Archives of Materials Science and Engineering

Volume 126
Issue 1
March 2024
Pages 34-41

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

DOI: 10.5604/01.3001.0054.5856

The effects of cutting speed and change in cutting tool materials on surface roughness in bone-cutting procedures

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ABSTRACT

Purpose: Surface roughness is a reliable indicator of bone cell damage in bone-cutting processes. This novel study investigates the effects of spindle speed, feed rate, and cutting tool materials on milling artificial bone specimens.

Design/methodology/approach: Since bone cutting is an orthogonal cutting technique, bone machining was carried out using the milling process. As per the requirements of the objectives, four milling cuts were carried out across each workpiece using two different materials-based customized cutting tools, SS316 and ZrO_2. The machining parameters used were 0.03 mm/tooth feed rate, 900 m/min and 1000 m/min cutting speed and 1.3 mm depth of cut. Surface roughness was measured in two parameters, R_a and R_z, for each machined cut from SS316 and novel ZrO_2 tools.

Findings: At 1000 m/mm, SS316-based cutting recorded a maximum cutting temperature of 39°C. With increased cutting speed, R_a values from both cutting tools were raised. While R_z values were unstable in 900 m/mm cuttings, they steadily increased with the rise in cutting speed. ZrO_2-based cutting at 900 m/mm speed produced the maximum groove possible, measuring 9.487 mm, the closest to the tool's 9.5 mm diameter. Experiment results demonstrate that increasing cutting speed has little impact on R_a values, but it generates uniformity in R_z, which leads to minimal surface roughness. In conclusion, ZrO_2-based cuttings have shown proper uniformity in R_z values against SS316.

Research limitations/implications: Further experiments based on changes in cutting tool materials, cutting parameters, and types of cutting tools will provide enough data to introduce ceramic tools in bone-cutting procedures.

Originality/value: The novelty of the study is the introduction of a customized ZrO_2 ceramic-based cutting tool for bone-cutting procedures.

Keywords: Bone cutting, Surface roughness, SS316, ZrO_2, Milling process

Reference to this paper should be given in the following way:

W. Sawangsri, P. Addepalli, S.A.C. Ghani, The effects of cutting speed and change in cutting tool materials on surface roughness in bone-cutting procedures, Archives of Materials Science and Engineering 126/1 (2024) 34-41. DOI: https://doi.org/10.5604/01.3001.0054.5856

BIOMEDICAL AND DENTAL MATERIALS AND ENGINEERING

1. Introduction

When the structural continuity of the bones breaks down, fractured bones occur. Broken bones are capable of rebuilding by generating new cells in fractured areas. Medical surgery and non-surgical are the two methods for repairing broken bones. Academic and corporate research has responded to this trend by inventing more effective surgical instruments and procedures, making orthopaedics an important field of study [1]. The cortical bone, the outer and tougher layer of the bone, will be the first layer to come into contact with the cutting tool during the surgical operation [2]. Performing the required validation procedures on the innovative surgical devices is a laborious and lengthy task due to the difficulty of recreating surgical conditions, such as working with real bones with vascular systems [3]. Due to that, artificial polyurethane bones are used as substitutes for actual bones for research purposes.

Given that live specimens (i.e. bone stock) are scarce, any sample size and quality required to generate statistically relevant, reliable data is difficult to obtain within a reasonable time frame before environmental degradation, such as dehydration or biological decay, takes effect and changes the specimen [4]. Drilling, milling, sawing, and grinding are a variety of bone machining techniques through which cutting procedures can be carried out [5-7]. Milling can be an alternative bone machining process to drilling, at least for research purposes. Eventually, both processes perform orthogonal cuttings.

High cutting forces raise temperatures, causing bone damage (thermal necrosis) and even tool breakage, which can lead to severe infections in bone tissues [8]. Milling from different cutting parameters demonstrated that the milling force was increased and the temperature decreased [6]. A model for both the force and temperature of bone milling is provided to evaluate the cutting stress in various osteon cutting angles [9].

Any machining process that is subjected to modification has a significant chance to generate distinct outcomes. Surface roughness is a crucial indicator of machining process results. It relates to friction, wear, and lubrication during the machining process in metal cutting. Studies on surface roughness in machining non-metals as a function of machining parameters are also being conducted in relation to product quality in machining [10]. In regards to the topic of surface roughness as a reaction in bone machining, references and studies are still actually restricted in the field [11,12]. Surface roughness response in bone machining serves as a representation of bone cell injury that may occur as a result of the machining process. The level of damage that transpires in bone cells during bone machining is known to correlate with bone surgery success levels and the time required for post-surgical healing [13,14].

