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MACHINE TOOL ABILITY REPRESENTATION: A REVIEW

Smart manufacturing and predictive maintenance are current trends in the manufacturing industry. However, the holistic understanding of the machine tool health condition in terms of accuracy, functions, process and availability is still unclear. This uncertainty renders the development of models and the data acquisition related to machine tool health condition ineffective. This paper proposes the term machine tool ability as an interconnection between the accuracy, functions, the process and the availability to overcome the lack of the holistic understanding of the machine tool. This will facilitate the further development of qualitative or quantitative methods as well as models. The research highlights the challenges and gaps to understand the machine tool ability.

1. INTRODUCTION

The manufacturing industry is undergoing a rapid digital transformation towards smart factories [1], enforced by initiatives such as “Produktion2030” in Sweden [2], “Industrie 4.0” in Germany [3], “Factory 2050” in the UK [4], “Horizon2020” in the EU [5], the “Revitize Manufacturing Plan” in the US [6], and the “4th Science and technology plan” in Japan [7]. The development towards smart factories intends products and production resources such as machines, robots and tools to have the inbuilt capabilities to communicate, make self-diagnose, become self-learning and possess the ability to perform self-adjustments, adaptations and optimizations; in other words, products and processes are intended to become more intelligent and autonomous[8].

Smart manufacturing initiatives merge different technologies like cyber-physical systems (CPSs), cloud computing, the internet of things (IoT), the internet of services (IoS), big data, robotics and augmented reality under a single umbrella. The selection of these advances is an integral part of the future intelligent manufacturing. Data based manufacturing and condition-based maintenance are the fundamental frameworks for the intelligent manufacturing process [9].

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Deep knowledge of physical characteristics such as their static and dynamic stiffness, kinematic/geometric and thermal properties in combination with technologies like big data, cloud computing and sensor-based metrology are the key assets and enablers of intelligent manufacturing. This supports the online decision making by providing the updated status of the machine tool. The exchange of information between the networked machine tools decides about the production system and individual value streams of products supported by CPS [10]. Smart manufacturing changes the point of view to the factories themselves on the component, machine and production system level. A potential development of key attributes and features from today's factory to an industry 4.0 factory are given in Table 1 [11].

Table 1. Comparison of current and industry 4.0 factory [4]

	Today's factory		Industry 4.0 factory	
	Key Attributes	Key Features	Key Attributes	Key Features
Component	Precision	Smart Sensor & Fault Detection	Behaviour Prediction	Degradation Monitoring & Life Prediction
Machine	Productivity and Performance	Condition-based Monitoring & Diagnostics	Self-Prediction and Comparison by smart technology	Predictive Health Monitoring
Production System	Productivity & OEE	Lean Operations	Self-organize and Self-Comparison	Smooth Productivity

Evolution of technological developments reveals that manufacturing industries operations completely centred to the data-driven decision making and productions in future. It clearly indicates that the data will become the supreme source of information to understand the machine tool condition. The acquired data from the machine tool may not be self-assured on its reliability, which would compromise the ability to define the condition of the machine tool. This uncertainty poses an obstacle for the quick implementation of smart manufacturing. Because of connecting the machine tool through the cyber physical system network does not ensures the acquired data are self-sufficient to determine the machine tool condition [12]. Since, the research and implementation of smart manufacturing are evolving area in the field of production, it is required to understand, define and capture the ability of a machine tool. This paper proposes and argues for a definition of the term *machine tool ability*, which includes aspects related to accuracy, performance, function and availability.

