British Journal of Applied Science & Technology
14(2): 1-9, 2016, Article no.BJAST.22211
ISSN: 2231-0843, NLM ID: 101664541

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An Outlook on Tool Wear Mechanisms of Selected Cutting Tool Materials

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Authors' contributions

This work was carried out in collaboration between all authors. Author OMO designed the study, wrote the protocol, and first draft of the manuscript. Authors CAI and KJA managed the analyses of the study and literature searches. Authors OOA and ARA supervised the study and interpreted the results. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/BJAST/2016/22211
Editor(s):
(1) Elena Lanchares Sancho, Department of Mechanical Engineering, University of Zaragoza, Zaragoza, Spain.
Reviewers:
(1) Anonymous, Selcuk University, Turkey.
(2) Siva Prasad Kondapalli, Anil Neerukonda Institute of Technology & Sciences, India.
Complete Peer review History: http://sciencedomain.org/review-history/12988

Review Article

Received 23rd September 2015
Accepted 16th October 2015
Published 15th January 2016

ABSTRACT

This study discusses the viabilities and performances of a variety of cutting tool mechanism under various conditions. It highlights the basic issues relating to tool life, tool wear and cutting forces and emphasizes the importance of proper selection of cutting tools in manufacturing of discrete component parts. Continuous search for improved methods herald the need for significant transformation through optimization in terms of improved quality products, high productivity and comparative cost advantage. Replacement and adjusting of machine tool associated with tool failure increase production cost and decrease productivity. There still lies a great significance for continuous optimization of the manufacturing process and study of tool wear mechanism for various categories of cutting tool materials, as our ability to continue the trend for improved materials will be severely tested in the coming decades. It is the failure issues associated with tool wear mechanism of selected cutting tool materials and their essential properties that this work addresses; hence it reveals salient information and this aspect will continue to receive attention in machining processes.

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Keywords: Cutting tool mechanism; tool life; tool wear; cutting forces; discrete component parts; significant transformation; optimization.

1. INTRODUCTION

The modern manufacturing in recent decades has undergone a significant transformation driven by factors including: the need to produce the lowest price possible; the need for greater accuracy of interchangeable and isolated parts; there are batches of more diverse part and more complex geometry; the need to machine increasingly resistant materials and by high cutting speeds; the search for reliability in measurements; and the need to make the smallest set of parts possible, tooling and machine tools after the design phase [1].

Machining is still indisputably the most popular manufacturing process in manufacturing of high precision discrete metal parts [2] and present day manufacturing demands high degree of accuracy for the part to work satisfactorily when assembled. To meet the challenges imposed on manufacturing engineer, it is desirable for him to have thorough knowledge of material sciences, design and manufacturing processes [3]. Apart from the demand of accuracy, quality and productivity play significant role in today's manufacturing market [4].

In today's world of increasing business competition, the long-term survival of any organization depends on its continuous ability to satisfy customers' needs and expectations in respect of the quality and cost of the products. In order to keep the product competitive in the market in terms of cost while still maintaining the quality of the product, the manufacturing engineer is expected to be capable of selecting optimum cutting tools and production machines.

For material removing or metal-cutting processes such as turning, milling, drilling, grinding, etc., the engineer must be fully aware of the use of optimum cutting speeds, feeds and depth of cut and selection of proper cutting tools and materials, so as to have substantial savings in machining time, a very important component of manufacturing cost.

Machining operations comprise a substantial portion of the world's manufacturing infrastructure [5], they create about 15% of the value of all mechanical components manufactured worldwide [6]. Because of its great economic and technical importance, a large amount of research has been carried out in order to optimize cutting process in terms of improving quality, increasing productivity and lowering cost.

However, machining of metal is still not completely understood because of the highly non-linear nature of the process and the complex coupling between deformation and temperature fields. Metal cutting can be associated with high temperatures in the tool-chip interface zone and hence, the thermal aspects of the cutting process strongly affect the accuracy of the machining process [5].

Different machining applications require different cutting tool materials and the classes of cutting tool materials currently in use for machining operations are high-speed tool steel, cobalt-base alloys, cemented carbides, ceramic, polycrystalline cubic boron nitride and polycrystalline diamond. High speed steel is commonly used for cutting tools, particular to form tools because of its toughness, good grinding properties and easy availability in various stock forms as round and flats. Compared to high speed steel tools, cemented carbide tips can be operated at 300 – 400 percent higher cutting speeds.

