic model of a machine tool (MandelliM5) was created, the structure of components, a model of the cutting process, and models of transmission chains and control systems were described. Although the author mentions digital twins and spindle unit in the article, he works specifically on digital twin of the machine, and not a spindle unit.

A tool wear monitoring system developed in [28]. A digital DT model with appropriate parameters was able to simulate the dynamics of the micro-milling process close to real-time data. The author monitors in detail the parameters of the spindle, such as rotation speed, load and other parameters using a controller on a CNC micro milling machine. Emphasis is placed on the importance of tracking tool wear, a digital model has been created that applies to the entire machine, not just the spindle. However, this idea allows you to use the sensors and elements already available on the machine, and monitor the results of the spindle using the existing software. Tool wear monitoring system for micro milling shown in fig. 6.

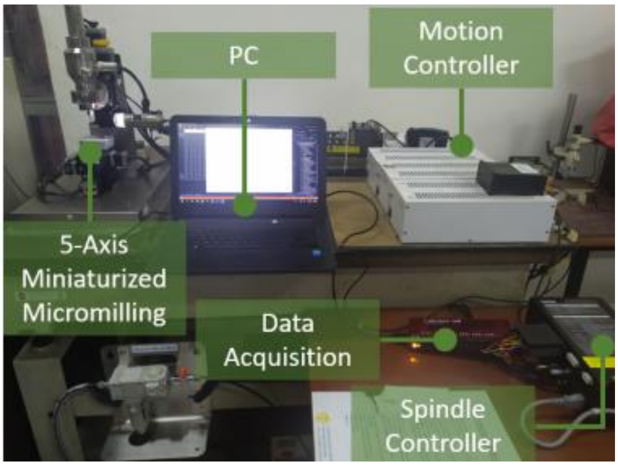

Fig. 6. Tool wear monitoring system for micro milling [28]

Creation of digital twin-driven thermal error prediction was considered in [29]. Model DT for thermal characteristics was developed at the first stage. After implementation of DT system was obtained theoretical value of thermal error. Long-short term memory was trained using experimental data. The implementation of the DT model shown on fig. 7.

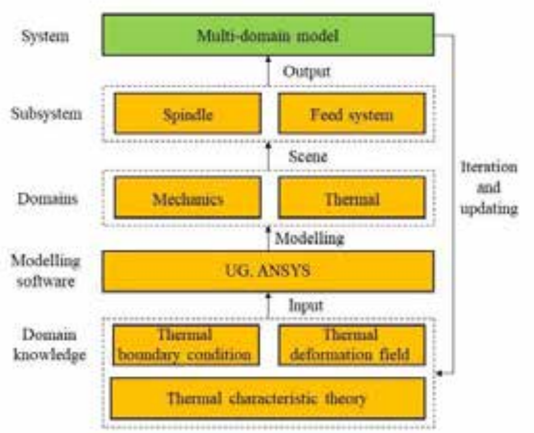

Fig. 7. The implementation of the DT model [29]

The document [30] describes the method of creating a digital twin based on planning and process data for processing processes using the example of components in the aerospace industry, but there is no information about a separate digital twin of the spindle unit.

In works [31], a model of a digital twin created to monitor thermal processes in the spindle. A program was developed and a data collection system and a physical model with embedded sensors created. Experimental setup shown on fig. 8.

In the [32] was proposed digital twin system includes three modules for thermal characteristic motorized spindle. The DT software, the data acquisition system, and the physical model with embedding sensors considered in article. Experimental setup shown on fig. 9.

In work [33] we obtained a mathematical model in MATLAB for a CNC milling machine. Data on spindle speed, motor load and axial deviation of the working tool were monitored and studied. Nevertheless study was based not only on spindle data, also were investigated axial movement and servo-motor parameter. Therefore this study more related to the part of DT machinery.