2. REPRESENTATION OF MACHINE TOOL ABILITY

A machining system is one of the most important manufacturing units in any production system and therefore its capability – capability as defined below – has an important bearing on the accuracy and flexibility of the system. A machining system described as a material processing unit where a machine tool structure, cutting tools, the workpiece holding fixtures and a workpiece interact with the cutting process to produce a part. To produce parts with required accuracy, the relationship between machining system characteristics (expressed concerning capability) and part accuracy/surface finish must be evaluated in order to control deviations within required tolerances [13]. Further, to uphold the performance and functions of the machine tool, proper maintenance activities need to be planned and executed. However, the machine tool has become a complex mechatronic system consisting of more than thousands of mechanical and electronical components, which are grouped into numerous subsystems. Hundreds of components interact and function together during the machining process thereby making the comprehension of the cause and effect of machine tool degradation at the component and subsystem level complex [14]. This complexity can lead to the point at which there may be complete lack of understanding of machine tool degradation. Thus, the effects of the failure of a single mechanical component or its propagation cannot be properly identified and assessed [15].

The term *machine tool ability* includes the individual and aggregated status of the machine tool related to accuracy and the workspace availability through determining functional ability of the machine tool structure. The functional ability is characterized by the variations in the performance of the machine tool. In other words, the machine tool ability is in second step related to the work piece characteristics through the machining system capability which is adding the effect of machining process.

2.1. STATE-OF-THE-ART CONNECTIONS

The term *machine tool ability* defines key characteristics of the machine tool structure. The aggregated effect of the degradation attributes (cf. Fig. 1) characterizes the overall machine tool degradation to a significant degree. Figure 1 illustrates a model which comprises two different viewpoints of the machine tool. On the left lies the representation of ability status and on the right lies the machine tool structure. The novelty introduced in this paper is the explanation of the term *machine tool ability status* as a combined key performance indicator of function, accuracy and availability status of the machine tool which has influence on the machining system capability.

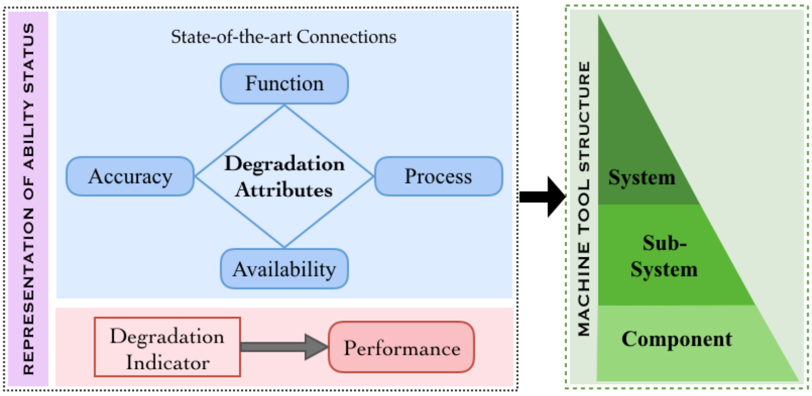

Fig. 1. Model to define Machine Tool Ability Status

The four degradations attributes, which potentially determine the ability of the machine tool need to be considered in every phase of the machine tool lifecycle. The lifecycle of the machine tool is considered to comprise six different phases such as specification, design and development, manufacture and testing, install and commission, operations and monitoring along with maintenance and repair [16]. In the following paragraph, the design and development phase of the machine tool lifecycle is considered to exemplify the interlinkage between degradation and ability status.

An objective of the design phase is to design an optimal component which fulfils the functional requirements (function attribute). The accuracy and availability attributes of the machine tool at the design phase can be considered as functional requirements. Both factors are contradictory, for example consider the different guideways used in the machine tool i.e. frictional guideways provide good damping against high load capacity than rolling guideways and relatively, the rolling guideways are high accurate than the frictional guideways for short distance [17]. Consequently, several design methodologies need to be applied to find the best trade-off i.e. process attributes. The relation of the degradation attributes (cf. Fig. 1) and their impact on the machine tool ability status turn into an interesting area for the research. However, determination of performance indicator level for every individual degradation attributes become complex without understanding the interfaces of the machine tool structure.