Cemented carbide tool tips consist of powders of tungstene, carbon and cobalt moulded together and heated to very high temperature. Tools with disposable ceramic inserts are used for finish and semi-finished turning of steels (both unhardened and hardened), cast irons, non-ferrous metals and alloys and non-metallics, feature low thermal conductivity and tend to develop cracks on rapid heating and particularly, on rapid cooling. Polycrystalline cubic boron nitride (PcBN) are used for turning hardened steel (45–70 Rockwell), while polycrystalline diamonds are used for machining abrasive aluminum – silicon alloys, fused silicon and reinforced plastics.

The ideal cutting tools have characteristics such as hardness, high temperature stability, wear and thermal shock resistance and chemical inertness to the work material and cutting fluid. Tool wear influences cutting power, machining quality, tool life and machining cost. When tool wear reaches a certain value, increasing cutting force, vibration and cutting temperature cause surface integrity, deterioration and dimension error greater than tolerance. The life of the cutting tool comes to an end. Then the cutting tool must be replaced or ground and the cutting process is interrupted [7,8].

The cost and time for tool replacement and adjusting machine tool increase cost and decreases productivity. Hence, tool wear relates to the economics of machining and study of tool wear is of great significance for the optimization of cutting process.

2. CONTRIBUTORY STUDIES ON TOOL WEAR

The wear of cutting tools has been one of the most extensively researched fields in engineering for the last forty (40) years [9]. The literature is full of studies using both theoretical and experimental approaches to outline the performance of a variety of cutting tools under various cutting conditions, addressing issues related to tool life, tool wear and cutting forces. [10] investigated tool life criteria in raw turning. A new tool-life criterion depending on a pattern-recognition technique was proposed and neural network and wavelength techniques were used to realize the new criterion. The experimental results showed that the criterion was applicable to tool condition monitoring in a wide range of cutting conditions.

Liao and Shive [11] studied carbide tool wear mechanism in turning of Inconel 718 super alloy and found out that the wear of carbide tools during high speed turning condition (V=35m min^{-1}) was caused by diffusion of elements (Ni or Fe) in work piece into tool binder (Co) by grain boundary diffusion mechanism. [12] reported that in cemented carbide cutting tools, flank and crater wears could develop by one or combination of plastic deformation under compressive stress, diffusion, attrition, abrasion and wear under slide conditions.

The use of Optical Profiler for the analysis of cutting tool wear during high speed machining employed in many manufacturing environments, including the automotive and avionics industries as carried out by [13] established that with excellent Z-height resolution and measurement range, white light interferometry is a suitable technique to characterize and optimize tool wear in high speed machining.

Assessment of cutting tool wear of difficult-to-machine materials, plastic lowering of the cutting edge is the predominant cause of premature tool breakage for general purpose carbide tool. However, from the wear progression model developed by [14], it was found that the lowest initial flank wear valves are obtained at a cutting speed of 183m/min, a feed rate of 0.10mm/rev under semi-dry cutting conditions when end–milling AISI 4340 Steel.

Luo et al. [15] carried out theoretical and experimental studies to investigate the intrinsic relationship between tool flank wear and operational conditions in metal cutting processes using carbide cutting inserts. The author developed the model to predict tool flank wear land width which combined cutting mechanics simulation and an empirical model. The study revealed that cutting speed had more dramatic effect on tool life than feed rate.

Singh and Kumar [16], studied the optimization of feed force through setting of optimal value of process parameters namely speed, feed and depth of cutting in turning of EN24 steel with TiC coated tungstene carbide inserts, concluded that the effect of depth of cut and feed in variation of feed force were affected more as compared to speed, using Taguchi parameter design approach.

