https://doi.org/10.20965/ijat.2016.p0727

Paper:

Strategies for Developing Milling Tools from the Viewpoint of Sustainable Manufacturing

A. M. M. Sharif Ullah*,†, Takeshi Akamatsu, Masahiro Furuno**, M. A. K. Chowdhury***, and Akihiko Kubo***

*Department of Mechanical Engineering, Kitami Institute of Technology
165 Koen-cho, Kitami, Hokkaido 090-8507, Japan
†Corresponding author, E-mail: ullah@mail.kitami.it-ac.jp
**Product Development Division, Mitsubishi Hitachi Tool Engineering, Japan
***Industrial Engineering Department, King Saud University, KSA
[Received May 24, 2016; accepted August 25, 2016]

This study addresses the strategies for developing the cutting tools used in the material removal process called milling from the viewpoint of sustainable manufacturing. Sustainable manufacturing can be achieved by improving the material, energy, and component efficiencies, simultaneously. Cutting tools are just as important as machine tools and process planning to the achievement of the abovementioned efficiencies. Accordingly, this study describes two strategies based on high cutting velocity and feed per revolution, respectively. Exercising the strategy of high cutting velocity requires a Monte Carlo simulation-driven optimization technique. It helps make a balance between the tool material driven environmental burden and the user-defined maximum allowable cutting velocity. Exercising the strategy of high feed per revolution requires an innovative problem-solving procedure (e.g., TRIZ). It helps create novel solutions (e.g., an oval-shaped milling tool) that eliminate the causes of unstable cutting forces or vibrations when the tool passes over sharp corners. Thus, this study clearly shows that developing a milling tool from the viewpoint of sustainable manufacturing requires a multi-faceted approach. Similar strategies can be used to solve the problems involved in developing other cutting tools.

Keywords: sustainable manufacturing, milling, cutting tool, monte carlo simulation, TRIZ

1. Introduction

The global cutting tool market is a large one – worth tens of billions of US dollars per year [1]. To support this market, cutting tool developers are providing innovative products (cutting tools) that help meet the diversified needs of the users in automotive, aerospace, biomedical, and energy industries around the globe.

This study deals with strategies for developing cutting tools to perform a material removal process called milling from the viewpoint of sustainable manufacturing. Before going into the strategies, it is important to describe the concepts of sustainability, sustainable manufacturing, and to review the relevant research trends.

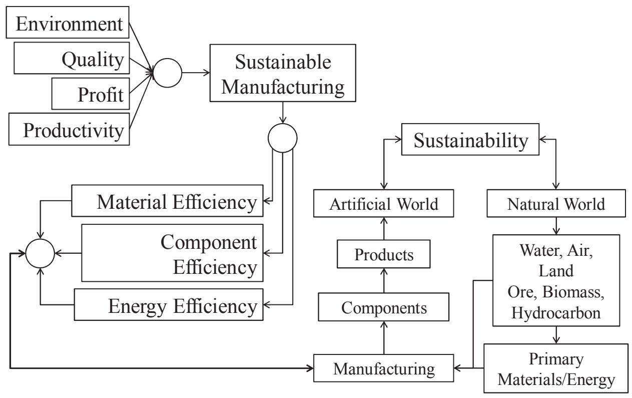


Fig. 1. The concept of sustainable manufacturing.

Refer to the scenario illustrated in **Fig. 1**. It describes the general concepts of sustainability and sustainable manufacturing.

First note in **Fig. 1** the interplay of manufacturing with the natural and artificial worlds. The natural world is full of resources – land, water, air, ores, biomass, and hydrocarbons – whereas the artificial world is full of products. Any product consists of certain components. Along with natural resources (land, water, and air) and enablers (e.g., investment, infrastructure, machines, tools, humans, and systems), primary materials and energy are needed to manufacture a component. Primary materials and energy, on the other hand, are extracted from such natural resources as ores, biomass, and hydrocarbons. As a result, enriching the artificial world using the products depletes the natural resources, exhausting the natural world's potential to meet the future human needs (i.e., future needs of products). Therefore, a synergistic co-existence of both natural and artificial worlds is desirable. To achieve this, the United Nations has adopted a broad concept called sustainability – fulfillment of current needs without lowering Earth's potentials to fulfill the future needs [2].

By now, the concept of sustainability has influenced almost all socio-economic sectors [3] including the manufacturing sector [4, 5]. In manufacturing, sustainability is practiced under the umbrella of sustainable manufacturing where the intention is to keep a fine balance among such issues as productivity, quality, profit, and environmental burdens (or resource depletion), as schematically illustrated in **Fig. 1**. Most importantly, three efficiencies, namely, material, component, and energy efficiencies, must be considered to ensure that a manufacturing activity preserves the norms of sustainable manufacturing [5]. Material efficiency in particular can be ensured by reducing the usages of materials, reducing material waste, increasing material yield, making lighter components/products, and using eco-friendly materials (i.e., using materials with smaller CO_2 footprints and materials that require fewer resources for their primary production) [5, 8]. On the other hand, energy efficiency can be improved by reducing energy usage and increasing the usage of cleaner or renewable energy sources in the manufacturing of finished components/products [4, 5]. The other efficiency is called component efficiency that has to do with the quality- and productivity-related issues of a component or product [5, 9]. Studies show that material efficiency is more effective than energy efficiency in terms of achieving sustainable manufacturing [5, 6]. In addition, improving material efficiency may affect energy and component efficiencies [5, 9]. Thus, the abovementioned efficiencies are interrelated, and sustainable manufacturing is supposed to provide solutions for dealing with this interrelation systematically.

Let us focus on the research trends in sustainable manufacturing. Studies on sustainable manufacturing can be divided into two major categories. In one category, the sustainability of manufacturing is studied from global perspective over relatively long timeframes [10]. This study does not have such focus. The focus of this study makes it fall in the other category, i.e., micro-level sustainable manufacturing, where the sustainability of manufacturing activities is studied at the process-level, especially from the viewpoint of process planning, machine tools, cutting fluids and subsurface damages, surface roughness, job-shop and factory-level activities. In most cases, the authors focus on the aspects of energy efficiency [11] and suggest better solutions, e.g., small-sized machine tools [12, 13], process planning [14, 15], coordination among machine tools in a factory [16], coolant usages [17], and the concept of the underground factory [18]. There have been studies other than the energy efficiency-related studies that have dealt with the material and component efficiencies, e.g., cryogenic machining technology to increase material efficiency by reducing subsurface damages caused by machining [19] and surface metrology-related studies [9]. Apart from machine tools, processing planning and other physical and metaphysical resources, a cutting tool is also required to remove materials from a job. The tool may leave a significant amount of environmental burden [8]. Thus, it is difficult to achieve material, energy, and component efficiencies, without having a properly designed cutting tool, even though the other factors (machine tools, process planning, and coolant) are designed and chosen properly. In the literature on sustainable manufacturing, the cutting tool has not yet been given proper attention. This study sheds some lights on this issue. In particular, the cutting tools used in milling operations – hereinafter referred to as milling tools – that are extensively used in die and mold industry are considered in this study. Some of the strategies for developing a milling tool from the perspective of sustainable manufacturing (i.e., from the perspective of materials, energy, and component efficiencies) are covered in this article.