Following the completion of the machining operation, some parameters for measuring surface roughness are available. R_a (arithmetic mean value of roughness profile) is considered to be sufficient and commonly used to determine machined surfaces. However, R_a might not be the only parameter to rely upon when measuring nonmetal surface roughness. R_z (average of the highest peak and deepest valley of roughness profile) is considered to be another efficient parameter for measuring surface roughness for nonmetal machined surfaces. However, previous studies on bone machining considered R_a as a reliable parameter for surface roughness evaluations [11,12,15]. Drilling, the most common method, incorporates specific metal-based, medically suitable drill bits commonly used in bone-cutting surgeries. To support that, a survey focused on bone-cutting tool materials, revealing that 98% of orthopaedic surgical cutting tools are made of stainless steel grade 316 [16]. In terms of properties, when compared to metals, ceramic materials are considered to be superior. Zirconium dioxide (ZrO_2) is a frequently employed ceramic material as an implant material in dentistry and orthopaedic operations. ZrO_2, commonly known as zirconia in medical terminologies, is a potential biomaterial used in surgical implants [17,18]. There is a large scope for introducing ZrO_2 as a bone-cutting tool, based on previous research where ZrO_2 is used as implant material.

Therefore, the study is conducted to evaluate the impact of changes in cutting parameters and tool materials on surface roughness in the bone machining process.

2. Materials and methods

2.1. Workpiece specimens

The artificial synthetic bone workpiece utilized in the experiments was a polyurethane block with a 2 mm cortical layer of 40 PCF density on top and 20 PCF density on the bottom, as shown in Figure 1 (bottom), designed and manufactured by Nacional Ossos in Brazil. The measurements of the workpiece are 9.5 cm × 4.5 cm × 3.2 cm. To obtain live temperature data, 1.5 mm diameter holes were drilled below the 2 mm cortical layer for embedding eight K-type thermocouples (4 on each side). The thermal conductivity of natural bone is 0.59 W/mK, while the thermal conductivity of the artificial bone used for the experiment was 0.570 W/mK.

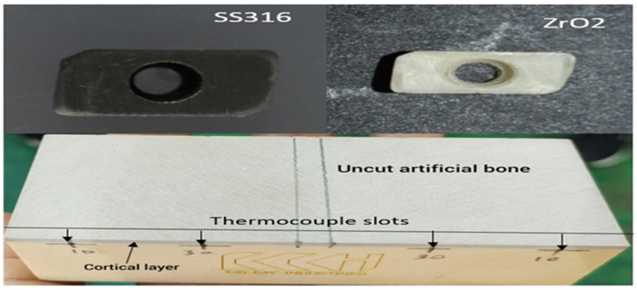

Fig. 1. Customized milling cutting tools SS316 (top left) and ZrO_2 (top right). Synthetic bone workpiece with thermocouple slots (bottom)

2.2. Tools

The study offers a novel approach by including a ceramic cutting tool in the bone-cutting technique. Milling was chosen as the machining method for the study, allowing the results to be used in real-life situations. Novel ceramic-based (ZrO_2) [19], bone-cutting milling inserts Figure 1 (top right), and customised stainless steel grade 316 (SS316) [20], Figure 1 (top left) inserts were manufactured to meet the needs of the bone-cutting assessments. ZrO_2 material has been considered for ceramic-based tools in place of standard SS316 due to its biocompatible qualities and successful use as implants. Milling inserts made of SS316 and ZrO_2 with dimensions of 11 mm × 6 mm × 3 mm, flank relief angle = 11°, and tool mounting slots ⌀ = 2.80 mm were manufactured. The cutting tools used in the experiment have thermal conductivities of 16.3 W/mK for stainless steel grade 316 and 2.5 W/mK for ZrO_2.

2.3. Experimental setup and procedure

The bone-cutting experiment was carried out using a milling method. The following are the major components of the experimental setup. The experiment used a 3-axis MAKINO KE55 CNC Vertical mill with a spindle speed range of 45-4000 rpm, as per Figure 2. SURFCOM FLEX 50, a surface roughness tester with a measuring range of X axis – 50 mm, Z axis – 800 µm, was used to calculate the surface roughness. The after-machining groove lengths from each cut were measured using a DINO-LITE DIGITAL MICROSCOPE, EDGE 3.0 AM73115MTF, with a viewing distance of 108 mm and a maximum magnification of 70x. A K-type thermocouple module with a measuring temperature range from 0 to 1024°C was deployed to collect temperature readings.

