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Current status, challenges and opportunities of sustainable ultra-precision manufacturing

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Abstract

Ultra-precision manufacturing (UPM) is a promising manufacturing technology for fabricating micro-components and its production volume raises in the coming future due to a significant increase in the production volume for highly technological products nowadays. Therefore, UPM industries are accountable for executing sustainability practices to minimize negative environmental impacts from their manufacturing activities. However, sustainable UPM is difficult to execute practically up to now due to different aspects such as technology and knowledge gap. With a high speed of technology advancement nowadays, UPM industries enable to leverage this technological chance and employ the Internet of Things (IoT) technique to move UPM toward sustainability. Therefore, in this article, the current status and future perspective of sustainable UPM, the major research and technological gap between UPM and sustainability development, specific technical challenges for integrated IoT to UPM for sustainability goal are discussed and revealed to promote sustainable UPM. And consequently, a preliminary framework of IoT based UPM system with particular suggestions was firstly presented for facilitating sustainable UPM and acts as the reference to related industries and academia for further developing this novel technique in the future.

Keywords: Internet of Thing; Ultra-precision machining; Sustainability development; Sustainable ultra-precision manufacturing

1. Introduction

Industries and academia have critically voiced concerns about sustainability practices in manufacturing today. Manufacturers acutely aware of sustainability issues, in particular, to identify and realize the relationships between manufacturing activities and the induced negative environmental impacts (Rosen and Kishawy 2012). Because of a considerable rise in the production volume of micro-technological products recently, ultra-precision manufacturing (UPM), as one of the essential parts in the manufacturing sector, starts to be one of the main fabrication approaches for scientific originalities.

Generally, UPM is one of the efficient fabricating approaches to generate optical and micro dimension components, which the application of the components cover wide areas such as illumination, communications, medical, automobile, and aerospace (S. J.Zhang et al. 2015). UPM technology is denoted as the reachable machining form accuracy less than 0.2μm and surface roughness less than 10nm (Ikawa et al. 1991; McKeown 1987). Surface roughness and form accuracy for UPM are one thousand times and one hundred times better than that of traditional machining approaches respectively. At the beginning state of UPM, UPM is planned to fabricate high precision components for soldierly purpose (Ikawa et al. 1991). And stepped into the 1970s, UPM was developed to fabricate components for various areas such as computer and electronics (Corbett et al. 2000). And thanks to technological advancement and the development of high precision machinery, UPM has been efficiently used to manufacture components with freeform surfaces having microstructures. And, the three main sub-technologies of UPM is single point diamond machining, ultra-precision milling and ultra-precision grinding. Generally, UPM is an evolutionary development of recent machining approaches, which a gradual trend and the reachable machining accuracy over the periods is shown in Figure 1. The generation of nanometric surface roughness by UPM is highly related to multiple factors including machine toolings (Shindo and Nishiwaki, 2020), machining parameters (D.Chen et al. 2017), tool materials and geometry (Rahman et al. 2018), material properties (Rahman et al. 2017) and machining vibration (Aggogeri et al. 2020). In general, the proper combinations of the above factors would result in better surface quality. The surface generation by UPM is featured by the unique machining response of UPM especially material swelling, those features occupy the cutting mechanism of UPM. Excellent surface quality generated from UPM reflects the significant cutting performance and is acted as the particular signature of UPM technology nowadays.

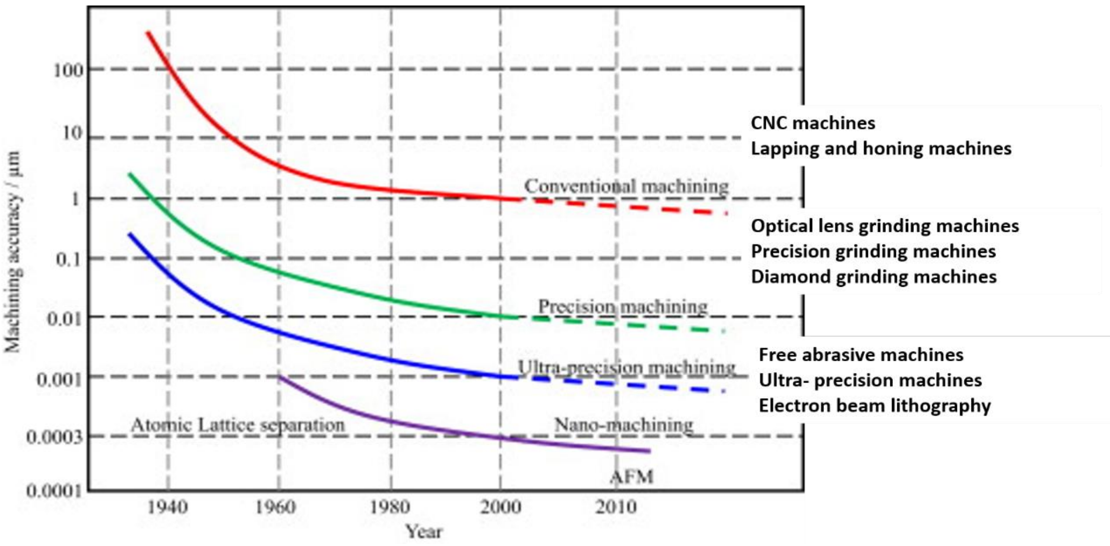

Figure 1. an evolutionary development of UPM (Shore and Morantz 2012)

According to the information on micromachining from the market analysis report, the value of the micromachining was equivalent to 2.51 billion USD in 2019 globally and is believed to grow to a compound annual growth rate at 7.3% from the year 2020 to the consequent seven years. The expansion of the market is mainly caused by the rising adoption of UPM (enable to perform micromachining), which has high capability to fabricate the micro-components especially in the areas of robotics, electronics and aeronautics (Kumar et al. 2019). At the national level, different big projects relating to UPM have been carried out. The United States starts the National Nanotechnology Initiative Plan and also Japan runs the Nanotechnology Support Project (Yuan et al. 2017). All of the above demonstrated the importance of UPM activities nowadays. Therefore, the environmental impacts from UPM activities to nature should be emphasized, which it is believed that the implementation of sustainable UPM will assuredly make enormous contributions to our society.

With the analysis of the influence of UPM activities on different sectors, the level of environmental impacts of UPM is dominant in our society and is similar to that of traditional manufacturing (Modica et al. 2011; Yip and To 2018). Therefore, sustainable development for UPM is urged to promote. Actually, sustainable manufacturing is treated as one of the main directions for future manufacturing (Jovane et al. 2008). However, implementations of sustainability practices for UPM remain challenges to industries as the sustainability concept is incredibly complicated (Rashid et al. 2013) with inclusions of various barriers in the research stages. For example, the strategies of choosing cutting fluids still need further investigations to reduce the health risk for operators (Mia et al. 2018). Although fluid lubricants cause damages to the environment and health, it is still widely used in mass production for the commercial purpose (Yip and To 2017). Also, and a weak synchronization of large data flows from different machinery needs to be resolved for smoothening the entire UPM process, which further imposes difficulty in the issues of energy and resource efficiency. In the following sections of this article, the current works and challenges of sustainable UPM, and the preliminary framework of IoT based UPM would be detailly discussed and acted as a reference to the related industries for enhancing sustainability development of UPM.