3. IMPORTANCE OF MACHINE TOOL ABILITY

The design of the machine tool is equally restricted by accuracy, reliability, automation and sustainability criteria [18]. Correspondingly, the complexity of the machine tool increases with the requirement of high functionality and flexibility. ISO 230 series, ISO 10791 and ASME B5.54 encompass the machine tool health parameters and their test protocols. Similarly, ISO 14649-201 supports the development of the machine tool capability profile. However, a universal standards or procedures has not been established to evaluate the developed test protocol [19].

A good deal of literature and research work has been published on machine tool capability and on health conditions of machine tools. The published works concern the tolerance limits of the produced parts and overall performance of the machine tool although it is lacking in the area of machine tool capability determination at the sub-system or component level. Furthermore, the identification of machine tool capability through the performance assessment of the produced part does not provide the complete status of the machining system or that of any sub-systems and the corresponding component status. Thus, the machine tool ability is proposed to understand the machine tool status at component level and its significance is discussed in the following four sections:

- Manufacturer/supplier, section 3.1;
- Maintenance, section 3.2;
- Manufacturing, section 3.3;
- Industrial metrology, section 3.4.

3.1. MANUFACTURER (SUPPLIER)

The machine tool is designed and constructed according to the required specifications to satisfy the needs of the customer and surpass the performance of competitors. The machine tool industry is moving towards the high-precision systems with a focus on customisation, modular production and products [20]. The trend shows that machine tool manufacturers are moving towards the servitization (service-oriented) of product development as a part of their global competitive strategy [21], [22]. Servitization refers to the tendency of delivering the services and related solutions for the machine tool problem that put forward the manufacturer products in the portfolio [23]. While, twelve service offerings were identified, only three are prominent to the machine tool field i.e., design and development services, installation and implementation services followed by maintenance and support services [24]. However, the servitization provided over the understanding the machine tool capacities through the analysis of captured data and converting them into the knowledgeable information [21].

The ability of obtaining the machine tool performance and sharing the data between the Original Equipment Manufacturer (OEM) and the customer will benefit the comprehensive understanding of machine tool. Most commonly, the machine tool components produced by different suppliers for the machine tool OEM signifies that the OEM has less control of defining the capacities of the machine tool at the component level. This may bring difficulties to understand of the machine tool behaviour at component level which benefits the servitization. Developing the machine tool ability profile along the production of the machine tool by understanding the capabilities at component level will improve the manufacturer servitization. Additionally, this might increase the overall performance of the machine tool at precision, flexibility and productivity which possibly support the better machine tool productions in future.

3.2. MAINTENANCE

Obtaining the best performance and functionality from the machine tool is a challenging task. The machine tool industries found the best solution as an integration of many different technologies to improve the performance and functionality of the machine tool. This trend leads to a constantly increase in complexity for maintenance planning owing to the interdependency of the different technologies is neither transparent nor straightforward [25]. This in turn might decrease the maintenance effectiveness or conversely increase the downtime of a machine tool. Maintenance planning depends on the maintenance policies and excellence management of production [26]. The maintenance management strategies or principles are strong-willed by the decision taking for ineffectual conditions. Today, it seems unclear whether the maintenance activities are performed to establish, uphold and maintain the machining system capability, or to improve capability and rectify a fault. Furthermore, it is extremely important to determine if the machine tool reliability or accuracy are biased or not before initiating the maintenance interventions [27]. On the whole, knowledge of the root cause of the problem for the maintenance activity is often unknown [14], since there is no clear approach to establish and characterize the uncertainties in the system [25]. Thus, the identification of the root cause is becoming complex with respect to the machine tool structure and henceforth, it might be a challenge to describe and measure the degradation of the mechanical component accuracy before a failure.