The remainder of this article is organized as follows. Section 2 describes the general strategies for developing milling tools. Section 3 describes a specific strategy for developing milling tools putting emphasis on cutting velocity. Section 4 describes another specific strategy for developing milling tools putting emphasis on feed per revolution. Section 5 contains our concluding remarks.

2. General Strategies for Developing Milling Tools

A cutting tool is needed to remove materials using milling, as in any other material removal processes. When the milling tool removes materials from a workpiece (job), four (main) cutting conditions, namely, *cutting velocity*, *feed rate*, *width of cut*, and *depth of cut* are got involved. These are described in Section 3. As mentioned above, an incorrectly designed cutting tool might affect the cycle time due to excessive tool wear and breakage, resulting in low productivity, profit, quality, and environmentally unfriendly manufacturing. While designing a cutting tool, (tool) developers consider certain strategies as they do in all product development processes [20, 21]. These strategies must be directed toward fulfilling the needs of the milling tool users, as schematically illustrated in **Fig. 2**. While using a milling tool (or any other cutting tools), the user simultaneously wants to be environmentally friendly, productive, economically sound (profitable), and quality-compliant (see **Fig. 1**, as well). To meet these needs, cutting tool developers consider a set of strategies that evolve from the answers to the following questions:

- Should we aim to develop a cutting tool that is suitable for a high cutting velocity?
- Should we aim to develop a cutting tool that is suitable for a high feed rate?
- Should we aim to develop a cutting tool that is suitable for a depth of cut?
- What kind of material we should use in fabricating the cutting tool?
- How do we prevent the breakage in a cutting tool that receives excessive vibrations?

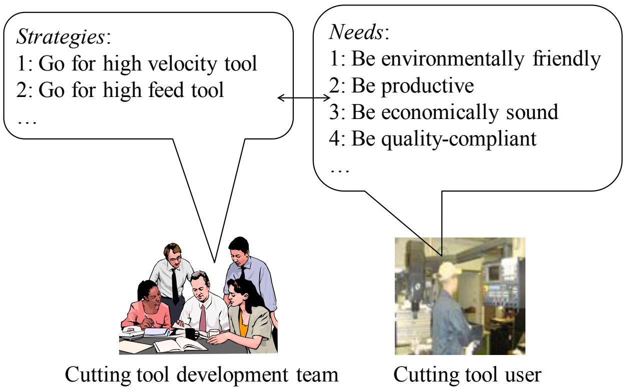


Fig. 2. A scenario of cutting tool development.

- How do we reduce the CO_2 footprint of a cutting tool while we are manufacturing and using it?
- How do we compete with other makers of cutting tools?

Needless to say, there are no straightforward answers to the above questions. Milling tool developers rely on some strategic procedures in tackling the challenges they face while answering the above questions. In most cases, the parameters associated with the material removal rate Q (cm^3/min) help identify the underlying strategies. This leads to three different general strategies: high cutting velocity, high feed rate, and high depth of cut strategies. Based on a previous study [8], these three strategies can be described, as follows.

As mentioned, when a milling tool removes materials from a workpiece (job), there are four main cutting conditions: cutting velocity, feed rate, width of cut, and depth of cut. Apart from these, the parameters of the tool are also involved, as shown in **Fig. 3**. The parameters shown in **Fig. 3** are the feed rate V_f (mm/min), depth of cut a_p (mm), width of cut a_e (mm), rotational speed of cutting tool N (rpm), and diameter of cutting tool D (mm). The other important parameters are the cutting velocity V_c (m/min), feed per cutting edge f_z (mm/cutting-edge-rev), and feed per revolution f_r (mm/rev), which are not directly illustrated in **Fig. 3**. The material removal rate Q (cm^3/min) of a milling operation is expressed as follows:

$$Q = \frac{a_p a_e V_f}{1000}. \qquad (1)$$

The feed rate is related to other parameters, as follows:

$$V_f = f_z Z N = f_r N. \qquad (2)$$

In Eq. (2), Z denotes the number of cutting edges (in **Fig. 3**, $Z = 4$) and f_r denotes the feed per revolution (mm/rev) i.e., the linear distance traveled by the tool in a full revolution.

The width of cut a_e depends on the diameter of the cutting tool D, and the maximum possible a_e is equal to D. This yields the following expression:

$$a_e = eD \qquad e = [0, 1]. \qquad (3)$$

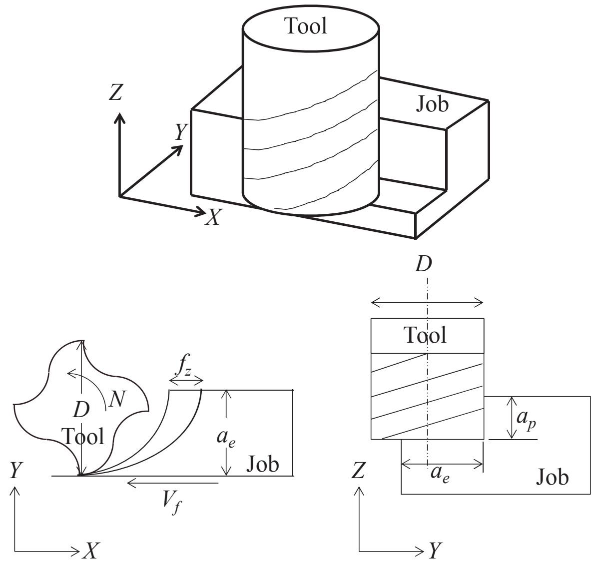


Fig. 3. Basic cutting conditions of an end milling operation.