2. Current works and challenges of sustainable UPM

2.1 Current works of sustainable UPM

UPM is performing a decisive role in the manufacturing sector which the sustainability development of UPM maintains steadily growing and filling industries. Nowadays, the executed approaches for sustainability development of UPM are normally in the two directions (1) reducing and adapting the lubrication strategies and (2) optimizing energy consumption models of UPM.

Researchers emphasize revising the lubrication strategies to attain the sustainability goals of UPM in these recent years. Selections of proper cutting lubricants with optimum usage rate become challenges for UPM industries (Schneider et al. 2019). The literature stated that UPM applied various lubrication strategies including ionic lubricant (Pham et al. 2014), cryogenic machining (Kakinuma et al. 2012; Zou et al. 2018), minimum quantity lubrication (Kuila and Melkote 2020; Vazquez et al. 2015), and dry UPM (R.Tan et al. 2019). Pham et al. (2014) used ionic liquids as lubricants in micro-machining, relatively quality machined surface was obtained in comparison with using traditional oil lubricants. Vazquez et al. (2015) and Kuila and Melkote (2020) facilitated sustainability development of micro-manufacturing by examining dry machining and minimum quantity lubrication in manufacturing of difficult to cut metals and accomplished significantly decrease cutting fluid consumptions. Kakinuma et al. (2012) implemented cryogenic micromachining of polymer using liquid nitrogen to successfully fabricate nano/microfluidic chips with high accuracy. Zou et al. (2018) used minimum quantity lubrication with nitrogen to enhance the cutting performances of the diamond tool in UPM and also offer a feasible way to machine ferrous metals. Tan et al. (2019) employed ultrasonic vibration-assisted diamond cutting without lubricants to successfully reduce tool wear and lubrication amount. Yip and To (2017) employed dry UPM, which the results showed that dry UPM with a magnetic field enabled to reduce diamond tool wear and increase the surface quality, with reduction of lubrication simultaneously. For the above particular lubricant strategies, however, tool and nozzle positions are needed to set detailly because of the extremely small size of the cutting interface in UPM, also, as the lubricant applied continuously, the chip generation will become highly curled which largely blocks the outflow of chip and therefore small fragment ship will output; this will interference the effectiveness of lubricant to cool down the surface as it does not have sufficient evacuation (Marksberry 2007). Because of the above, the involved tool and nozzle calibration are conspicuously time-consuming and therefore these lubricant strategies are not completely considered as environmentally friendly. Furthermore, as the high cutting temperate is generated at UPM processes, a reduction in lubricant amount for attaining the environmental goal normally lowers the machined surface quality which is not satisfied for the requirement of high precise level for UPM products. Another concern for the lubrication in UPM is the safety risk of the operators (Schneider et al. 2019), the cutting fluids are a medium for the growth of microorganism; also, as the chips generated from UPM are extremely small, which causes easy inhale of them. The use of the lubricant in UPM will cause respiratory issues to skillful workers because of the vaporization of chemicals (Carr and Feger 1993). However, in order to obtain the optimum quality of the machined surface from UPM, the uses of lubrication are hard to avoid. These drawbacks make lubrication strategies hard to implement for the green direction of UPM.

Apart from the direction of reducing the lubrication usage, researchers engaged in the energy reduction strategies by optimizing energy consumption models for sustainability improvement of UPM too. Normally, the energy models involve the parameters relating to manufacturing efficiency and resource consumptions such as diamond tool-related energy, material removal rate and energy used for removing per unit materials etc. (Yip and To 2018). Cui et al. (2019) employed statistic and theoretical energy modeling using the factors of diamond tool geometry, cutting force and specific cutting energy to achieve the sustainability target by minimizing the cutting energy consumed in micro-machining. Bi and Wang (2012) investigated the kinematic and dynamic energy consumption model denoting the features of manufacturing tools in micro-machining, the results showed a decrease in energy consumption for specific drilling operations. Franco et al. (2016) investigated the energy consumption of micro-manufacturing using a specific energy consumption model for boosting the production profit with the consideration of energy use in industrial practices. However, as the unique machining mechanism of UPM, the inputs for energy consumption modeling are required to consider a large number of factors with atomic scale, such as hydrostatic stress distribution, cutting forces, friction force at the tool/workpiece interface, subsurface temperature and surfacel energy (Dai et al. 2017). The considerations and balance of a large number of factors for the energy model of UPM add challenges to sustainable development. Moreover, machine tools in UPM are connected with numerous auxiliary devices, causing it hard to obtain the explainations of the energy consumption of machine tools (Yoon et al. 2014). The above act as the blocks of application of energy consumption model to support sustainable UPM.

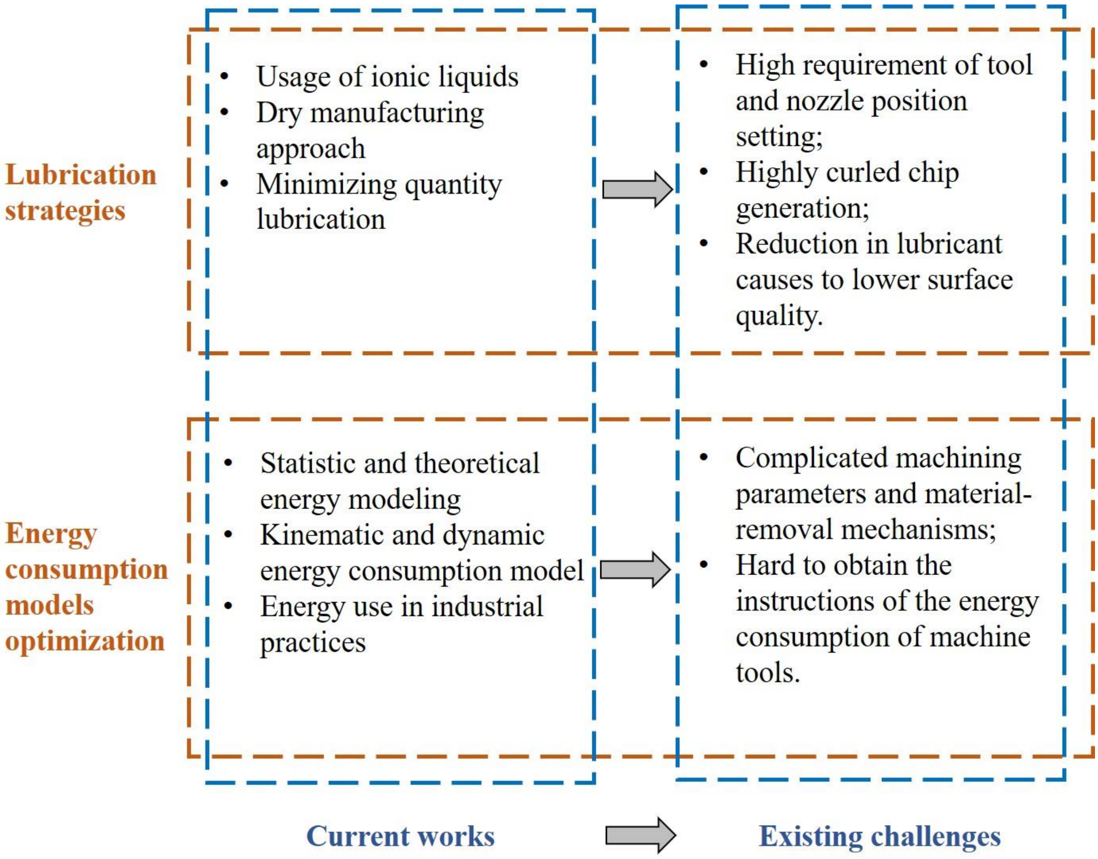

Figure 2. The overall current works of sustainable UPM

2.2 Main challenges of sustainable UPM

Up to now, the barriers of sustainable manufacturing fall into technical, political, and commercial categories. In this article, only technical barriers in sustainable UPM are discussed as it is fitted to the scope of the journal and able to be managed by IoT technique. An impracticability of realizing the sustainability concept in UPM is because of below technical barriers:

(1) High experimental cost for analysis and modeling

Normally, the cutting tools employed in UPM are a single and polycrystalline diamond tool, which they are always high cost (Yuan et al. 2017). A polycrystalline diamond tool is a good choice for the materials for high-performance cutting tools for manufacture due to its ultra-high hardness which is up to 8000 HV and outstanding thermal conductivity which is 560 W/m K (Pan et al. 2013; Wu et al. 2018). However, a high wear rate in UPM for PCD tool causes difficulties in application and resulting in enormous manufacturing costs which severely retards the expansion of its applications. For single crystalline diamond tools, it enables to cut traditional alloys, such as copper alloys and aluminum alloys, to achieve excellent surface quality, however, it degrades rapidly in UPM processes especially in manufacturing difficult to cut materials for highly technological products such titanium alloys and metallic glasses (X.Chen et al.

2017). Diamond tool wear not only increases the machining cost but also deteriorates the manufactured product quality. On the other hand, problematic tool wear is also serious when machining large radius and components with complicated geometry (Yan et al. 2003), which freeform surface is frequently required for high technological products nowadays. Because of the high tool wear rate in fabricating complicated shapes of components, the tool is needed to change frequently which causes large consumptions in natural and human resources, they are all uneconomically friendly in UPM.

(2) Long manufacturing time

In UPM, meticulous calibrations and precise measurements are fundamentally needed for satisfying the demanding requirements of accurate levels for micro-manufactured products. Also, due to the separated and unlinked natures for the above processes, the time involved in the initiation and completion of entire UPM processes is always long for UPM (Huang et al. 2018). For instance, although some researchers have started to build up an automatic calibration model for UPM by using evolution algorithms, manual calibration is still a common approach nowadays. And the work shift from manual to automatic calibration leaves a long-time gap. Similarly, the studies of automatic measurements for UPM are also limited. For example, if we like to fabricate a component made with easy to cut materials such as aluminum alloys with a volume of $5cm^3$, the processing time for polishing surface or produce mirror surface quality is normally 70 minutes per unit including tool calibration, workpiece fixation, tool monitoring and measurement of surface quality. The long duration of fabricating components causes high consumption of resources in term of energy, natural materials human power, which it adds obstacles in sustainability development of UPM.

(3) Complicated energy-saving model

In UPM, molecular dynamics (MD) simulation is popularly used and confirmed as one of the effective approaches for modeling machining processes in micro and nanometric scales (Dai et al. 2017). However, MD simulation for energy-saving models is a complicated procedure and it needs high numbers of input parameters such as stress distributions over the tool and workpiece, hydrostatic stress distribution (Dai et al. 2017), atomic displacement, material removal rate, cutting forces, frictional coefficient, subsurface temperature (Guo et al. 2017) and potential energy. The lengthy formulation poses challenges for researchers to build up the model for energy saving purpose. The sustainability level will be increased because of the high manufacturing cost and energy consumption induced in UPM, which increases the economical aspect in the sustainability of manufactured products by UPM (Schneider et al. 2019). Furthermore, the resolution of the model in MD is based on the atomic scale which highly relates to the inter-nodal distances (Komanduri andRaff 2001), and, unfortunately, they are not matched with UPM practical situation especially for cutting depth and speed. Also, the size of the workpieces in UPM is commonly small so it causes difficulty in modeling, the determination of manufacturing parameters is not easy under the strict requirements for small workpieces (Aly et al. 2006). Those intricate computation and developmental steps require higher consumptions of human, electrical, and computation powers which oppose sustainability goals in manufacturing.

(4) Infeasible adjustment of models

The existing UPM model is built up for particular machining conditions. Once the dominant parameters in the machining processes are adjusted, the entire model is infeasible to update as real-time changes (Rao et al. 2014). Additionally, because the cutting quality of UPM is sensitive to uncertainties in chip formation processes, the impact of change in manufacturing parameters becomes remarkably difficult to evaluate (Cheng et al. 2015). Moreover, complicated interactive relationships exist within various manufacturing parameters in UPM, which leads to an infeasibility of model adjustment (Yip et al. 2020). All the above lengthen the total modeling time and technology cycle of UPM, and consume human and machining tool resources heavily. Consequently, they are not preferable for the fast-technological change and the customer demand on the high technical product in this era.

(5) Lack of accurate real-time for monitoring UPM processes

Researchers indicated that it is difficult to obtain optimum machining conditions (Yip et al. 2020) because of the limitations in acquiring real-time data technique in UPM (Cheng et al. 2015; Kan et al. 2016). The primary difficulty for real-time monitoring for UPM is the constitutional complexity and problematic computational overhead. The detection is sensitive to manufacturing parameters in a UPM environment as the manufacturing parameters involved in UPM are extremely small in values, which potentially increase the possibility for delayed detections (Shamsan and Cheng 2019). Due to the difficulty of situ data-driven monitoring of UPM, traditional ways such as simulations, integral neural network analysis are ineffective in depicting complicated UPM. As a result, researchers tend to establish complex models to determine the transient dynamics of UPM rather than make use of other effective tools especially real-time monitoring techniques.