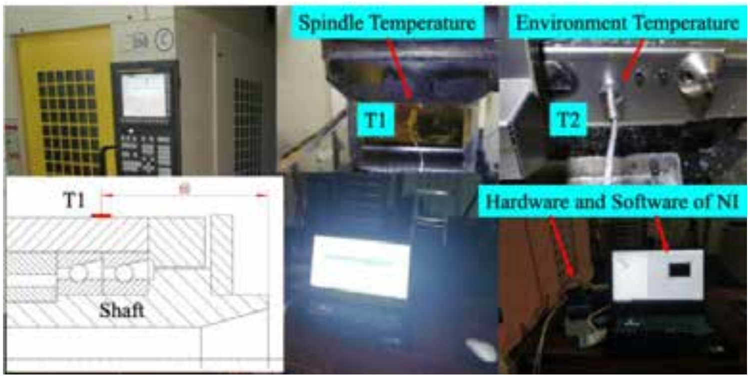

Fig. 8. Experimental setup [31]

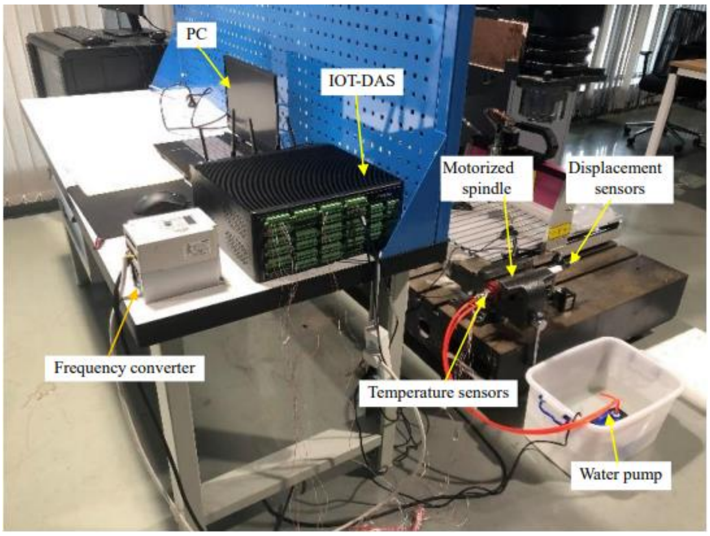

Fig. 9. Experimental setup [32]

Experimental DT have been developed for a CNC machine tool, which allows simulating and predicting changes in surface quality based on feed adjustment and spindle rotation speed in operation [34].

The authors of [35] work on the problem of durability of a working tool, using a digital twin. They measure the load on the spindle and the vibration signals of the tool during operation and adjust the operation of the spindle drive to avoid tool breakage. However, the work does not directly concern the creation of a digital twin of the spindle. Tool condition prognostic system shown on figure 10.

Fig. 10. Tool condition prognostic system [35]

For CNC machines, an approach to fault detection and re-planning of the work process based on digital twin shown in [36]. The authors experimentally check the operation of a digital twin model for a CNC machine for checking rolling bearing faults (Fig. 11) and the effect on interruptions in work due to faults. However, the work was not related to the spindle assemblies.

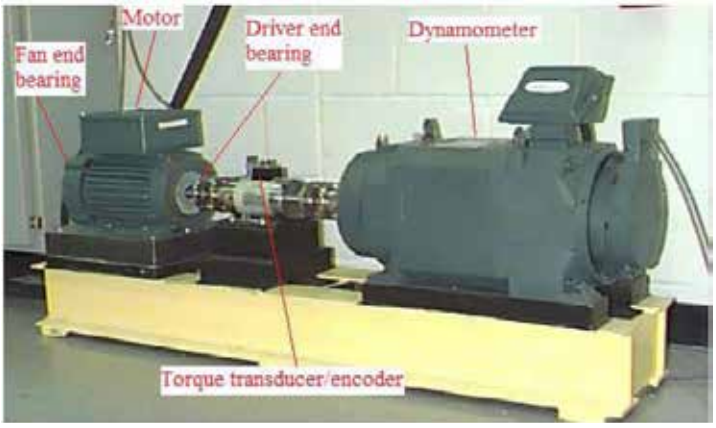

Fig. 11. Bearing fault test [36]

The authors [9] describe the method of creating a digital twin, which allows simulate the processing process in real time and transfer data to the analysis control center. To achieve this, the authors use smart sensors and data transmitters to collect information about the processing process. Experimental setup shown in fig. 12.