The cutting velocity V_c is given as

$$V_c = \frac{\pi D N}{1000}. \qquad (4)$$

Thus, the rotational speed N can be expressed as

$$N = \frac{1000 V_c}{\pi D}. \qquad (5)$$

Substituting N from Eq. (5) into Eq. (2) yields

$$V_f = f_r \left(\frac{1000 V_c}{\pi D}\right). \qquad (6)$$

Substituting a_e and V_f from Eq. (3) and Eq. (6), respectively, to Eq. (1) yields

$$Q = \left(\frac{e}{\pi}\right) a_p f_r V_c. \qquad (7)$$

As seen in Eq. (7), the material removal rate Q can be increased by increasing e, a_p, f_r, and V_c. The parameter e depends on the tool path, on the diameter of the tool, and on the shape of the workpiece (i.e., it is a user-defined or operation-dependent quantity). Thus, this parameter is somewhat difficult to consider at the cutting tool development stage. The other three parameters, i.e., depth of cut a_p, feed per revolution f_r, and cutting velocity V_c, lead to three different strategic procedures for the development of a milling tool, as schematically illustrated in **Fig. 4**. The rectangular box in **Fig. 4** shows the amount of Q. As seen in **Fig. 4**, one of the strategies is to develop a milling tool that performs well at a very high cutting velocity, as schematically illustrated in the first case on the left in **Fig. 4**. Another strategy is to develop a milling tool that performs well at a very high feed per revolution, as schematically illustrated in the middle case in **Fig. 4**. The other strategy is to develop a milling tool that performs well at a very high depth of cut, as schematically illustrated in the last case on the right in **Fig. 4**.

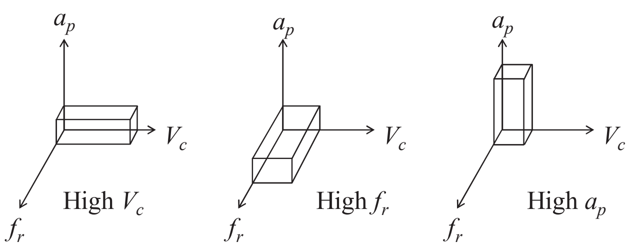


Fig. 4. The general strategies for developing milling tools.

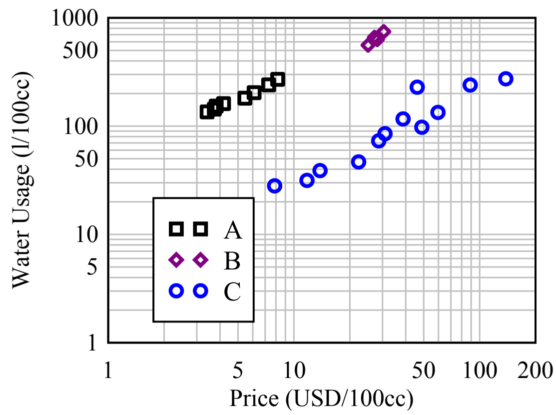
However, these strategies are interrelated, i.e., implementing one of the strategies requires the support of others. To elucidate the relations among these strategies, the interplay of the first two strategies is described in detail in the following two sections. For the ease of description, the strategy of high cutting velocity is described first followed by the strategy of high feed per revolution.

3. Implementing the Strategy of High Cutting Velocity

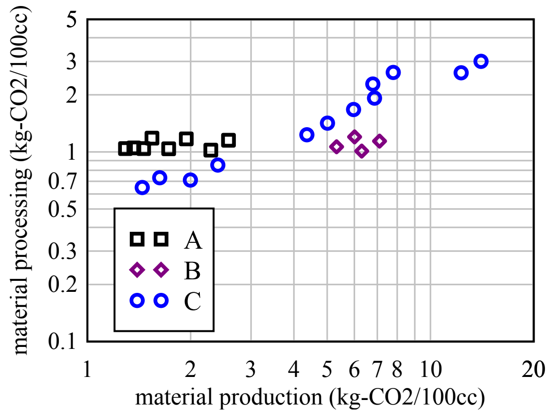
This section describes how to implement the strategy of high cutting velocity (the strategy shown on the left in **Fig. 4**). While developing a milling tool (or any other cutting tools) by applying this strategy, the interdependency of the cutting tool material, cutting tool wear and its environmental burden, and cutting velocity must be dealt with, systematically. Otherwise, the tool cannot be realized.

First, consider the interdependency of the cutting velocity, tool wear, and tool material. In most material removal cases, the degree of tool wear predominantly depends on the cutting velocity. An increase in the cutting velocity results in an increase in the tool wear or a decrease in the tool life. Therefore, the maximum allowable cutting velocity of a cutting tool depends on the material used to fabricate it. (Other factors, e.g., rake angle, clearance angle, and coating, are not considered at the level of strategic decision. These are considered downstream in the tool development process. These issues are out of scope of this study, however.) Here, the maximum allowable cutting velocity means the cutting velocity beyond which the tool exhibits an unacceptable degree of tool wear resulting frequent tool change, high material loss and cost, and low productivity. Therefore, developing a cutting tool that performs well at a very high cutting velocity means selecting a cutting tool material that allows a high maximum allowable cutting velocity.

On the other hand, the wear resistivity of a tool material increases with the increase in its hardness, modulus of elasticity, and fracture toughness. It is, however, difficult to maintain all these three properties in a concurrent manner. Therefore, it is difficult to have a material that is perfect for a cutting tool. Nevertheless, as far as the high cutting velocity (or maximum allowable cutting velocity) is concerned, the single crystal diamond is the best material, followed by the single crystal Cubic Boron Nitride (CBN), Polycrystalline diamond, polycrystalline CBN, cermets, tungsten carbide, and High-Speed Steel (HSS). In addition, different types of single or multilayer coatings make the tool more wear resistive at high cutting velocities.



(a) water usage versus price



(b) CO_2 emissions of primary material production versus material processing

Fig. 5. Material efficiency of commonly used tool materials.

In terms of material efficiency of a tool material, the material of a tool that exhibits high maximum allowable cutting velocity is, unfortunately, low. To understand this more clearly, let us consider some of the commonly used cutting tool materials denoted as A, B, and C. Here, A means the materials based on HSS, B means the materials based on HSS but further hardened by adding Tungsten or Molybdenum alloys, and C means the materials based on cermets, carbides, or Boron Nitrides. It is worth mentioning that the materials denoted as C are now more wildly used than tool materials A or B. The maximum allowable cutting velocity of A is quite low compared to that of B. The maximum allowable cutting velocity of B is quite low compared to that of C. Therefore, from the viewpoint of maximum allowable cutting velocity, the preference list of tool materials is C $\succ$ B $\succ$ A. If material efficiency is considered, then the preference list, C $\succ$ B $\succ$ A, may not be right for all cases. To understand this, consider the material efficiency relevant information of A, B, and C as shown by the plots in **Fig. 5**.