In Industrial Product-service Systems, the establishment of the foundation of product degradation is referred to as the principal motivation for continuous maintenance [28]. An EU commission action plan for the circular economy aims to enhance reliability and durability of the product which is achievable through continuous maintenance [29]. Diagnostics and prognostics are among the six foundations of the continuous maintenance [30]. Even though many novelty methods and models are proposed for the prognostic analysis and continuous maintenance, there are significant technical challenges to measure the uncertainties related to the machine tools Remaining Useful Life (RUL) [31]. Consequently, the estimation of the RUL accuracy level plays crucial role in the predictive maintenance [32]. The RUL accuracy level depends on the machine tool assessment model which could express the degradation level and the condition monitoring methods [33]. The condition-based maintenance is directly linked to the predictive maintenance strategy and also the machine tool condition. The machine tool condition depends on the machine tool component health status. The component health status is provoked by defining the different modes of degradation states from present to the variation development which prevent the system from failure [34].

The ability management of the machine tool is proposed to understand the machine tool functionality and determine the machine tool degradation status at the component level. Hence, the ability management might support assessment of the remaining useful life (RUL) of the machine tool by distinguishing its health condition and this might prevent the failure by prior prediction of the event.

3.3. MANUFACTURING

High-precision machine tools plays a critical role in producing high accuracy products at an efficient rate. Due to rapid transformation of the manufacturing industry towards adopting an advanced technology dependent machine tool, it is hard to gain a comprehensive understanding of machine tool ability and to measure its behaviour throughout the lifecycle. Process planning and tool selection require an in-depth intelligence and real-time information on machine tool capability to assist in the decision-making process [35].

The machining process decisively depends upon the static and dynamic properties which required to estimate the capability of the machine tool [36]. The optimization and control of the machining process allows the machine tool to operate at its adequate level. Furthermore, it is challenging to determine the machine tool condition [14]. Failure phenomena bear a considerable risk to the quality of the machining product and can even cause a machine tool breakdown. The identification of the root cause could become a solution to a number of obstacles. The advanced instruments and evaluation models support assessment of the machine tool capability through measurement and analysis of physical quantities. It is unlikely that characterizing the machine tool behaviour at the component level would determine the root cause of the failure. Considering technologies not tested or used to its full potential for worthwhile information like root cause identification. In spite to the fact, it raises the question on the scope of the technology [37]. Access to precise and updated information for different models and methods becomes a fundamental requirement for the evaluation of machine tool [38].

The information acquired from the machine tool discloses different functions through the lifecycle of the system. For example, information on the functional and mechanical properties as knowledge base of the machine tool which has potential influences on process planning and also decision making while acquiring new machine tool [39]. Information is the knowledge base but the reliability of the data remains uncertain. The placement and quality of the sensor used for monitoring, the type of physical properties assessed and the consistency of the models and methods used for evaluation could all be sources of for unreliability of the acquired data. The extensive amount of data captured from the machine tool is much higher than a decade ago. The lack of standards and procedures for evaluating the acquired data to obtain generic information has an impact on the machine tool ability determination [40].

The machine tool capability considered in various contexts like metrology and maintenance [41], manufacturing resources development [42] which helps to define and identify the machine tool error and the machine tool health. The evaluation of machine tool capability index help analyses its availability and checks whether the manufacturing processes fulfils the required tolerance limits [43]. In [35], the capability profile is proposed wherein all the machine tool health data are fed into a model and utilised by it through the lifespan. It contains geometric, kinematic and technological configuration as in addition to the overall health information of the machine tool. These elements have an impact on the capability index. At the same time, analysis of the machine tool life cycle with capability index representation is insufficient since machine capability acts as the indication of an error but does not define the root cause of the error at the component level.

The detection of machine tool error and its root cause using advanced instruments and evaluating the reliable data could help uphold the machine tool functions. Therefore, developing a machine tool ability profile supports the manufacturing process by determining the machine tool accuracy and workspace availability for efficient production.

3.4. INDUSTRIAL METROLOGY

The increasing complexity of machine tool structure requires distinct measurement procedures and instruments to ensure its accuracy at the highest level during operations [12]. The measurement data acquired from the machined part shows the capability of the machine tool and also helps to determine the capability indices [43]. Different measurement techniques are need to be established to identify the behavioural changes in the machine tool properties. The foundation of understanding the machine tool properties purely depends on the performance output of the machine tool. While, the performance output is captured using different metrological equipment, the lack of measurement procedures and uncertainties regarding the measurement increases the degree of complexity on understanding machine tool behaviour variations.