Selection of cutting tool for turning α-Titanium Alloy Bt5 by [17] reported tungstene carbide cemented carbide tool BK 60M as the most appropriate turning tool for semi-finishing operations of the alloy material used for the study. [18] studied on turning operation using High-Speed-Steel (HSS) cutting tool with 45^o approach angle. This tool showed that it could perform cutting operation at higher speed and longer tool life than traditional tool with 90^o approach angle. The study finally determined optimal cutting speed for high production rate and minimum cost, tool life, production time and operation costs. [19] did a survey on research progresses on polycrystalline cubic boron nitride (CBN) tool wear in hard turning and suggested that abrasion, adhesion and diffusion might probably govern the CBN tool wear in hard turning.

Tsao and Hocheng [20] submitted that drill wear is a serious concern in hole-making industry, as it is necessary to prevent damage of cutting tools, machine tools and workpieces in their study of the effect of tool wear on delamination in drilling composite materials. [21] found that increasing cutting speed resulted in a protective layer from the diffusion of the bond material of the CBN cutting tool to form on the chip-tool interface, leading to reduced wear rate and prolonged tool life.

In general, a lower friction concentration was found for variable edge tooling and temperature and stress distributions and tool wear contours revealed the advantages of variable edge micro-geometry design.

Tool wear monitoring in turning processes using Vibratory Analysis by [22] resulted in the development of a signal processing strategy to provide an efficient tool wear monitoring system able to increase machining performance. [23] carried out turning tests in order to establish the relationship between flank wear and cutting force on the machining of Martenistic Stainless Steel by Super Hard Tools. The result from the test indicated that lower cutting force leads to low flank wear and low cutting force provides good dimensional accuracy of the work materials including low surface roughness.

Chandrasekaran and Persson [24] did experimental work on machinability and tool wear during high speed milling of some hardened tool steels, using cemented carbide inserts and CBN cutting tool. They concluded that successful milling of most of the hardened steels with cemented carbide tools appeared feasible but that correct selection of cutting conditions and type of CBN could result in high productivity for some of the steels.

Lubrication and Tool–wear in turning of hard powdered metals was studied by [25] using statistical analysis and human judgment to evaluate the three metal working fluids that were used for the work. It was concluded that the most suitable metal working fluid to machine the high nickel value seat are M3680 and M240T, followed by Q381.

Gubeis et al. [26] reported on wear of diamond tool when cutting amorphous polymers. He however submitted that, though tribo-chemical tool wear is one of the known wear mechanism, further work would be needed to establish the dominant tool wear mechanism in the cutting of amorphous polymers.

The causes of tool wear in interrupted cut [27] was discovered to be friction and wear of tools made of sintered carbide and is very intensive in the conditions of interrupted dry cutting. [28] did experimental investigation of the influence of tool wear and chip forming mechanisms on tool vibrations and confirmed the hypothesis that changes in tool wear degree directly chip form and type of segmentation.

Sulaiman et al. [29], in the study of wear process on uncoated carbide turning tool in machining titanium alloy, reported that the cutting tool failed when the flank wear average value (V_{Bavg}) reached 0.3 mm. The results from the experimental study by [30,31] on effect of dry machining on tool wear during turning AL 6061 by using different type physical vapour deposition (PVD) and chemical vapour deposition (CVD) coated carbide inserts showed that the CVD coated inserts have lower tool wear when compared to PVD coated carbide inserts. Also that the wear progress of (Ti, W, Si) N-coated WC-Ni based cemented carbide insert became slower with a decrease in Ni content and that WC-Ni based cemented carbide could be used as a substrate for cutting tool materials in their experimentally investigated study of tool wear of (Ti, W, Si) N-Coated WC-Ni- based cemented carbide in cutting hardened steel.

Nebojsa et al. [32] reported on wear of diamond-coated cutting tool inserts upon machining of Al-12% Si and glass fiber/polyester resin composites and concluded that, generally, the wear resistance of the diamond-coated cutting insert is superior over the conventional tool. [33] carried out experimental study on thermal and tool wear on Mild Steel turning using high speed steel (HSS) and established that tool wear is minimum for cutting speed range of 400-450rpm for Mild Steel turning and that cutting speed has significant effect on the temperature developed as well as the tool wear.

3. MECHANISMS OF TOOL WEAR AND THEIR MODELS

Prediction of tool wear is complex because of the complexity of machining system. Tool wear in cutting process is produced by the contact and relative sliding between the cutting tool and the workpiece and between the cutting tool and the chip under the extreme conditions of cutting area; temperature at the cutting edge can exceed 1000℃. Thus, knowledge of tool wear mechanisms and capability of predicting tool life are important and necessary in metal cutting.