Figure 5(a) shows the relative positions of the materials on a plot of water usage (l/100cc) versus price (USD/100cc) whereas **Fig. 5(b)** shows the relative positions of the materials on a plot of the CO_2 footprint of primary material production (kg-CO_2/100cc) versus the CO_2 footprint of material processing (kg-CO_2/100cc). Both plots use the sustainability data available in the database supplied by the CES Selector developed by Granta Design [22]. Here, the CO_2 footprint of material processing for A and B means the average CO_2 footprint of casting, forging, rolling, machining, grinding, vaporization, and powder forming. On the other hand, the CO_2 footprint of material processing for the other group of materials (C) means the average CO_2 footprint of ceramic powder forming, only, because powder forming is the most widely used for processing C. However, as seen in **Fig. 5(a)**, the primary production of A and B needs more water than does the primary production of C, and the CO_2 footprints of the primary production of B and C are much higher than that of A. In addition, as seen in **Fig. 5(b)**, CO_2 footprints of material processing are almost the same for both A and B, whereas, it is high for C with some exceptions. The CO_2 footprint of primary production of A is much lower than that of B. The CO_2 footprint of primary production of some of the materials in C is comparable to those in A and B, whereas it is quite high for some other materials in C. Therefore, from the viewpoint of material efficiency, the preference list of tool materials is $A \succ B \succ C$, not $C \succ B \succ A$. Thus, a conflict between the material efficiency and strategy of high cutting velocity (i.e., high maximum allowable cutting velocity) persists. To address this conflict, an optimization procedure is needed. One plausible optimization procedure is described in the following subsection.

3.1. Optimization

This subsection describes an optimization procedure for dealing with the conflict between the material efficiency and strategy of high cutting velocity (i.e., the highest allowable cutting velocity). The proposed optimization procedure centers on a concept called critical cutting velocity – a limiting cutting velocity from the viewpoint of the tool users. This means that the critical cutting velocity depends on the needs of the users. If tool users use a cutting velocity beyond the critical cutting velocity, then some of the milling operations will not be carried out due to some physical limitations (e.g., cutting power limitation). An immediate question is; how can the critical cutting velocity be determined? An answer to this question is as follows.

Let P_c (kW) be the power consumed during a milling operation due to material removal, only, and let K_c be the specific cutting energy or pressure (MPa or N/mm^2) of the job material. The following expression holds:

$$P_c = \frac{QK_c}{60^4}. \quad (8)$$

In milling, the specific cutting force K_c decreases exponentially with the increase in the feed per revolution f_r [23, 24]. As a result, the following expression holds:

$$K_c = a\,(f_r)^b \quad (9)$$

In Eq. (9), a and b are two coefficients that depend on the job material [23, 24]. Rearranging Eqs. (7)–(9) yields the following:

$$P_c = \left(\frac{a \cdot e \cdot a_p\,(f_r)^b}{\pi \cdot 60^4}\right) V_c. \quad (10)$$

Let $P_{\max}$ (kW) be the maximum power output of the machine tool used for performing the milling operations and $\eta \in [0,1]$ be the fraction of $P_{\max}$ that can be utilized for removing materials, only. Therefore, the maximum available cutting power for removing materials is equal to $\eta P_{\max}$, and it must be greater than the power needed P_c. Otherwise, the intended milling operation cannot be performed. It is worth mentioning that most of the machine tools nowadays exhibit a relationship between $P_{\max}$ and spindle rpm (N) [25]. As a result, the user often keeps the spindle rpm within the stipulated range to ensure the rated power output. In addition, it is not a good idea to change the rpm drastically during a milling operation cycle from the viewpoint of energy efficiency [26]. This means that the limits of the cutting power and rated rpm constrain the maximum allowable cutting velocity. Other cutting conditions are also involved in this constraining process. Thus, the underlying constraining process yields the following inequality:

$$\eta \cdot P_{\max} > P_c = \left(\frac{a \cdot e \cdot a_p \cdot (f_r)^b}{\pi \cdot 60^4}\right) V_c. \quad (11)$$

If the expression in Eq. (11) is used, a parameter called success state denoted as $S_i \in \{0,1\}$, $i = 1, \ldots, n$, can be defined, as follows:

$$S_i = \begin{cases} 1, \ \eta \cdot P_{\max} > \left(\dfrac{a \cdot e_i \cdot a_{pi} \cdot (f_{ri})^b}{\pi \cdot 60^4}\right) V_{ci} \\ 0, \ otherwise \end{cases} \quad (12)$$

In Eq. (12), e_i, a_{pi}, f_{ri}, and V_{ci}, denote the cutting conditions at the i-th cutting instance, $i = 1, \ldots, n$, (n being total number of cutting instances). The maximum available cutting power ($\eta P_{\max}$) remains the same for all instances, and so do a and b, as a and b depend on the job material. If $S_i = 1$, then the power needed to remove materials from the given job under the given cutting conditions (e_i, a_{pi}, f_{ri}, and V_{ci}) is less than the maximum available cutting power, i.e., the cutting takes place, or the milling operation is successful. If $S_i = 0$, then the power needed to remove material from the given job under the given cutting conditions (e_i, a_{pi}, f_{ri}, and V_{ci}) is greater than the maximum available cutting power, i.e., the cutting does not take place or the milling operation is unsuccessful. Therefore, $S_i = 1$ is desirable and $S_i = 0$ is undesirable. In order to see how S_i varies from one instance to another, some of the cutting conditions can be varied randomly, and some others can be kept constant. For this particular case (i.e., the strategy of high cutting velocity), S_i, $i = 1, \ldots, n$, can

Table 1. A scenario for determining critical cutting velocity.

Parameter	Scenario	Range/Value
P_{max}	Job shop type spindle	$\{2, 3, 4, 5\}$ kW
K_c	Job material = low alloy steels	$a = 1441.7$, $b = -0.186$
η	–	0.4
e	$a_e = D$	1
a_p	Moderate a_p	[1,2] mm
f_r	For relatively high f_r	[0.1, 0.6] mm/rev
V_c	User defined	$\{10, \ldots, 250\}$ m/min

be determined using Monte Carlo simulation where the cutting velocity is kept constant, i.e., $V_{ci} = V_c$, and other cutting conditions, e_i, a_{pi}, and f_{ri}, vary randomly, for all $i = 1, \ldots, n$. The simulated Si can be aggregated to determine the total rate of success denoted as S, as follows,

$$S = \frac{\sum_{i=1}^{n} S_i}{n} \quad \ldots \ldots \ldots \ldots \ldots \quad (13)$$

If $S = 1$, then the maximum available cutting power is greater than the power needed for removing materials from the given job under the fixed cutting velocity and all other randomly generated cutting conditions. If $S < 1$, then the maximum available cutting power is less than the power needed for removing materials from the given job under the fixed cutting velocity and some of the randomly generated cutting conditions. If $S = 0$, then the maximum available cutting power is less than the power needed for removing materials from the given job under the fixed cutting velocity and all other randomly generated cutting conditions. Thus, the limit of cutting velocity corresponding to $S = 1$ is the critical cutting velocity from the sense that the cutting tool cannot remove materials beyond this cutting velocity for some of the given cutting conditions. As a result, a tool developer must develop a milling tool that works well up to the critical cutting velocity. Here, the phrase "works well" reflects the fact that the tool life is long enough for the users to be satisfied using it. This means that the critical cutting velocity manifests the needs of the tool user (or a group of users) from the viewpoint of cutting velocity. Thus, the maximum allowable cutting velocity of the to-be-developed cutting tool must match the critical cutting velocity of the tool user(s).