Henceforth, identifying the measurement uncertainties and developing new metrological equipment as well as techniques that couples the machine tool with the cutting process are required to understand the machine tool behaviour. An example of an existing device is the loaded double ball bar that emulated the cutting force of a static component during measurement [44]. The understanding of machine tool behaviour enhances the machine tool ability profile and simultaneously expands the research on industrial metrology. For instance, spindle motor vibrations used to analyse and understand the effects of machine crash with spindle and its component [45]. In the following section, the concept of machine tool ability is explained with the help of a case concerning machine tool thermal error.

4. CASE STUDY

The major influencing factor for 75% of overall geometric error on the workpiece is induced by the effects of temperature fluctuation [47]. The thermal error in the machine tool occurs due to the temperature difference and effect of the heat fluctuation on any machine tool component could result in its functional degradation and tool centre point (TCP) error. The temperature induced error probably be avoided and controlled during the design phase or compensated after the installation and operational phase of the machine tool. The following case on spindle thermal error is examined to understand the concept of machine tool ability.

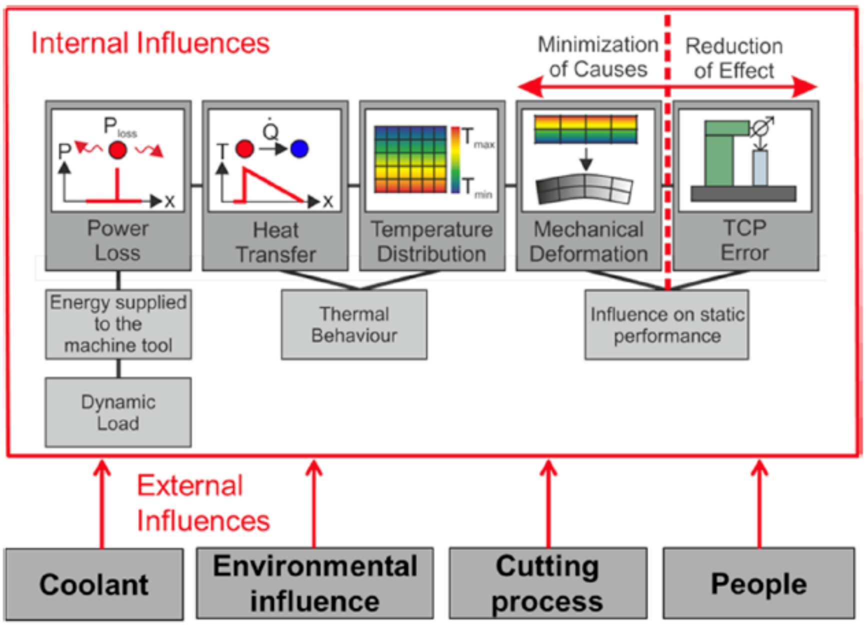

Fig. 2. Chain of causes for Thermal TCP-errors [47]

One of the critical parts of the machine tool structure is the spindle unit which supplies the necessary power for the machining process. The spindle is a high precision system which comprises of several parts, for instance the rotor shaft, electric motor, bearings and the clamping system which are a few major components. However, all the components of the spindle unit should deliver their function within the specification limits which defines their ability and overall the machine tool status. The thermal error in the spindle unit primarily arises from the internal and external heat sources and conduction of the heat leads to its distribution.