Any element changing contact conditions in cutting area affects tool wear [34]. These elements come from the whole machining system comprising workpiece, tool, interface and machine tool. In order to find out suitable way to slow down the wear process, many works are carried out to analyze the wear mechanism in metal cutting [35]. It is found that tool wear is not formed by a unique tool wear mechanism but a combination of several tool wear mechanisms. Tool wear mechanisms in metal cutting include abrasive wear, adhesive wear, solution wear, diffusion wear, oxidation wear, etc., as shown in Fig. 1 [36].

As the tool wear in cutting operations involves complex wear mechanisms, researchers have attempted to directly correlate the results of tool life to the applied machining parameters (cutting speed, feed rate, and etc.). Many models are developed to describe tool wear in quantity. They can be categorized into two types: tool life models and tool wear rate models, which are shown in Table 1 [37].

Tool life models give the relationship between tool life and cutting parameters or variables. For example, Taylor's tool life equation reveals the exponential relationship between tool life and cutting speed, see Table 1. The constants n, x, Y and Z are defined by doing a lot of experiments with cutting speed changing and fitting the experimental data with the equation. It is very convenient to predict tool life by using this equation. Tool wear rate models are derived from one or several wear mechanisms. They provide the information about wear growth rate due to some wear mechanisms. In these modes, the wear growth rate, i.e. the rate of volume loss at the tool face (rake or flank) per unit contact area per unit time, is related to several cutting process variables that have to be decided by experiment or using some methods [38,39]. The usual pattern or geometry of wear of turning and face milling inserts are typically shown in Figs. 2a and b) and Fig. 3 respectively.

4. FAILURE OF CUTTING TOOLS

According to [24] some of the factors affecting the smooth, safe and economic machining necessitate prevention of premature and catastrophic failure of the cutting tools and reduction of rate of wear of tool to prolong its life. These factors include:

i) Mechanical breakage due to excessive forces and shocks. Such kind of tool failure is random and catastrophic in nature and hence are extremely detrimental.
ii) Quick dulling by plastic deformation due to intensive stresses and temperature. This type of failure also occurs rapidly and are quite detrimental and unwanted.
iii) Gradual wear of the cutting tool at its flanks and rake surface.

Table 1. Empirical tool life and tool wear rate models

Empirical tool life models	Tool wear rate models
Taylor's basic model: $VL^n = x_1 (n, x_1 = \text{constants})$	Takeyama's wear model: (considering diffusive and abrasive wears): $\frac{dW}{dt} = G(V,f) + D\exp\left(-\frac{E}{RT}\right)$ (G, D are constants)
Taylor's extended model: $L = \frac{x_2}{V^p f^q d^r}$ (p,q,r,$x_2 = \text{constants}$)	
Taylor's extended model: $V = \frac{x_3}{L^m f^p d^q (BHN/200)^r}$ (m, p, q, r,$x_3 = \text{constants}$)	Usui's wear model: (considering adhensive wear): $\frac{dW}{dt} = Y\sigma_n V_s \exp\left(-\frac{Z}{T}\right)$ (Y, Z are constants)
Taylor's basic model: $TL^n = x_4 (n, x_4 = \text{constants})$	

L = Tool life; σ_n = Normal stress; V_s = Sliding velocity; d = Depth of cut; T = Cutting temperature; V = Cutting speed; f = Feed rate; E = Activation energy; R = Universal gas constant; BHN = Workpiece hardness; dW/dt = Wear rate (volume loss per unit contact area/ unit time)