Let us apply the concept of S and determine the critical cutting velocity for a typical job-shop-type manufacturing environment where the maximum power output P_{max} of a machine tool lies in the range of 2 kW to 5 kW and the rpm lies below 15000 rpm [27]. A typical setting of the parameters associated with S for the job-shop type-manufacturing environment is shown in **Table 1**. A Monte Carlo simulation system [28] is developed to determine S for this particular case. **Fig. 6** shows a plot of S versus cutting velocity for $V_c = 10, 20, \ldots, 250$ m/min for four different machine capacities, $P_{max} = 2$, 3, 4, and 5 kW. As seen in **Fig. 6**, the critical cutting velocities are equal to 30, 50, 60, 80 m/min for $P_{max} = 2$, 3, 4, and 5 kW, respectively. For example, consider that for a tool user,

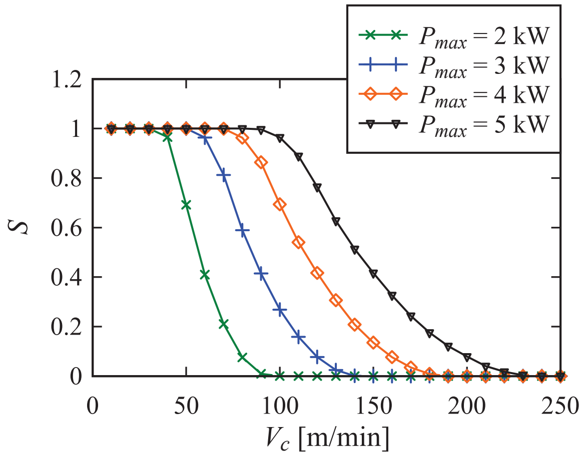


Fig. 6. Total rate of success versus cutting velocity for different machine capacities.

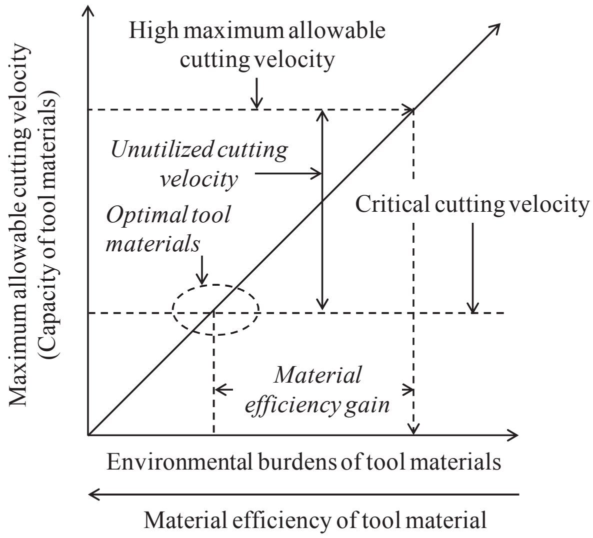


Fig. 7. Cutting tool development using the strategy of high cutting velocity.

$P_{max} = 3$ kW. The user uses the cutting conditions listed in **Table 1**. For this particular user, if the cutting velocity is greater than 50 m/min (see **Fig. 6**), then there is no guarantee that all milling operations can be carried out. Therefore, if a tool developer finds a group of tool users with the machine capacity of 3 kW and cutting conditions listed in **Table 1**, then the developer should consider that the group of tool users does not need a cutting tool that performs well beyond the cutting velocity 50 m/min. This also means that if a cutting tool is designed to work well up to a specific cutting velocity, such as 100 m/min, then the tool will remain underutilized for the cutting velocity range [50, 100] m/min. This is not desirable from the viewpoint of the material efficiency of tool materials, as described in the above.

The above descriptions lead to an optimization procedure, as schematically illustrated in **Fig. 7**. As shown in **Fig. 7**, if the maximum allowable cutting velocity of a tool material is about the same as the critical cutting velocity of the user, then it is an optimal tool material. In this case, a gain in the material efficiency can be achieved and the unutilized cutting velocity can be avoided, as well. As a result, the critical cutting velocity of the user restricts the allowable cutting velocity of the tool material from the viewpoint of sustainable manufacturing.

In synopsis, applying the strategy of high cutting velocity while developing a milling tool comes down to the following procedure – find the critical cutting velocity for a user (or a group of users), and, then find or develop a cutting tool material with a maximum allowable cutting velocity that matches the critical cutting velocity.

4. Implementing the Strategy of High Feed per Revolution

When a milling tool passes sharp corners (which often happens while dies and molds are being produced), it is subjected to highly unstable cutting forces, and, thereby, unwanted vibrations. To understand this phenomenon, let us take an example. **Table 2** lists the cutting conditions of an ordinary milling tool when it passes a sharp corner of a workpiece made of Carbon Steel S50C (JIS). (To avoid commerciality, the other specifications are not disclosed here.)

Table 2. Milling conditions.

Parameters	Specifications
Job material	Carbon Steel S50C (JIS)
Tool diameter (D)	10 mm
Cutting velocity (V_c)	157 m/min
Rotational speed (N)	5000 rpm
Table feed (V_f)	3000 mm/min
Feed per cutting edge (f_z)	0.15 mm/cutting-edge-rev
Depth of cut (a_p)	0.6 mm
Width of cut (a_e)	3 mm

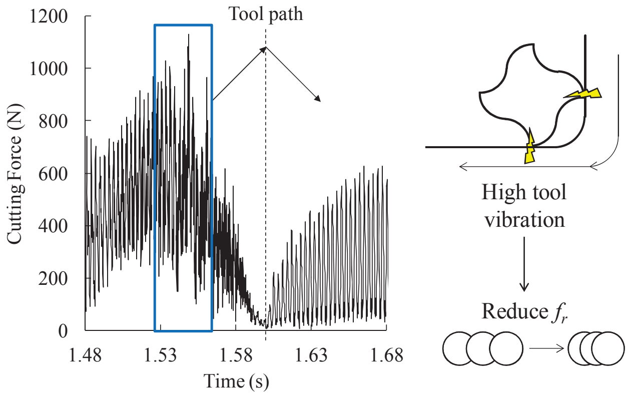


Fig. 8. Consequences when a cutting tool passes a sharp corner.