Fig. 2. Milling operational set-up with thermocouple module and In SITU Microscopic camera

2.4. Cutting parameters

The objective of the study is to investigate the impact of cutting parameters by the machining of artificial bone specimens. As machining began with two distinct tool materials, a series of experiments were carried out by varying cutting speeds from 900 m/min to 1000 m/min. A feed rate of 0.03 mm/tooth was decided on as the common factor for all the cuttings as per Table 1.

Table 1.
Cutting parameters for bone machining procedure

Tools	Feed, mm/tooth	1st cutting speed, m/min	2nd cutting speed, m/min
SS316	0.03	900	1000
ZrO_2	0.03	900	1000

Changes in cutting parameters were made to identify the surface roughness R_a and R_z values. R_a can be calculated by averaging the heights and depths over the given surface. R_z is the average of the absolute values of the highest-profile peaks' heights and the depths of the deepest alleys within the evaluation length. Changes in cutting parameters and tool materials will yield broader outcomes in the search for better circumstances for bone-cutting techniques.

3. Results and discussion

3.1. Analysis of temperature readings

The milling procedure was used to design four cuts for each workpiece. For four cuts, 8 K-type thermocouples were embedded in the slots to record live temperature during the milling process. According to live thermocouple data, Table 2 demonstrates the recorded maximum temperatures from cutting at different speeds with different materials.

Table 2.
Live temperature recorded during the bone machining

Tools	Feed, mm/tooth	Max temp °C at 900 m/min	Max temp °C at 1000 m/min
SS316	0.03	36.25°	39°
ZrO_2	0.03	39.25°	37.25°

The maximum temperature the novel ZrO_2 tool generates during the milling operation at 900 m/min speed is 39.25°C (temp range: 31.7°C–39.25°C). SS316 recorded a max temperature of 36.25°C (temp range: 31.5°C–36.25°C). The conventional SS316 tool appears to cause less damage due to a lower cutting temperature than the novel ZrO_2 tool. During the milling operation at 1000 m/min speed, the maximum temperature generated by the novel ZrO_2 tool is 37.25°C (temp range: 30.5°C–37.25°C), whereas SS316 generated a maximum temperature of 39°C (temp range: 31.5°C–39°C). Temperature readings at 1000 m/min speed contrast cutting temperatures at 900 m/min speed. LamNgeun Virasak [21] states that the recommended cutting speed is also heavily influenced by the hardness of the cutting tool material. The faster the cutting speed, the harder the tool. The slower the optimum cutting speed, the softer the tool. In such a case, the ZrO_2 is a harder material than SS316, and a temperature difference can be observed with the increase in cutting speed. ZrO_2 generated a lesser temperature at 1000 m/min, creating less thermal damage to the bone at maximum speed than SS316.

3.2. Analysis of surface roughness

In contrast to the objective to measure surface roughness in machined metals or nonmetals, the response of surface roughness in bone machining is used to indicate bone cell damage that may occur as a result of the machining process.

It is well known that the amount of bone damage sustained during the machining process directly impacts the bone restoration process. Figure 3 illustrates the bone-cutting procedure with four programmed cuts on each workpiece. The length of each cut is 40 mm, and the width of each is required to be 9.5 mm, equal to the tool holder's diameter. Figure 3 also shows the surface roughness test placed on one of the cuts to evaluate the surface roughness values.

Some surface roughness parameters can represent the surface roughness of a machined component. R_a (arithmetic mean value of roughness profile) and R_z (average of the