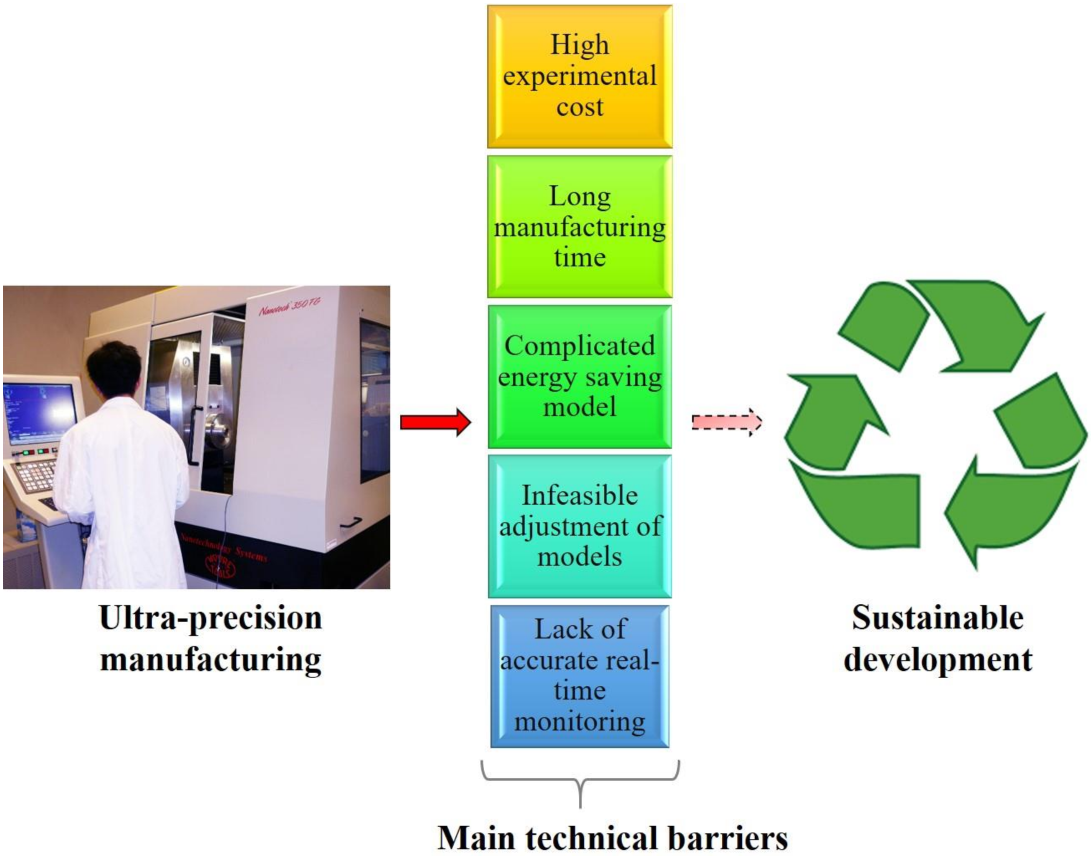

Figure 3. The overall difficulties for sustainable UPM

3. IoT technique in manufacturing

Literature showed that an accomplishment of sustainable UPM is strongly dependent on energy consumption models and the lubrication conditions, however, as mentioned in previous sections, they consist of drawbacks that compensate for the benefits to the sustainable development of UPM. Apart from these two directions, up to now, there are limited research works carried out for the sustainability direction of UPM (Bi andWang 2012). With a rapid evolution in technology and recognition of IoT technique nowadays, IoT technique covers a promise of new manufacturing page, UPM units should take this technical chance and employ IoT technique to execute sustainable UPM easier.

The basic concept of the IoT technique is to make devices smart. It applies a smart device network to obtain critical data from the target devices with installations of sensors and uses cloud computations to convert the real-time data into valuable information which all above support to speed up the operation rate of different devices (Oztemel and Gursev 2020). In recent years, the IoT technique has been merged and applied to conventional manufacturing to deliver its definite advantages in sustainability development in manufacturing processes (Redelinghuys et al. 2019). Park et al. (2020) examined IoT techniques on the energy management of a manufacturing system and found out that the energy consumption and efficiency of different production steps decreased sharply by using the IoT technique. Liu et al. (2017) applied an IoT-based assembled system for mechanical products, they obtained the results that the efficiency of pre-planning and production for the system with IoT considerably improved. Babiceanu and Seker (2016) examined the predictive manufacturing of cyber-physical systems for cloud manufacturing and showed a high capacity in processing by employing the IoT technique. Tan et al. (2017) announced IoT software for following energy consumption in a manufacturing shop floor, the software permitted to help managers to implement better energy management practices and minimize the energy wastages in the manufacturing shop floor. Other than the above energy reduction spotlights, the IoT technique also supports management (Y. Zhang et al. 2017), security measurement (Yi 2020) and data noise removal (Liu et al. 2020) in manufacturing.

Although the IoT technique has been formerly employed in different aspects of conventional manufacturing, it has never been employed in UPM to enhance the sustainable development of it. The potential reasons for that are mainly because of the fragmented nature of UPM. UPM is denoted as one of the non-conventional manufacturing technologies and comprised of extensive knowledge of complicated cutting mechanics and machinery theory; therefore, the higher threshold of understanding UPM knowledge makes the mislinkage between UPM and the IoT technology nowadays. Actually, precision productions highly rely on skilled operators with mechanical knowledge for controlling high technological machinery because of the necessity of high precision productivity levels. However, the skill and knowledge of high precision products are formidable to transfer within industries (Sadoi 2009), mostly because of the obstacle from manufacturing firms that they likely apply licenses for precision technology to protect the manufacturing skill (Maher et al. 2001) and take capital-intensive technology to maintain the manufacturing cost, the technology development and transfer, therefore, are distorted (Amin 1977). Furthermore, an integration of information technology with the sustainable UPM is difficult to reach since there is a large technological gap between them; IT is in a mature stage with accurately defined areas currently while sustainable UPM is still in a progressing stage and has not been converted to a well-developed knowledge. For instance, the expert database of ultra-precision cutting, grinding, and polishing processes has not been established (Yuan et al. 2017), which can cause a lack of raw data for the sustainability development of UPM. Therefore, a convergence IoT technique and sustainable UPM still lags in both academic and industrial areas, affinities of interdisciplinary knowledge are required for widening IoT technique capabilities and to offer the chances to deploy IoT technique to achieve sustainable UPM. IoT technique is recommended to apply to the UPM to enhance its sustainable development, in terms of energy efficiency, manufacturing resources, and human power supporting.

4. Linkage of IoT to sustainable UPM

As mentioned in the previous section, one of the main problems of executing sustainable UPM is to handle a large amount of data with dissimilar patterns, which leads to long processing time, difficulty in modeling and real-time data monitoring. Indeed, the sustainability of manufacturing should be responsible for the establishment of new products and fabrication with the continuous improvements to the social, economic and economical aspects to meet the public, industries and academic contentment (Suma 2019). With this expectation, we could expect that IoT technology could act as a support to bridge the gap between UPM and its sustainable development. More specially, combining two technologies enables to facilitate productivity by circulating data, conducting specialization in processing UPM data and smoothening the data processes in the entire UPM. Although the complicated UPM processes generate large data flow, which is treated as a block of extracting meaningful information to enhance the sustainable development of UPM, at the same time, the large data flow could be made use to generate valuable information by IoT technology, which this blocks will turn to be an opportunity to facilitate sustainable UPM. IoT technology generates a new way for UPM to increase the performance in social, environmental, and economic aspects for sustainability development.

With the recently fast growth in sensor and communication sectors, a new pulse to IoT Technology and its application in manufacturing are generated. IoT enables the integration of lots of sensors in different locations and connects them, which the data from the sensors obtain enriched information of operation signal of machinery, and consequently, an excellent opportunity for the manufacturers to obtain instant machining conditions and thereby control and monitoring of machining processes. The use of big data analysis is essential to realize the IoT technology in manufacturing. More specially, IoT based manufacturing involves data processing, network modeling for data transfomation, status monitoring, and error diagnosis (Kan et al. 2018). Firstly, the algorithm to distinguish the dissimilarity of data patterns from machinery is established. After that, The network based algorithm is used to develop a large scale network for machinery involved in the IoT network, in which the distinguished data patterns from different machinery are maintained in the memory chips of network members. When the machining operation changes, the data flow and data locations within the network members follow to change too, and then the network members reflect the diagnostic information of machining conditions. The large amount of data generated from the network members are now computable because of the strong network based algorithm. With advanced knowledge in IoT, parallel computing strategies are good for the multiple processors for accelerating network modeling of such a large amount of data with the variations of characteristics and cyclic patterns (Kan et al. 2018). In the IoT network of machining, the heterogeneous types of data are continuously obtained which the data types include machining vibration, force, tool condition, acoustic wave, and power consumption of machinery, etc. These data contain the real-time features of the devices in manufacturing. For example, the power consumption profiles, the information of the energy consumption of the devices over time, and, the cutting force in three cutting directions, are obtained. All the data input from the network members to network based algorithm are sufficient to show different cutting conditions such as lubrication, tool and the surface generation. Therefore, the above benefit from IoT are believed to accelerate the sustainable development of UPM in terms of energy consumption modeling, tool condition, machining time and the connections between individual UPM processes especially in measurement and machining in UPM, supporting UPM toward sustainability.