The left side of **Fig. 8** is a plot of the cutting force. The highly unstable cutting force can be observed from the plot marked by a rectangular box. This phenomenon causes unwanted vibration and tool breakage. When a tool vibrates or breaks, it immediately poses a threat to the component, and to the material efficiency, as well. In order to avoid tool vibration or breakage, it is customary to reduce the feed per revolution f_r when it passes over the sharp corners, as schematically illustrated in **Fig. 8** (the right side illustration in **Fig. 8**). Therefore, it is difficult to achieve the strategy of high feed per revolution using the conventional milling tools. To overcome this challenge, the tool developer must create new solutions, and solve the problem of unstable cutting force.

It is therefore difficult to achieve the strategy of high feed per revolution using conventional milling tools. To overcome this challenge, the tool developer must create new solutions. One of the ways to create new solutions is to apply the Theory of Inventive Problem Solving known as TRIZ [20, 29, 30]. TRIZ defines 39 common parameters to solve a problem. In addition, it provides 40 principles to deal with any contradictions among these 39 parameters. In this particular case, the tool developer wants the milling tool to perform well in all situations, including when it passes over sharp corners. This means that the tool must adapt to different features of a job design. As such, the parameter 35 of TRIZ, Adaptability ([20], p. 137), is involved. The tool developer must improve the adaptability of the milling tool by suggesting some new solutions. On the other hand, the strategy here is to develop a milling tool used for high feed per revolution. As a result, parameter 9 of TRIZ, Speed ([20], p. 137), is also involved here, as is Adaptability. The tool must not sacrifice its speed (i.e., it must maintain a high feed per revolution) while passing over different segments of a workpiece, including the sharp corners. Thus, a contradiction between the Adaptability and Speed exists in this particular case. To address this contradiction, TRIZ provides three principles, namely, Parameter changes (principle 35), Preliminary action (principle 10), and Curvature (principle 14) ([20], p. 138), as summarized in **Table 3**. For this particular case, applying the Parameter changes principle means changing the parameter of the milling tool, e.g., changing the diameter of the tool, increasing or decreasing the number of cutting edges, etc. In addition, applying the Preliminary action principle means doing something beforehand to eliminate the main cause of the problem. Moreover, applying the Curvature principle means reconsidering the curvature of the cutting tool. Based on the above contemplation, the tool developer can consider a new solution creation scenario, as illustrated in **Fig. 9**.

As seen in **Fig. 9**, a solution is proposed that employs an oval-shaped cutting tool instead of a circle-shaped one. Since the oval-shaped cutting tool has a major diameter and a minor diameter, its *curvature* changes continually along its circumference. This helps reduce the possibility that the cutting edge may rub workpiece when it is not removing materials. As a result, the milling tool may not exhibit highly unstable cutting force while passing a sharp corner. Thus, applying the principles of TRIZ, Curvature principle, in particular, helps eliminate the main cause of the problem. How is the performance of the oval-shaped

Table 3. Applying TRIZ while developing a milling tool for high feed per revolution.

	Parameter not to be sacrificed: *Speed* (Parameter 9)	
Parameter to be improved: *Adaptability* (Parameter 35)	Principle 35	*Parameter changes*
	Principle 10	*Preliminary action*
	Principle 4	*Curvature*

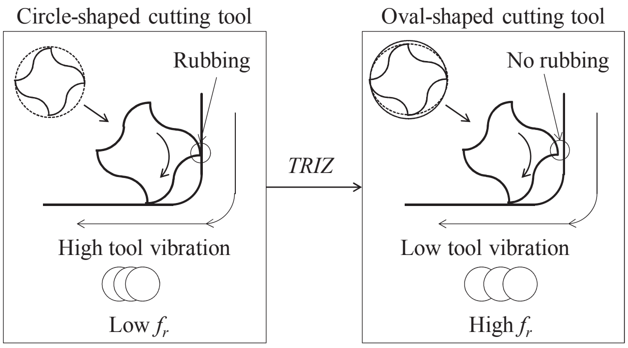


Fig. 9. Applying TRIZ in developing a milling tool.

milling tool? In order to answer this question, a cutting tool with a major diameter of 10 mm and a minor diameter of 9.9 mm is developed. The other specifications of the tool are not described here to avoid any commerciality. **Fig. 10** shows a plot of the cutting force when the oval-shaped milling tool passes a sharp corner. The other cutting conditions associated with the cutting force shown in **Fig. 10** are already listed in **Table 2**. The cutting force this time (**Fig. 10**, marked by a rectangular box) does not exhibit that instability that it often shows otherwise (**Fig. 8**). Therefore, when the oval-shaped milling tool passes a sharp corner at a relatively high feed per revolution, it does not experience the unstable cutting forces, i.e., it vibrates much less than does a circle-shaped tool.

5. Concluding Remarks

Sustainable manufacturing is still an evolving research field. Though most of the micro-scale studies on sustainable manufacturing deal with energy efficiency, two other efficiencies, namely, material and component efficiencies, are equally important. In this respect, the role of a cutting tool is also important.

In this study, milling tool development is considered from the viewpoint of the abovementioned efficiencies.

In particular, to develop a milling tool, a commonly used general strategy is to maximize the material removal rate. This general strategy leads to three working strategies: "maximize cutting velocity," "maximize feed per revolution," and "maximize depth of cut."

To implement each of these strategies, one needs to

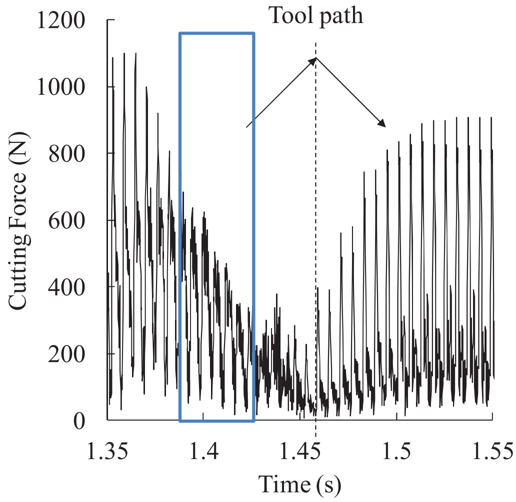


Fig. 10. Cutting force underlying an oval-shaped milling tool.

solve the underlying technical problems using a multi-faceted approach. In particular, in the case of cutting velocity, a Monte Carlo simulation-driven optimization helps find solutions. On the other hand, in the case of feed per revolution, an innovative problem-solving procedure, e.g., TRIZ, helps find solutions.

In particular, the presented Monte Carlo simulation driven optimization technique helps make a balance between the tool material-driven environmental burden and user-defined maximum allowable cutting velocity. Using TRIZ helps create novel solutions, e.g., an oval-shaped milling tool, to eliminate the causes of unstable cutting force or vibration when the tool passes over sharp corners at a relatively high feed rate.

Similar approaches can be applied to develop cutting tools for other material removal process, such as turning and drilling, as well. This issue remains open for further research.

Procedures for developing cutting tools from the viewpoint of high depth of cut have not been considered in this study. This issue also remains open for further research.