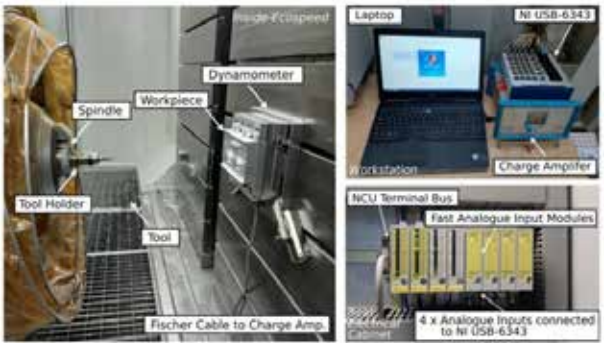

Fig. 12. Inside Ecospeed machining centre (AMRC, Sheffield, UK), hardware and IO modules [9]

In [37] was designed experimental scheme, was build experimental platform and was obtained experimental data of thermal characteristics for motorized spindle. Temperature measurement stand shown on fig. 13.

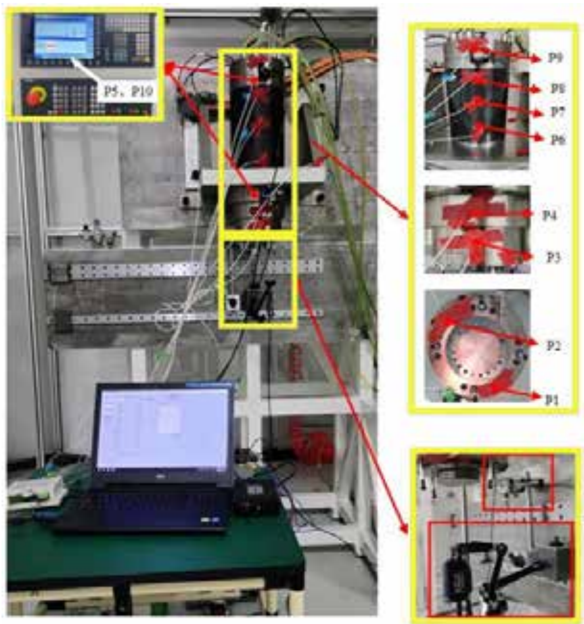

Fig. 13. Temperature measurement stand [37]

It is worth noting that the number of works in which digital twins of spindle are mentioned does not reflect the real amount of work done in the direction of creating DT of spindle – for example, in many articles there is a mention of digital twins and their effect on the operation of the spindle unit, but these works do not consider the creation of DT spindle.

Rest of articles – 19, which shown searching systems, do not included work with digital twins of spindle or machine tools, although articles have digital twin and spindle in title or key words.

Among the machines in which the system of digital twins has already been implemented and have already working, it is worth highlighting the Gepro 502 at the MASA Aerospace plant in Logrono (Spain) and the COMAU at the Renault car plant in Cleon (France) [38], but the system descriptions are not available in scientific articles. As for works where DT of spindleare implemented in the production cycle, such works have not been identified.

Conclusions

There is an increase in the demand for the creation of DT, but still most of the articles related to the creation of DT for metal cutting machines do not include the issue of creating DT for spindle units, there is not enough systematization, research is in the initial stages of creating DT. Most of the available works consider individual factors affecting the technological system, for example, only temperatures, tool wear, or vibrations, but do not work out a set of measures that can affect the operation of the technological system as a whole. Most of the works on the given topic are in English and Chinese. Acknowledgments very often state that the works are financed by the Chinese government. No Ukrainian developments on the given topic were found. In the reviewed literature, more attention is paid to the creation of the DT of systems of the machine tool, the processing center, but there are few works on the creation of the DT of the metal cutting machine, the issue of the integration of the DT of the metal cutting machine into the DT system of the metal cutting machine is not resolved.

This review shows that the issue of creating a digital twin of spindle unit is relevant and understudied, despite the development of research in the direction of the implementation of DT systems of metal-cutting machines.

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