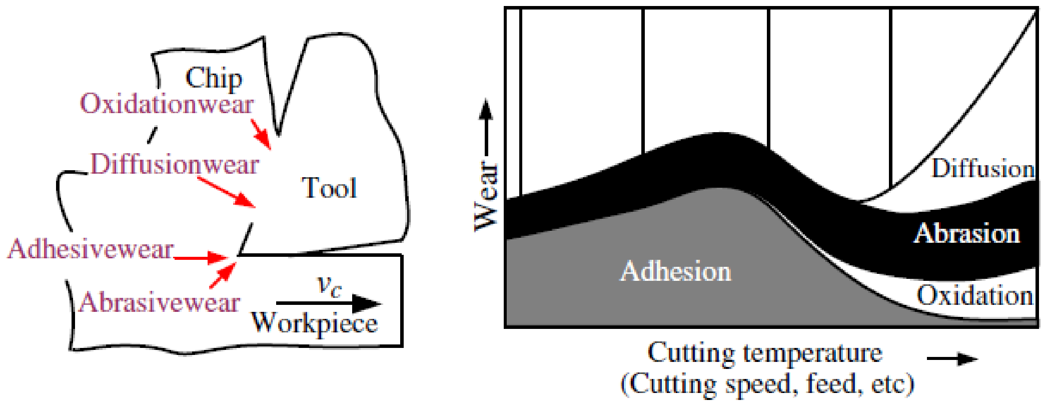

Fig. 1. Wear mechanism in metal cutting

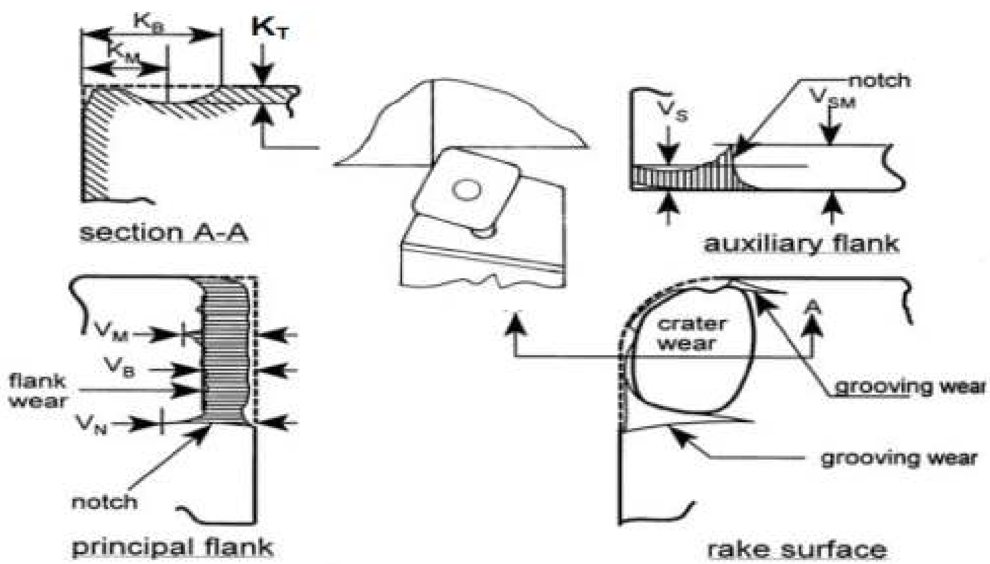

Fig. 2a. Geometry and major features of wear of turning tools

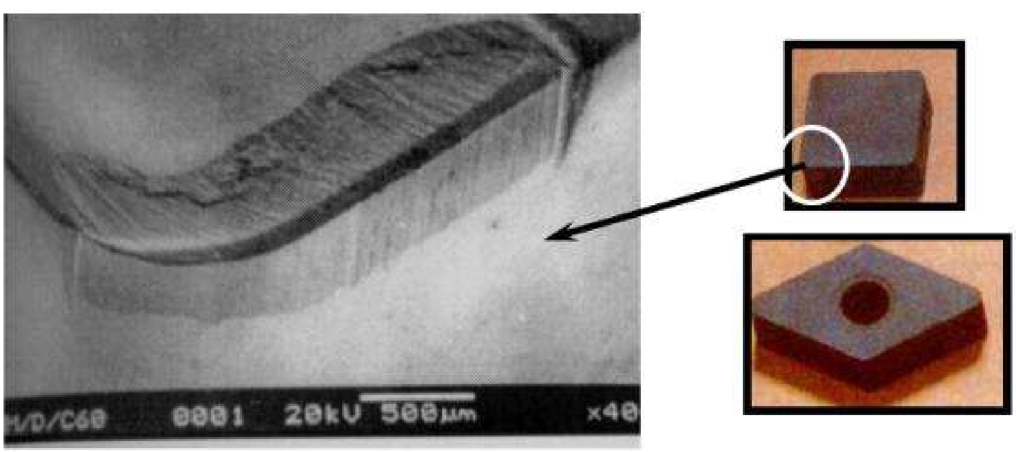

Fig. 2b. Photographic view of the wear pattern of a turning tool insert

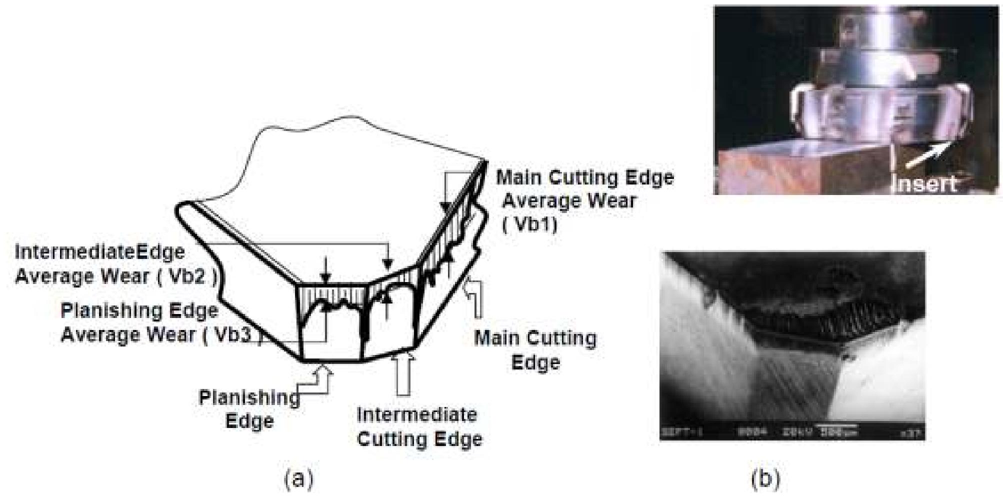

Fig. 3. Schematic (a) and actual view (b) of wear pattern of face milling insert

The first two modes of tool failure are very harmful not only for the tool but also to the job and machine tool. But failure by gradual wear, which is inevitable, cannot be prevented but can be slowed down only to enhance the service life of the tool. The cutting tool is withdrawn immediately after it fails or, if possible, just before it totally fails.

In addition to ultimate failure of the tool, the following effects are also caused by the growing tool-wear, they include: increase in cutting forces and power consumption mainly due to the principal flank wear; increase in dimensional deviation and surface roughness mainly due to wear of the tool-tips and auxiliary flank wear (V_s); odd sound and vibration; worsening surface integrity; mechanically weakening of the tool tip.

4.1 Essential Properties for Cutting Tool Materials

The cutting tool materials need to be suitable to meet the growing demands for higher productivity and economy as well as to machine the exotic materials which are coming up with the rapid progress in science and technology.

The cutting tool material of the day and future essentially require the following properties to resist or retard the phenomena leading to random or early tool failure:

i) *High mechanical strength* – compressive and tensile;
ii) *Fracture toughness* – high or at least adequate;
iii) *High hardness for abrasion resistance*;
iv) *High hot hardness to resist plastic deformation and reduce wear rate at elevated temperature*;
v) *Chemical stability or inertness against work material, atmospheric gases and cutting fluids;*
vi) *Resistance to adhesion and diffusion*;
vii) *Thermal conductivity* – low at the surface to resist incoming of heat and high at the core to quickly dissipate the heat entered;
viii) *High heat resistance and stiffness*; and
ix) *Manufacturability, availability and low cost.*

5. CONCLUSIONS

Recent significant transformation driven by a number of factors, and increasing business competition are reasons for many research study in manufacturing in order to optimise process in terms of improving quality, increasing productivity and lowering cost. A very important aspect of these studies is the selection of proper cutting tools in manufacturing of discrete component parts.

The time and cost for tool replacement and adjusting machine tool associated with tool failure increase production cost and decrease productivity. The study of tool wear as reviewed in this paper is of great significance for the optimization of the manufacturing process. Hence, it is safe to conclude that the study of tool wear mechanisms for all categories of cutting tool materials will continue to receive top priority attention in the consideration of machining processes.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
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