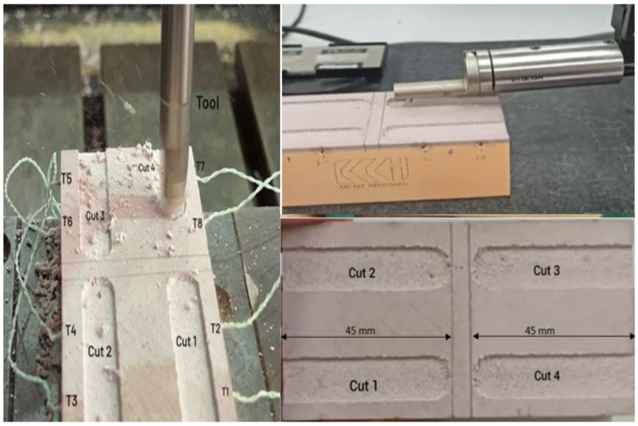

Fig. 3. In-process artificial bone cutting with 8 K-type thermocouples attached (left). (Bottom right) displays the artificial bone workpiece with four cuts (top right); SURFCOM FLEX 50 a surface roughness tester for R_a valuation

highest peak and deepest valley of roughness profile) are the most sufficient and commonly used to represent machined surfaces. A series of incisions were machined on the bone workpiece, as shown in Figure 3 above (bottom right section). Figure 4 illustrates the evaluated R_a and R_z values from bone-cutting procedures by SS316 and ZrO_2 tools at cutting parameters of feed f = 0.03 mm/tooth and spindle speed S = 900 m/min. Across each cut, seven surface roughness values were determined, and the average values were evaluated. We can observe in the Figure that both materials demonstrate a slow constant increase in R_a value, while ZrO_2's R_a values are significantly lower than those of SS316. The surface roughness R_a value of ZrO_2 is between 10.5 μm and 13.5 μm, whereas SS316 values are between 13 μm and 15 μm. Rz levels in SS316 are more unpredictable than in ZrO_2.

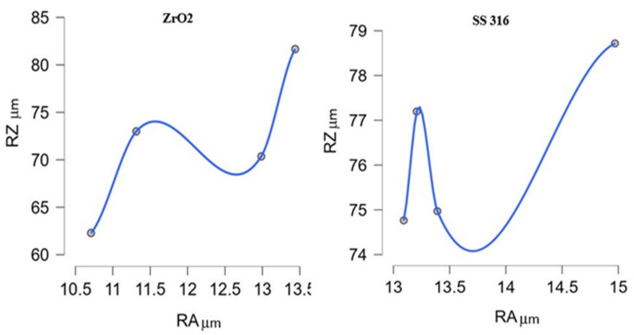

Fig. 4. R_a and R_z plots for ZrO_2 and SS316 at f = 0.03 mm/tooth, S = 900 m/min

Rz is the average of the highest peak and deepest valleys of a surface profile, and we can observe in Figure 4 that SS316 R_z values vary significantly throughout the machining process. R_z increased drastically from 74.8 µm to 77.2 µm and then dropped from 77.2 µm to 75 µm until gradually increasing to 78.9 µm.

The R_z performance of ZrO_2-based cuttings is also inconsistent but appears to be better than that of SS316. There is a continuous increase in R_z from 63 µm to 73 µm and a fall from 74 µm to 68 µm before reaching 83 µm in ZrO_2 cuts. Because of the irregular peaks in SS316 R_z values, it can cause greater damage to the bone surface than ZrO_2. Figure 5 illustrates the second set of bone-cutting procedures with f = 0.03 mm/tooth and an increased speed of S = 1000 m/min. Here, we can observe the increase in R_a values for ZrO_2 cuttings and the decline in SS316 cuttings. R_a values for ZrO_2 are between 10.5 µm and 14 µm. SS316's R_a values range from 8.8 µm to 14 µm). The variations in R_a values can be observed due to continuous cutting from a single tool, where tool behaviour also creates an impact. With the increase in cutting speed, we can observe the consistency in R_z from.

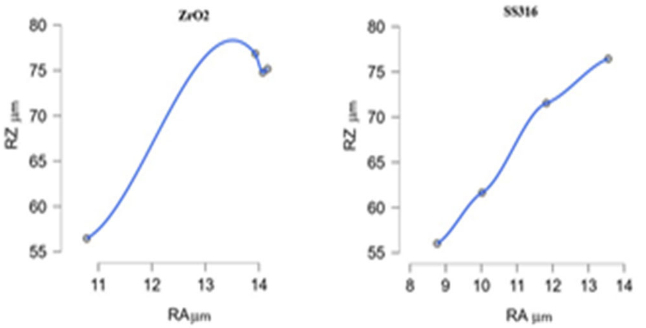

Fig. 5. R_a and R_z Plots for ZrO_2 and SS316 at f = 0.03 mm/tooth, S = 1000 m/min

The cuttings. R_z in ZrO_2 cuttings increases exponentially from 56 µm to 77 µm and then drops to 75 µm. In SS316 cuts, the R_z value increased from 56 µm to 76 µm without a drop until the end.