Generally, data analysis and sustainability are the main disciplines in manufacturing processes. They consist of the elements leading them convergence, which include a design for disassembling and assembling, the involvement of the life cycle assessment, green management for efficient resource consumption; sustainable strategies for reducing safety risks of stakeholders, and removal of toxics compositions in manufacturing processes (Machado et al. 2020). Therefore, we could expect that IoT technology benefits to various areas including enhancing productivity (Yao et al. 2019); reduction in energy consumption (Marrocco et al. 2017); encouragement of stakeholders' cooperation, which all of the above are the goals of sustainable UPM. Moreover, because of the expectable synchronization between each step of UPM by IoT technology, the opportunities for IoT to manufacturing could be extended to the development of the energy model and product life cycle (Zheng et al. 2020), industry symbiosis networks for resource efficiency (J. Zhang et al. 2019) and sustainable process design (Stock and Seliger 2016), which the above enable to lead UPM toward sustainble.

4. Proposed preliminary IoT based UPM toward sustainability

This part discusses how to embed the IoT technique into UPM practically in order to enhance the sustainable development of UPM. The proposed IoT technique enables the modification of UPM machinery and forms a smart machinery network for UPM to achieve sustainability goals.

UPM machinery especially fixture for holding the workpiece, diamond tool holders, tool calibration equipment, thermal camera for detecting cutting temperature, and force sensors are installed with self-developed sensors and RFID kits, making the UPM machinery smart. The above can facilitate the data circulation and synchronization to enhance the data processing within UPM machinery. The real-time collected data from the smart UPM machinery is then transmitted to the established cloud computation layer to perform modeling. The preliminary designed IoT based UPM makes use of the technology advancement nowadays to enhance sustainability improvement of UPM, modifying UPM to cost-efficient and environmentally friendly manufacturing techniques and benefiting industries producing highly technological products. In the preliminary design, smart UPM machinery using sensors and RFID techniques are suggested to develop at first. After that, a cloud computation platform for conducting computation using historical and real-time data is developed for sustainable UPM energy modeling with focusing the parameters of resource-related such as material removal rate, energy usage from machines and tool usages, etc., which the parameters reflect the human and natural resource consumptions. Then, a user-friendly view system is recommended to develop in order to show the online machining status and monitor the analyzed reports to the end-users. The preliminary design of IoT based UPM machinery network is illustrated in Figure 4. Basically, the proposed IoT based UPM machinery network composes of a few smart UPM machinery, UPM network composed of smart UPM machinery, a computation platform and data processing servers, the detail of the suggested IoT based UPM and the illustration graph are shown below, and Figure 5.

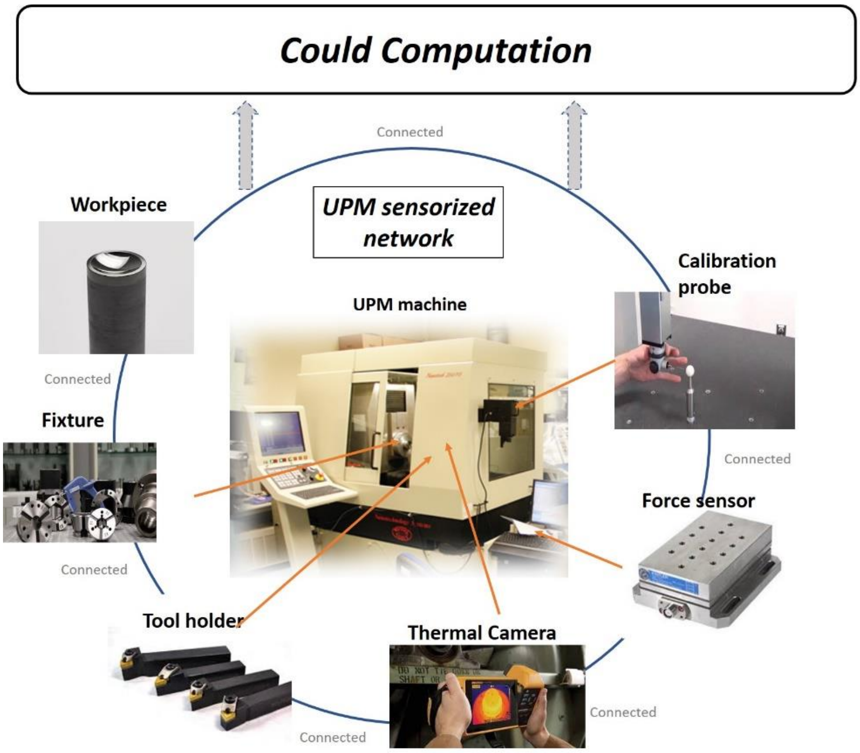

Figure 4. The preliminary design and IoT based UPM machinery network

Smart UPM machinery: Various sensors are recommended to install into the UPM machinery to make the UPM machinery smart. The type of sensors will be chosen base on the nature of the devices. For example, a vibration sensor is installed at the tool holder while a temperature sensor is installed at the fixture with the position near the workpiece. Position sensors and optical sensors are also suggested to be selected for applying to the smart UPM machinery too.

UPM machinery network: Smart UPM machinery with sensors are collected all together and so that the smart machinery could be "communicated" with each other smoothly. Smart connections between UPM machinery are developed based on the communication standard in communication technology nowadays. Wi-Fi, Bluetooth and physical cable are all advised to employ for linking the smart UPM machinery. The basic requirement of smart connections is to provide accurate data communications and offer the central cloud computation platform to monitor the connections precisely.

Cloud computation platforms: A large amount of real-time and historical data is obtained through individual smart UPM machinery and shuffled within the smart UPM machinery network. Therefore, in order to carry out an analysis of the collected data, computation platforms are required to develop to categorize various heterogeneous and homogenous data from UPM smart machinery. The expected data formats of collected data should follow the International Organization for Standardization (ISO), American and industry standards. After processing the data into an accessible format, the data will be accessed by cloud-based computations for building different energy models for sustainable UPM. Specific models, algebra algorithms, autoencoder and deep machine learning approaches are employed to perform computations for developing the energy saving models for sustainable UPM, which the above contribute to eliminating the complicated steps in energy modeling and providing feasibility to adjust the model depending on the practical UPM environment. The sustainability development of UPM will speed up and become smarter for the time being with more executions of manufacturing activities because the accuracy and performance of the model are undertrained in each data collection time, which all above reduce the consumptions in human resources and energy.

Smart viewing systems: Smart UPM view systems should be developed and installed for monitoring the interface between the end-users and the smart UPM machinery,and demonstrating the real-time status of machinery. The analysis results obtained for sustainable UPM will be shown to the users with the formats of chart, words and numerical values through the smart view systems. This smart view system enhances the visibility of the real-time status and the information of UPM machinery.

Sustainable UPM database: The data collected from the IoT based UPM system is suggested to be stored in SQL server and developed as a database for industrial uses. SQL Server is a database server offered by Microsoft and it can be used by other interfaces or applications at the user level, therefore the access of the database is much wider and the concept of sustainable UPM could be expanded.