References:

[1] N. N. Global cutting tool market to reach US$22 billion in 2003, Metal Powder Report, Vol.53, No.2, p. 8, 1998.
[2] N. N. Report of the World Commission on Environment and Development. Annex to General Assembly document A/42/427, Nairobi, Kenya. United Nations, New York, 1987.
[3] Y. Umeda, T. Nishiyama, Y. Yamasaki, Y. Kishita, and S. Fukushige, "Proposal of sustainable society scenario simulator," CIRP Journal of Manufacturing Science and Technology, Vol.1, No.4, pp. 272-278, 2009.
[4] Z. Bi, "Revisiting System Paradigms from the Viewpoint of Manufacturing Sustainability," Sustainability, Vol.3, No.9, pp. 1323-1340, 2011.
[5] A. M. M. Sharif Ullah, A. Fuji, A. Kubo, and J. Tamaki, "Analyzing the sustainability of bimetallic components," International Journal of Automation Technology, Vol.8, No.5, pp. 745-753, 2014.
[6] A. M. M. S. Ullah, H. Hashimoto, A. Kubo, and J. Tamaki, "Sustainability analysis of rapid prototyping: Material/resource and process perspectives," International Journal of Sustainable Manufacturing, Vol.3, No.1, pp. 20-36, 2013.
[7] J. M. Allwood, M. F. Ashby, T. G. Gutowski, and E. Worrell, "Material efficiency: A white paper," Resources, Conservation and Recycling, Vol.55, No.3, pp. 362-381, 2011.

[8] A. M. M. Sharif Ullah, K. Kitajima, T. Akamatsu, M. Furuno, J. Tamaki, and A. Kubo, "On some eco-indicators of cutting tools," Proceedings of ASME 2011 International Manufacturing Science and Engineering Conference, MSEC 2011, Vol.2, No.2011, pp. 105-110, 2011.

[9] A. M. M. Sharif Ullah, A. Fuji, A. Kubo, J. Tamaki, and M. Kimura, "On the surface metrology of bimetallic components," Machining Science and Technology, Vol.19, No.2, pp. 339-359, 2015.

[10] Y. Mizuno, Y. Kishita, S. Fukushige, and Y. Umeda, "Envisioning sustainable manufacturing industries of japan," International Journal of Automation Technology, Vol.8, No.5, pp. 634-643, 2014.

[11] E. O'Driscoll, D. Ó. Cusack, and G. E. O'Donnell, "The characterisation of energy consumption in manufacturing facilities – A hierarchical approach," International Journal of Automation Technology, Vol.7, No.6, pp. 727-734, 2013.

[12] N. Suzuki, Y. Morimoto, K. Takasugi, R. Kobashi, R. Hirono, Y. Kaneko, and Y. Tokuno, "Development of desktop machine tool with pipe frame structure," International Journal of Automation Technology, Vol.9, No.6, pp. 720-730, 2015.

[13] S. Ogawa, S. Okumura, T. Hirogaki, E. Aoyama, and Y. Onchi, "Investigation of eco-friendly fixed-abrasive polishing with compact robot," Advanced Materials Research, Vol.126-128, No.2010, pp. 415-420, 2010.

[14] H. Narita, "A method for using a virtual machining simulation to consider both equivalent CO2 emissions and machining costs in determining cutting conditions," International Journal of Automation Technology, Vol.9, No.2, pp. 115-121, 2015.

[15] A. Ghandehariun, Y. Nazzal, H. Kishawy, and N. S. N. Al-Arifi, "Investigation of sustainability in machining processes: Exergy analysis of turning operations," International Journal of Exergy, Vol.17, No.1, pp. 1-16, 2015.

[16] Q. Chang, G. Xiao, L. Li, and S. Biller, "Energy management in manufacturing systems," Proceedings of ASME 2011 International Manufacturing Science and Engineering Conference, Vol.2, No.2011, pp. 119-125, 2011.

[17] T. Wakabayashi, S. Suda, I. Inasaki, K. Terasaka, Y. Musha, and Y. Toda, "Tribological action and cutting performance of MQL media in machining of aluminum," CIRP Annals – Manufacturing Technology, Vol.56, No.1, pp. 97-100, 2007.

[18] I. Inasaki, "Towards symbiotic machining processes," International Journal of Precision Engineering and Manufacturing, Vol.13, No.7, pp. 1053-1057, 2012.

[19] Y. Kaynak, T. Lu, and I. S. Jawahir, "Cryogenic machining-induced surface integrity: A review and comparison with dry, mql, and flood-cooled machining," Machining Science and Technology, Vol.18, No.2, pp. 149-198, 2014.

[20] A. M. M. Sharif Ullah, M. Sato, M. Watanabe, and M. M. Rashid, "Integrating CAD, TRIZ, and customer needs," International Journal of Automation Technology, Vol.10, No.2, pp. 132-143, 2016.

[21] A. M. M. Sharif Ullah and J. Tamaki, "Analysis of Kano-model-based customer needs for product development," Systems Engineering, Vol.14, No.2, pp. 154-172, 2011.

[22] N. N. CES Selector, Eco-module, Version 5.1.0, Granta Design Limited, UK.

[23] A. M. M. Sharif Ullah, K. H. Harib, M. Awda, and S. Zenieh, "Application of Axiomatic Design Principles for Process Planning in Milling," SAE Technical Paper 2009-01-0792, doi: 10.4271/2009-01-0792, 2009.

[24] N. N. Cutting power for face milling, http://www.mitsubishicarbide.com/en/technical_information/tec_rotating_tools/face_mills/tec_milling_formula/tec_milling_power_formula (last accessed on 17 May 2016).

[25] H. Schulz, "Machining concepts for high speed cutting," Proceedings of the International Seminar on Improving Machine Tool Performance, La Baule, Frankreich, 2000.

[26] N. Diaz, M. Helu, A. Javis, S. Tonissen, D. Dornfeld, and R. Schlosser, "Strategies for Minimum Energy Operation for Precision Machining," The Proceedings of MTTRF 2009 Annual Meeting.

[27] E. Abele, Y. Altintas, and C. Brecher, "Machine tool spindle units," CIRP Annals – Manufacturing Technology, Vol.59, No.2, pp. 781-802, 2010.

[28] A. M. M. Sharif Ullah and M. Shamsuzzaman, "Fuzzy Monte Carlo Simulation using point-cloud-based probability- possibility transformation," Simulation, Vol.89, No.7, pp. 860-875, 2013.

[29] G. Altshuller, "The Innovation Algorithm, TRIZ, Systematic Innovation and Technical Creativity," Worcester, MA: Technical Innovation Center.

[30] G. Cascini, "TRIZ-based anticipatory design of future products and processes," Journal of Integrated Design and Process Science, Vol.16, No.3, pp. 29-63, 2012.