Following the completion of bone-cutting operations with both SS316 and ZrO_2 tools, we can conclude that although an increase in cutting speed does not greatly impact Ra, it certainly impacts the R_z of surface roughness phenomena. ZrO_2-based cuttings exhibited better surface roughness R_a and R_z values than SS316. SS316's uneven surface finish can harm the bone regeneration process and can lead to osteonecrosis phenomena.

3.3. Groove lengths analysis

The experiment's primary feature was bone machining using cutting tools made of SS316 and ZrO_2. Each workpiece from the machining process experienced four cuts in proper sequence. Analysing the effects of cutting tools and parameters on bone machining also requires consideration of the lengths between each cut's grooves to determine the cutting performance.

Figure 6 demonstrates the maximum groove length identification after the bone machining procedure from SS316 and Novel ZrO_2 tools at f = 0.03 mm/tooth, s = 900 m/mm. Each cut is performed to achieve 40 mm of length with 1.3 mm of DOC. The Instrument used for measuring groove lengths is DINO-LITE DIGITAL MICROSCOPE, EDGE 3.0 AM73115MTF, with a viewing distance of 108mm and a maximum magnification of 70x. In such an instance, groove length is completely based on tool diameter ⌀ = 9.5 mm. Cuttings that have groove lengths closest to the tool diameter will be considered successful. The left image from the Figure shows the maximum groove length achieved by the SS316 tool, which is 9.179 mm. The ZrO_2 tool has achieved the maximum groove length of 9.487 mm, nearest to the tool's diameter. By providing equal cutting parameters, a change in tool material has enhanced the cutting performance; in this case, the material is ZrO_2.

Figure 7 illustrates identifying the maximum groove length resulting from bone machining using SS316 and Novel ZrO_2 tools at f = 0.03 mm/tooth, s = 1000 m/mm. The speed is increased from 900 m/min to 1000 m/mm for the second sequence of bone-cutting procedures. Any change in cutting parameters will undoubtedly result in a change in tool performance and results.

Results show that the performance of the SS316 tool is slightly better after the increase in cutting speed. The recorded groove length from SS316 tool machining is 9.221 mm; for ZrO_2, the recorded groove length is 9.171 mm, with a difference of 0.05 mm. They were the highest recorded groove lengths from all four cuts from each cutting tool. Cutting temperature might have a created impact on groove lengths. In the first set of cuttings, ZrO_2 generated the highest temperature of 39.25°C and the maximum groove length of 9.487 mm. Similarly, in the second set of cuttings, SS316 generated the highest temperature of 39°C and the maximum groove length of 9.221 mm. The change in cutting parameters and tool materials' in-process cutting temperatures have also impacted groove lengths on bone work pieces.

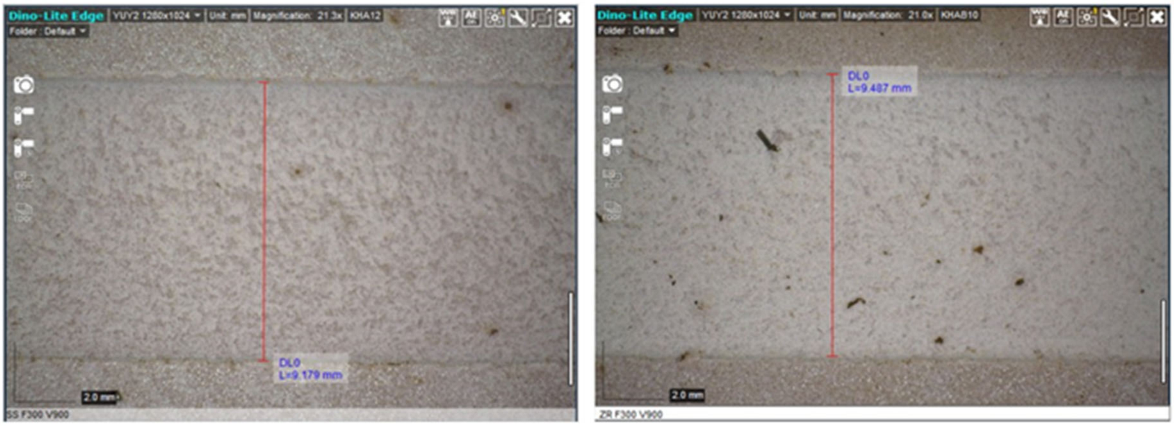

Fig. 6. Maximum groove lengths after machining the cuts from f = 0.03 mm/tooth and s = 900 m/min SS316 (left) and ZrO_2 (right)