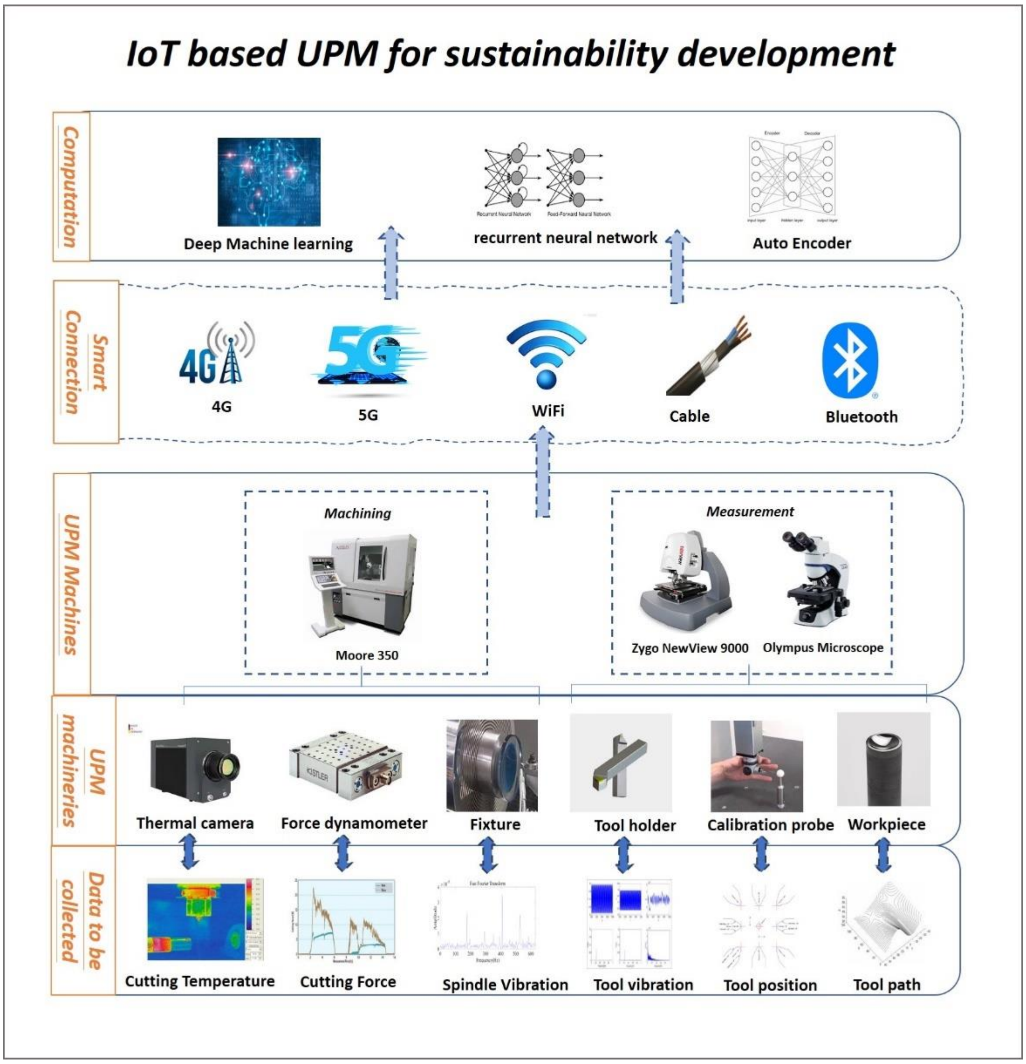

Figure 5. The detail IoT based UPM and the detail component

The conventional approaches now become unfeasible to digest the data of UPM processes due to the complexity and unrelated data patterns between each UPM process. The handling approaches by IoT for obtaining valuable information of UPM from the large data flow are better than that of conventional approaches such as data processing software. The proposed IoT UPM system integrates UPM with IoT technology to provide a platform to analyze and extract meaningful information from the large data flow in the UPM processes by different kinds of connected smart devices. More specially, The proposed IoT UPM system is to offer intelligence to the manufacturing processes, enable the device connections and make them in charge of the data processing as same as a human being, which it supports to analyze the enormous data in real-time and decision machining in UPM with faster time and higher accuracy. Taking the example of large data generated by the sensors from different UPM units in various locations, the data gathered from those devices in real-time could be processed by the network members in the proposed IoT based UPM network with high speed and instant analysis, this resolves the problem of long processing time and enormous human recourse for executing real-time monitoring of UPM processes. One more example is illustrated, the large data flow from a force sensor in the IoT based UPM system contains the information about cutting mechanics of UPM, especially cutting, plowing and sliding created in the manufacturing processes; with the high-speed computing platform and the built-in sophisticated instrumentation linked with IoT concept, the analysis of tribological and cutting behaviors between tool/workpiece interface becomes feasible, and therefore the operators can know the energy consumption involved into the particular cutting mechanic with the true precision level. All of the benefits from IoT technology push UPM toward sustainability, they increase the machined surface quality of UPM, reduce production cost and risk in long term, which enable us to retain the UPM in the future without bringing environmental damage to our nature and satisfying the needs of global business by resolving the underlying problems of UPM.

6. Future prospects and notices for sustainable UPM leveraging by IoT technique

To realize sustainable UPM, the IoT based UPM has been proposed in this study and focused on knowledge integration between mechanical and information technology. The preliminary design of IoT based UPM is shown in Figure 5. As shown in Figure 5, the main concerns of IoT based UPM cover the equipment, collection data in the manufacturing process, and the computation platform. Every single component relating to smart UPM machinery is needed to fabricate, installed, and tested comprehensively in order to complete the whole IoT based UPM system perfectly, which is the common difficulty dealing with intelligent data mining (Wang and Huang 2017). However, they are the new opportunities for manufacturing and commercial units as the above processes trigger the commercial and manufacturing sectors to produce and sell micro-devices, sensors, RFID kits, and new vacancies of skillful technicians for installing and quality check. Therefore, it further boosts the job and product markets and brings positive influences on our society. On the other hand, synchronizations and deviations of manufacturing parameters, the upstream and downstream relationships between UPM smart machinery are also important for this newly proposed technique in order to connect all the smart UPM machinery to form the smart UPM network. Actually, this intelligent UPM manufacturing should have mature and continuous human and machine interaction for successfully implementing, the below lists the relating issues needing to be noticed.

(1) **The issue of component reliability.** As mentioned before, every single smart UPM machinery is needed to synchronize precisely and so that they can "communicate" smoothly with each other. It ensures that the whole IoT based UPM system works perfectly.

(2) **The issue of showing the status of each smart machinery clearly.** It is essential to get a clear visual control panel to monitor the smart machinery online. It is a kind of tool to support and enhance the capability of human-machine interaction for IoT based UPM system

(3) **The issue of adapting the change in the UPM environment toward sustainability development**. This is a long-standing problem for UPM industries. The changes in the UPM environment due to fast evolutions and demands in high technological products cause constant modification of UPM machinery. Therefore, the challenges will be added on analysis of integral real-time and historical data, because of getting sufficient data analysts for particular manufacturing processes of UPM.

UPM units should seriously address the above issues in applying the intelligent IoT based manufacturing system. An information technology, mechanical and environmental development experts should cooperate and involve in the development processes, so that all the processes will include crucial elements including human, machine, product development, environment and factory management for executing IoT based UPM system successfully to enhance the sustainable development of UPM.