Name:
A. M. M. Sharif Ullah

Affiliation:
Associate Professor, Department of Mechanical Engineering, Faculty of Engineering, Kitami Institute of Technology

Address:
165 Koen-cho, Kitami, Hokkaido 090-8507, Japan

Brief Biographical History:
1992 BSME, BUET, Bangladesh
1996; 1999 MSME; PhD, Kansai University, Japan
2000-2002 Assistant Professor, AIT, Thailand
2002; 2006 Assistant Professor; Associate Professor, UAE University
2009- Associate Professor, Kitami Institute of Technology, Japan

Main Works:
- "Evaluation of Hard Materials using Eco-Attributes," Advanced Materials Research, Vol.325, No.2011, pp. 693-698, 2011.
- "Sustainability analysis of rapid prototyping: material/resource and process perspectives," International Journal of Sustainable Manufacturing, Vol.3, No.1, pp. 20-36, 2013.
- "Analyzing the Sustainability of Bimetallic Components," International Journal of Automation Technology, Vol.8, No.5, pp. 745-753, 2014.
- "Integrating CAD, TRIZ, and Customer Needs," International Journal of Automation Technology, Vol.10, No.2, pp. 132-143, 2016.

Membership in Academic Societies:
- Association for the Advancement of Artificial Intelligence (AAAI)
- Japan Society of Mechanical Engineers (JSME)
- Japan Society for Abrasive Technology (JSAT)

Name:
Takeshi Akamatsu

Affiliation:
General Manager, Products Development Department, Narita Plant, Mitsubishi Hitachi Tool Engineering Ltd.

Address:
13-2 Shinizumi, Narita-Shi, Chiba 286-0825, Japan

Brief Biographical History:
1996 Baccalaureate, Kansai University, Japan
1996; 1998; 2003 Product Technology Dept; Product Development Dept.; Assistant Manager, Product Development Dept., Yasu Plant Hitachi Tool Engineering Ltd., Japan
2006 PhD, Kansai University, Japan
2008-2012 General Manager, Product Development Dept., Yasu Plant Hitachi Tool Engineering Ltd., Japan
2012-2015 General Manager, Product Development Dept., Narita Plant Hitachi Tool Engineering Ltd., Japan
2015- General Manager, Product Development Dept., Narita Plant Mitsubishi Hitachi Tool Engineering Ltd., Japan

Main Works:
- "Influence of Material of Small Radius Ball End Mill on Cutting Accuracy in Deep Precision Machining (second report)," Key Engineering Materials, Vols.291-292, No.2005, pp. 471-474, 2005.
- "On Some Eco-Indicators of Cutting Tools," Proceedings of the ASME MSEC2011, Vol.2, No.MSEC2011-50071, pp. 105-110, 2011.

Membership in Academic Societies:
- Japan Society for Abrasive Technology (JSAT)
- Japan Society of Mechanical Engineers (JSME)
- Japan Society for Precision Engineering (JSPE)

Name:
Masahiro Furuno

Affiliation:
General Manager, Quality Assurance Department, Yasu Plant, Mitsubishi Hitachi Tool Engineering Ltd.

Address:
35-2 Mikami, Yasu-Shi, Shiga 520-2323, Japan

Brief Biographical History:
2001-2012 Product Development Dept, Hitachi Tool Engineering Ltd., Japan
2012 PhD, Kansai University, Japan
2013-2014 Vice Manager of Product Development Dept, Hitachi Tool Engineering Ltd., Japan
2014-2015 Vice Manager of Quality Assurance Dept, Hitachi Tool Engineering Ltd., Japan
2015- General Manager of Quality Assurance Dept, Mitsubishi Hitachi Tool Engineering Ltd., Japan

Main Works:
• "Effect of ground surface roughness of tool on adhesion characteristics by PCD coating," Advanced Materials Research, Vol.126-128, No.2010, pp. 609-614, 2010.
• "Effect of ground surface roughness of tool on adhesion characteristics by PVD coating – 2nd report: Effect of cutting characteristics by coating and surface roughness –," Journal of the Japan Society for Abrasive Technology, Vol.55, No.1, pp. 48-53, 2011.
• "On Some Eco-Indicators of Cutting Tools," Proceedings of the ASME MSEC2011, Vol.2, No.MSEC2011-50071, pp. 105-110, 2011.

Membership in Academic Societies:
• Japan Society for Abrasive Technology (JSAT)

Name:
M. A. K. Chowdhury

Affiliation:
Assistant Professor, Industrial Engineering Department, King Saud University, Kingdom of Saudi Arabia

Address:
King Saud University, P.O. Box 800, Riyadh 11421, KSA

Brief Biographical History:
2002 BSME, BUET, Bangladesh
2008 MSE, Chalmers University of Technology, Sweden
2014 PhD, Kitami Institute of Technology, Japan
2003-2004 Research Lecturer, CUET, Bangladesh
2005-2007 Lecturer, CUET, Bangladesh
2014- Assistant Professor, King Saud University, KSA

Main Works:
• "Computer aided simulation of rotary diamond dressing based on kinematic analysis," Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol.7, No.4, pp. 506-520, 2013.
• "Recent development on surface texturing in enhancing tribological performance of bearing sliders," Surface and Coatings Technology, Vol.272, pp. 102-120, 2015.

Membership in Academic Societies:
• Japan Society for Precision Engineering (JSPE)
• Institution of Engineers, Bangladesh (IEB)

Name:
Akihiko Kubo

Affiliation:
Assistant Professor, Department of Mechanical Engineering, Kitami Institute of Technology

Address:
165 Koen-cho, Kitami, Hokkaido 090-8507, Japan

Brief Biographical History:
1978 National Institute of Technology, Kushiro College, Japan
1978- Kitami Institute of Technology, Japan

Main Works:
• "Sustainability analysis of rapid prototyping: material/resource and process perspectives," International Journal of Sustainable Manufacturing, Vol.3, No.1, pp. 20-36, 2013.
• "Visualization of 3D Topography of Grinding Wheel Surface Dressed by Rotary Diamond Dresser," Advanced Materials Research, Vol.797, pp. 751-756, 2013.
• "Wear Characteristics of Nano-polycrystalline Diamond Tool in Cutting of Tungsten Carbide," Int. J. Mechatronics and Manufacturing Systems, Vol.7, Nos.4/5/6, pp. 227-245, 2014.
• "Kinematic Analysis of Dressing Process using Prismatic Diamond Rotary Dresser," Journal of the Japan Society for Abrasive Technology, Vol.59, No.4, pp. 197-204, 2015.

Membership in Academic Societies:
• Japan Society for Precision Engineering (JSPE)
• Japan Society of Mechanical Engineers (JSME)
• Japan Society for Abrasive Technology (JSAT)