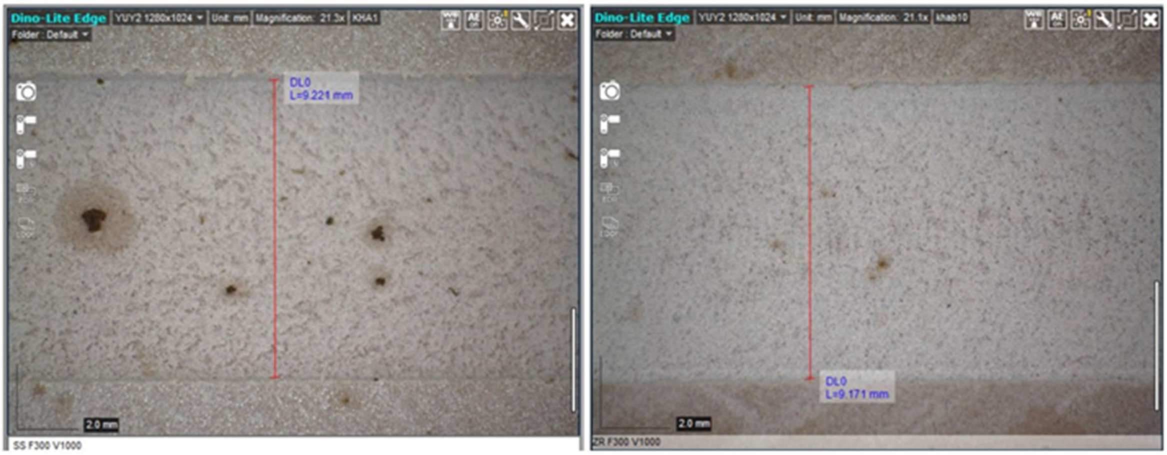

Fig. 7. Maximum groove lengths after machining the cuts from f = 0.03 mm/tooth and s = 1000 m/min SS316 (left) and ZrO_2 (right)

4. Conclusions

Changes can influence the R_a and R_z of surface roughness in tool materials. Unstable R_z can be stabilized by increasing the cutting speed, which will be beneficial in preventing osteonecrosis after bone-cutting surgeries. Cutting temperature immediately affects groove lengths, which can be tracked from tool to tool. The performance of the novel ZrO_2 tool was superior in both sets of cutting procedures. The surface roughness of R_a and R_z was lower in ZrO_2 than in SS316. ZrO_2 had a high cutting temperature of 39.25°C, but it had less influence on surface roughness than SS316 and attained a maximum groove length of 9.487 mm, closest to the tool diameter. Further research will be needed to validate the introduction of ceramic-based cutting tools for orthopaedic surgeries. The study aimed to evaluate the impact of changes in cutting parameters and tool materials in bone-cutting procedures, which were performed successfully.

Patents

1. 1 P. Addepalli, W. Sawangsri and S. A. C. Ghani, "Manufacturing of Zirconium Oxide based Milling Insert". INDIA Patent 202341032191, 06 May 2023.
2. P. Addepalli, W. Sawangsri and S. A. C. Ghani, "Manufacturing of Stainless Steel 316 Grade Milling

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Research funding

The research is funded by Faculty Of Engineering, Kasetsart University, Bangkok, Thailand.

Authors contribution

1. P. Addepalli: 60%,
2. W. Sawangsri: 20%,
3. S.A.C. Ghani: 20%.

Conflict of interest

There is no conflict of interest.

Acknowledgements

The research project was financially supported by the Faculty of Engineering, Kasetsart University, Thailand. The authors gratefully acknowledge the financial support from the Malaysia Ministry of Higher Education, Universiti Malaysia Pahang, for the fundamental research grant scheme (FRGS) RDU160135. For experimental support special thanks to Mohamad Faizal Ridzwan, Mohd Haslizam Abdullah, and Adlina Syafiqah Samsudin from the Faculty of Mechanical and Automotive Engineering and Technology, Universiti Malaysia Pahang, Malaysia.

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