7. Conclusion

This article has discussed the current status of sustainable UPM, the major issues of sustainable UPM and, the research and technological gap between UPM, sustainability development and information technology. Based on all-round analysis and elaborations in this article, challenges, suggestions with future directions of sustainable UPM were examined. And consequently, the preliminary framework of IoT based UPM system for sustainable UPM was demonstrated. In the end, the potential issues with special suggestions to the IoT based UPM system for further development have been discussed too. With the collaborations and supports of experts from various areas, the proposed IoT based UPM technique employs the power of information technology with the best fit to the main trend of technological development in recent years, expecting to leverage the substantial benefits from big data to achieve sustainable UPM.

Declarations

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References:

Aggogeri, F., Merlo, A., & Pellegrini, N. (2020). Active vibration control development in ultra-precision machining. *Journal of Vibration and Control*, 1077546320933477.

Aly, M. F., Ng, E., Veldhuis, S. C., & Elbestawi, M. A. (2006). Prediction of cutting forces in the micro-machining of silicon using a "hybrid molecular dynamic-finite element analysis" force model. *International Journal of Machine Tools and Manufacture*, *46*(14), 1727–1739.

Amin, S. (1977). *Imperialism and unequal development* (Vol. 26). Monthly Review Press New York.

Babiceanu, R. F., & Seker, R. (2016). Big Data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook. *Computers in Industry*, *81*, 128–137.

Bi, Z. M., & Wang, L. (2012). Optimization of machining processes from the perspective of energy consumption: A case study. *Journal of manufacturing systems*, *31*(4), 420–428.

Carr, J. W., & Feger, C. (1993). Ultraprecision machining of polymers. *Precision Engineering*, *15*(4), 221–237.

Chen, D., Gao, X., Dong, L., & Fan, J. (2017). An evaluation system for surface waviness generated by the dynamic behavior of a hydrostatic spindle in ultra-precision machining. *The International Journal of Advanced Manufacturing Technology*, *91*(5–8), 2185–2192.

Chen, X., Xiao, J., Zhu, Y., Tian, R., Shu, X., & Xu, J. (2017). Micro-machinability of bulk metallic glass in ultra-precision cutting. *Materials & Design*, *136*, 1–12.

Cheng, C., Wang, Z., Hung, W., Bukkapatnam, S. T. S., &Komanduri, R. (2015). Ultra-precision machining process dynamics and surface quality monitoring. *Procedia Manufacturing*, *1*, 607–618.

Corbett, J., McKeown, P. A., Peggs, G. N., & Whatmore, R. (2000). Nanotechnology: international developments and emerging products. *CIRP Annals*, *49*(2), 523–545.

Cui, P., Shi, Z. Y., Li, X., & Duan, N. M. (2019). Evaluation of specific cutting energy considering effects of cutting tool geometry during micro-machining process. *The International Journal of Advanced Manufacturing Technology*, *102*(5–8), 1127–1139.

Dai, H., Chen, G., Zhou, C., Fang, Q., & Fei, X. (2017). A numerical study of ultraprecision machining of monocrystalline silicon with laser nano-structured diamond tools by atomistic simulation. *Applied Surface Science*, *393*, 405–416.

Franco, A., Rashed, C. A. A., & Romoli, L. (2016). Analysis of energy consumption in micro-drilling processes. *Journal of Cleaner Production*, *137*, 1260–1269.

Guo, X., Li, Q., Liu, T., Kang, R., Jin, Z., & Guo, D. (2017). Advances in molecular dynamics simulation of ultra-precision machining of hard and brittle materials. *Frontiers of Mechanical Engineering*, *12*(1), 89–98.

Huang, R., Zhang, X., Neo, W. K., Kumar, A. S., & Liu, K. (2018). Ultra-precision machining of grayscale pixelated micro images on metal surface. *Precision Engineering*, *52*, 211–220.

Ikawa, N., Donaldson, R. R., Komanduri, R., König, W., McKeown, P. A., Moriwaki, T., &Stowers, I. F. (1991). Ultraprecision metal cutting-the past, the present and the future. *CIRP Annals-Manufacturing Technology*, *40*(2), 587–594.

Jovane, F., Westkämper, E., & Williams, D. (2008). *The ManuFuture road: towards competitive and sustainable high-adding-value manufacturing*. Springer Science & Business Media.

Kakinuma, Y., Kidani, S., & Aoyama, T. (2012). Ultra-precision cryogenic machining of viscoelastic polymers. *CIRP annals*, *61*(1), 79–82.

Kan, C., Cheng, C., & Yang, H. (2016). Heterogeneous recurrence monitoring of dynamic transients in ultraprecision machining processes. *Journal of Manufacturing Systems*, *41*, 178–187.

Kan, C., Yang, H., & Kumara, S. (2018). Parallel computing and network analytics for fast Industrial Internet-of-Things (IIoT) machine information processing and condition monitoring. *Journal of manufacturing systems*, *46*, 282–293.

Komanduri, R., & Raff, L. M. (2001). A review on the molecular dynamics simulation of machining at the atomic scale. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *215*(12), 1639–1672.

Kuila, P. D., & Melkote, S. (2020). Effect of minimum quantity lubrication and vortex tube cooling on laser-assisted micromilling of a difficult-to-cut steel. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 0954405420911268.

Kumar, K., Zindani, D., Kumari, N., Davim, D., & others. (2019). *Micro and Nano Machining of Engineering Materials*. Springer.

Liu, M., Ma, J., Lin, L., Ge, M., Wang, Q., & Liu, C. (2017). Intelligent assembly system for mechanical products and key technology based on internet of things. *Journal of Intelligent Manufacturing*, *28*(2), 271–299.

Liu, Y., Dillon, T., Yu, W., Rahayu, W., & Mostafa, F. (2020). Noise removal in the presence of significant anomalies for Industrial IoT sensor data in manufacturing. *IEEE Internet of Things Journal*.

Machado, C. G., Winroth, M. P., & daSilva, E. H. D. (2020). Sustainable manufacturing in Industry 4.0: an emerging research agenda. *International Journal of Production Research*, *58*(5), 1462–1484.

Maher, M., Christiansen, H., & Fortanier, F. (2001). Growth, technology transfer and foreign direct investment. *New Horizons and Policy Challenges for FDI in the 21st Century, OECD, Mexico City*.

Marksberry, P. W. (2007). Micro-flood (MF) technology for sustainable manufacturing operations that are coolant less and occupationally friendly. *Journal of Cleaner Production*, *15*(10), 958–971.

Marrocco, V., Modica, F., Fassi, I., & Bianchi, G. (2017). Energetic consumption modeling of micro-EDM process. *The International Journal of Advanced Manufacturing Technology*, *93*(5–8), 1843–1852.

McKeown, P. A. (1987). The role of precision engineering in manufacturing of the future. *CIRP Annals-Manufacturing Technology*, *36*(2), 495–501.

Mia, M., Gupta, M. K., Singh, G., Królczyk, G., & Pimenov, D. Y. (2018). An approach to cleaner production for machining hardened steel using different cooling-lubrication conditions. *Journal of Cleaner Production*, *187*, 1069–1081.

Modica, F., Marrocco, V., Copani, G., & Fassi, I. (2011). Sustainable micro-manufacturing of micro-components via micro electrical discharge machining. *Sustainability*, *3*(12), 2456–2469.

Oztemel, E., & Gursev, S. (2020). Literature review of Industry 4.0 and related technologies. *Journal of Intelligent Manufacturing*, *31*(1), 127–182.