The thermally influenced spindle unit performance is coupled with the performance of linked components directly and indirectly linked to it. In the spindle unit, the electric motor and bearings are considered to be the major heat sources. In Fig. 2, the power loss could dissipate as heat and induce heat transfer which results in the temperature distribution across the components and the system. This type of behaviour is referred to as the thermal behaviour of the system. The fluctuation of thermal behaviour leads to the mechanical deformation and the TCP error [47]. Under this scenario, consider the TCP error due to the spindle shaft deviation which is caused by the mechanical expansion of the steel balls in the bearing or mechanical deformation of the shaft itself. The key causes for the rise of temperature and the deformation or elongation of the component is however undetermined. For instance, the rise of lubrication temperature is considered as a primary cause for the expansion of the bearing balls but other possibilities such as the degradation of the cooling system, the selection of an inappropriate lubricant, the chemical composition of the lubricant and many more factors could be possible reasons for the rise of lubrication temperature. Additionally, the primary error induced factor on the system remains unless identified during maintenance. At this stage, the ability profile supports identifying the root causes of the error by comparing the real time functional status of the component and its linked component within the defined functional limit.

From the maintenance perspective, inadequate or improper lubrication is the reason for the temperature rise in the bearing. The ability management which is a part of ability profile of the machine tool may possibly determine the degradation status of the spindle, bearing and other linked components from the analyses of captured performance data. Besides the degradation status, the reliability of acquired spindle performance data is required to identify the remaining useful lifecycle of the machine tool. Eventually, the remaining useful lifecycle of the machine tool also determine the availability status for the further manufacturing operations as well as the machining process. Advanced sensors and different measuring instruments are required to measure the degradation and understand the performance variation effects on workpiece error. The acquired performance data using advanced sensors and evaluation model might support to update the machine tool ability profile and absorb the transformation of functional deviation for the further development.

In [48], compensation of spindle thermal error in machine tool was reviewed. From the review, it is clear that the thermal error could be predicted by developing standard methods and models for certain conditions and error sources. In [49], the spindle thermal error was predicted using analytical methods by considering the shaft thermal elongation due to heat transfer from bearing and its effects on linear thermal error in the axial direction. In [50], the effects of the surrounding temperature fluctuation on the workpiece quality was tested using controlled environment. From the previous studies [48],[49],[50], it is clear that the thermal error could be avoided, controlled and compensated. Compensation on the thermal error shows more promise on resolving the thermal error in the system. However, this is not the permanent solution to eliminate the machine tool error and uphold the machine tool capability.

As long as the machine tool ability profile is developed by understanding the overall functionality and effects of thermal fluctuation as well as possible causes of failure, it enables to uphold the machine tool capability. Therefore, the component level deviation has a significant impact on the overall performance of the machine tool. Moreover, this highlights the need for understanding the component functions and capturing the corresponding component performance data which will benefits in identifying and eliminating the production disturbances.

5. CONCLUSION & DISCUSSION

The significance of the proposed term *machine tool ability* is discussed under four distinct sections and also elaborates on the machine tool ability profile which comprises of ability management to strengthen the determination of remaining useful lifecycle. The case study indicates that the function, accuracy, availability and performance of a single component in the machine tool has a significant impact on the ability of the machine tool. Accordingly, reliable data from different stages of the machine tool structure are required to understand its condition. Since, smart manufacturing is in an evolving phase, it is recommended to understand the feasibility of machine tool performance and the causes for the performance deviations. In conclusion, the performance data and characterization of every single component function is essential to understand the machine tool condition and thus uphold the machine tool ability. Henceforth, it is recommended that the primary move be to establish the standards and procedures required to characterize the machine tool ability from the component level by developing novel methods and tools for a smooth transition towards smart manufacturing and futuristic industries.

The most compelling challenges through this study is the combination of terms used in the research article, for example, the definition of machine capability, machining capability, machine tool capability and machining system capability. Authors used different terms which holds the same meaning which might lead to a point of confusion in the scientific field of production. The solution is to regulate the usage of terms in the research works by developing global guidelines. The few areas of research required includes understanding of behaviour interactions between the machine tool components and characterizing the performance variations which might support the development of a machine tool ability profile at the component level. These research developments could signify the necessity of developing new metrological instruments and methods to determine machine tool ability status. Establishing the standards and procedures to integrate the different technologies into the machining system might increase reliability and the possibility of adopting smart manufacturing for the efficient production in the near future.

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