Pan, W. C., Kondaiah, B., Ding, S. L., & Mo, J. (2013). Tool wear and surface integrity in end milling of Ti6Al4V with Polycrystalline Diamond tools. In *Advanced Materials Research* (Vol. 820, pp. 134–137).

Park, K. T., Kang, Y. T., Yang, S. G., Zhao, W.Bin, Kang, Y. S., Im, S. J., et al. (2020). Cyber physical energy system for saving energy of the dyeing process with industrial Internet of Things and manufacturing big data. *International Journal of Precision Engineering and Manufacturing-Green Technology*, *7*(1), 219–238.

Pham, M.-Q., Yoon, H.-S., Khare, V., & Ahn, S.-H. (2014). Evaluation of ionic liquids as lubricants in micro milling--process capability and sustainability. *Journal of cleaner production*, *76*, 167–173.

Rahman, M. A., Rahman, M., & Kumar, A. S. (2017). Modelling of flow stress by correlating the material grain size and chip thickness in ultra-precision machining. *International Journal of Machine Tools and Manufacture*, *123*, 57–75. https://doi.org/https://doi.org/10.1016/j.ijmachtools.2017.08.001

Rahman, M. A., Rahman, M., & Kumar, A. S. (2018). Influence of relative tool sharpness (RTS) on different ultra-precision machining regimes of Mg alloy. *The International Journal of Advanced Manufacturing Technology*, *96*(9), 3545–3563. https://doi.org/10.1007/s00170-018-1599-4

Rao, P., Bukkapatnam, S., Beyca, O., Kong, Z. J., & Komanduri, R. (2014). Real-time identification of incipient surface morphology variations in ultraprecision machining process. *Journal of Manufacturing Science and Engineering*, *136*(2).

Rashid, A., Asif, F. M. A., Krajnik, P., & Nicolescu, C. M. (2013). Resource Conservative Manufacturing: an essential change in business and technology paradigm for sustainable manufacturing. *Journal of Cleaner production*, *57*, 166–177.

Redelinghuys, A. J. H., Basson, A. H., & Kruger, K. (2019). A six-layer architecture for the digital twin: a manufacturing case study implementation. *Journal of Intelligent Manufacturing*, 1–20.

Rosen, M. A., & Kishawy, H. A. (2012). Sustainable manufacturing and design: Concepts, practices and needs. *Sustainability*, *4*(2), 154–174.

Sadoi, Y. (2009). Japanese skill and knowledge transfer: the case of exporting high-precision production technology to China and Vietnam. *Meijo Rons*, *9*(4), 39–50.

Schneider, F., Das, J., Kirsch, B., Linke, B., & Aurich, J. C. (2019). Sustainability in ultra precision and micro machining: a review. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 1–10.

Shamsan, A., & Cheng, C. (2019). Intrinsic multiplex graph model detects incipient process drift in ultraprecision manufacturing. *Journal of Manufacturing Systems*, *50*, 81–86.

Shindo, R., & Nishiwaki, S. (2020). Latest Machine Tool Structural Design Technology for Ultra-Precision Machining. *International Journal of Automation Technology*, *14*(2), 304–310.

Shore, P., & Morantz, P. (2012). Ultra-precision: enabling our future. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *370*(1973), 3993–4014.

Stock, T., & Seliger, G. (2016). Opportunities of sustainable manufacturing in industry 4.0. *Procedia Cirp*, *40*, 536–541.

Suma, V. (2019). Towards sustainable industrialization using big data and internet of things. *Journal of ISMAC*, *1*(01), 24–37.

Tan, R., Zhao, X., Guo, S., Zou, X., He, Y., Geng, Y., et al. (2019). Sustainable production of dry-ultra-precision machining of Ti-6Al-4V alloy using PCD tool under ultrasonic elliptical vibration-assisted cutting. *Journal of Cleaner Production*, 119254.

Tan, Y. S., Ng, Y. T., & Low, J. S. C. (2017). Internet-of-things enabled real-time monitoring of energy efficiency on manufacturing shop floors. *Procedia CIRP*, *61*, 376–381.

Vazquez, E., Gomar, J., Ciurana, J., & Rodríguez, C. A. (2015). Analyzing effects of cooling and lubrication conditions in micromilling of Ti6Al4V. *Journal of*

Cleaner Production, *87*, 906–913.
Wang, J., &Huang, Z. (2017). The recent technological development of intelligent mining in China. *Engineering*, *3*(4), 439–444.
Wu, X., Li, L., He, N., Zhao, G., Jiang, F., & Shen, J. (2018). Study on the tool wear and its effect of PCD tool in micro milling of tungsten carbide. *International Journal of Refractory Metals and Hard Materials*, *77*, 61–67.
Yan, J., Syoji, K., & Tamaki, J. (2003). Some observations on the wear of diamond tools in ultra-precision cutting of single-crystal silicon. *Wear*, *255*(7–12), 1380–1387.
Yao, X., Zhou, J., Lin, Y., Li, Y., Yu, H., & Liu, Y. (2019). Smart manufacturing based on cyber-physical systems and beyond. *Journal of Intelligent Manufacturing*, *30*(8), 2805–2817.
Yi, H. (2020). Systolic Inversion Algorithms for Building Cryptographic Systems Based on Security Measurement in IoT-Based Advanced Manufacturing. *Measurement*, 107827.
Yip, W. S., & To, S. (2017). Tool life enhancement in dry diamond turning of titanium alloys using an eddy current damping and a magnetic field for sustainable manufacturing. *Journal of Cleaner Production*, *168*, 929–939.
Yip, W. S., & To, S. (2018). Sustainable manufacturing of ultra-precision machining of titanium alloys using a magnetic field and its sustainability assessment. *Sustainable Materials and Technologies*, *16, 38-46*.
Yip, W. S., To, S., & Zhou, H. (2020). Social network analysis for optimal machining conditions in ultra-precision manufacturing. *Journal of Manufacturing Systems*, *56*, 93–103.
Yoon, H. S., Lee, J. Y., Kim, M. S., & Ahn, S. H. (2014). Empirical power-consumption model for material removal in three-axis milling. *Journal of Cleaner Production*, *78*, 54–62.
Yuan, J., Lyu, B., Hang, W., & Deng, Q. (2017). Review on the progress of ultra-precision machining technologies. *Frontiers of Mechanical Engineering*, *12*(2), 158–180.
Zhang, J., Ding, G., Zou, Y., Qin, S., & Fu, J. (2019). Review of job shop scheduling research and its new perspectives under Industry 4.0. *Journal of Intelligent Manufacturing*, *30*(4), 1809–1830.
Zhang, S. J., To, S., Wang, S. J., & Zhu, Z. W. (2015). A review of surface roughness generation in ultra-precision machining. *International Journal of Machine Tools and Manufacture*, *91*, 76–95.
Zhang, Y., Zhang, G., Liu, Y., & Hu, D. (2017). Research on services encapsulation and virtualization access model of machine for cloud manufacturing. *Journal of*

Intelligent Manufacturing, *28*(5), 1109–1123.

Zheng, P., Xu, X., & Chen, C. H. (2020). A data-driven cyber-physical approach for personalised smart, connected product co-development in a cloud-based environment. *Journal of Intelligent Manufacturing*, *31*(1), 3–18.

Zou, L., Huang, Y., Zhou, M., & Yang, Y. (2018). Effect of cryogenic minimum quantity lubrication on machinability of diamond tool in ultraprecision turning of 3Cr2NiMo steel. *Materials and Manufacturing Processes*, *33*(9), 943–949.