Proceedings of the World Congress on Engineering 2012 Vol III
WCE 2012, July 4 - 6, 2012, London, U.K.

Surface Quality Improvement in CNC End Milling Machined Aerospace AL-2017-T4 Alloy using Carbon Onion Nanolubrication with DLC Cutting Tool

M. Sayuti, Tomohisa Tanaka, Ahmed A. D. Sarhan, Yoshio Saito, M. Hamdi

Abstract **- Aerospace applications and energy saving strategies in general raised the interest and study in the field of lightweight materials, especially on aluminum alloys. Aluminum AL2017-T4 alloy which is used in this research work has low specific weight and high strength to rate ratio and also high electrical and thermal conductance. This alloy is widely used in industry and in particular in aircraft structure. The (CNC) milling machine facilities provides a wide variety of parameters setup, making the machining process of the duralumin AL-2017-T4 excellent in manufacturing complicated special products compared to other machining processes. However, the demand for high quality focuses attention on the surface condition and the quality of the product, especially the roughness of the machined surface, because of its effect on product appearance, function, and reliability. The key solution for this issue is by increasing the effectiveness of the existing lubrication systems as it could reduce the friction component in machining process. For more improvement, introducing the nanolubrication could produce much less friction in the tool chip interface as the rolling action of billions units of nanoparticle could reduce the coefficient of friction significantly. The tool selection is the other significant parameter for better machined surface quality. Diamond like carbon (DLC) coated tool application is providing less coefficient of friction between the tool chip contact surfaces. In this research work, the DLC coated tool has been used to machine the duralumin AL-2017-T4 while the carbon onion nanoparticle has been mixed with ordinary mineral oil as a nanolubrication system. The 38.68% reduction of surface roughness could be obtained when 1%wt of carbon onion nanolubricant concentration is used compared with the case of using ordinary lubrication. This is mainly attributed to the tribological properties of the DLC coated cutting tool in conjunction with the carbon onion nanolubricant to reduce the coefficient of friction in the tool chip interface.**

Index Terms **- Aerospace AL-2017-T4 alloy, Carbon onion nanolubrication, DLC cutting tool, End milling, Surface quality**

M. Sayuti is with the Centre of Advanced Manufacturing and Material Processing, Department of Design and Manufacturing, Engineering Faculty, University of Malaya, 50603, Kuala Lumpur, Malaysia (phone: +60379674489; fax: +60379674489; e-mail: mdsayuti@um.edu.my).

Tomohisa Tanaka is with the Department of Mechanical and Engineering, Graduate School of Science and Engineering, Tokyo Institute of Technology, Tokyo, e-mail: tanakat@mep.titech.ac.jp

Ahmed A. D. Sarhan is with the Centre of Advanced Manufacturing and Material Processing, Department of Design and Manufacturing, Engineering Faculty, University of Malaya, 50603, Kuala Lumpur, Malaysia (e-mail: ah_sarhan@um.edu.my).

Yoshio Saito is with the Department of Mechanical and Engineering, Graduate School of Science and Engineering, Tokyo Institute of Technology, Tokyo , e-mail: saitoy@mep.titech.ac.jp

M. Hamdi is with the Centre of Advanced Manufacturing and Material Processing, Department of Design and Manufacturing, Engineering Faculty, University of Malaya, 50603, Kuala Lumpur, Malaysia (e-mail: hamdi@um.edu.my).

I. INTRODUCTION

Aluminum and its alloys are today considered one of the most practical of metals for a variety of reasons. Its low cost, light-weight, and modern appearance are among the primary reasons for its widespread use. It is non-sparking, electrically conductive, thermally conductive, non-magnetic, reflective, and chemically resistant. It is popular in the construction, marine and aircraft industries because of its ease of fabrication, non-toxicity, strength (pound-for pound), and resistance to the corrosive atmospheres of industry and marine environments. Aluminum Alloy 2017-T4 is one of the highest strength and hardest aluminium alloys with excellent fatigue strength available. Heat-treating increases its strength considerably. It is used for various applications from high strength structural components, aircraft, machine construction, military equipment, rivets. Alloy 2017 also has very good machining characteristics in the T4 temper. In the annealed condition machinability is less good. Thus it is best to perform machining with the alloy in the T4 condition, however, it is recommended to use suitable end mill tool.

The usage of suitable tool for the duralumin AL-2017-T4 workpiece is significant to reduce the friction component in the chip tool interface during the machining process. However, due to the soft and "sticky" nature of aluminium, specific geometries and characteristics of the end mill are required for efficient machining. Many cutting tool manufacturers offer end mills specifically designed for aluminium machining for this reason [1]. By using diamond like carbon (DLC) end mills with the correct cutting geometries and coatings, metal removal rates can increase by four to five times—or higher—than that of steel. Surface finishes of 16µ or better are also easily achieved, reducing finishing time considerably. The diamond like carbon (DLC) coated tool has been specially developed so it can attribute to the better performance in milling aluminium alloy based workpiece. Diamond-like carbon (DLC) is an amorphous hard thin film that can comprise different kinds of carbon-based materials. It has the properties such as low friction coefficients, high hardness, high chemical stability, and high wear resistance [2]. The most important thing is their tribological properties make DLC film suitable for a constellation of engineering applications. The smaller friction component is the main favourable benefit that could be obtained while using DLC coated tool during the machining compared to ordinary cutting tool, however it is recommended to use of oil lubricants for all machining operations. The existence of clean surfaces and high hydrostatic stresses favors the formation of strong adhesive friction junctions; the extent of these can be limited by the provision of a suitable lubricant [3-4]. Correct application of lubricants has been proven to greatly reduce friction. This results in surface quality improvement.

Although the significance of lubrication in machining is widely recognized, the usage of conventional flooding application in machining processes has become a huge liability. Not only does the Environmental Protection Agency regulate the disposal of such mixtures, but many countries and localities also have classified them as hazardous wastes. Beside that economically, the cost related to the lubrication and cutting fluid is 17 % of total production cost which is normally higher than that of cutting tool equipments which incurs only 7.5 % of total cost. At present, many efforts are being undertaken to develop advanced machining processes using less lubrications [5]. Promising alternatives to conventional flood coolant applications are the minimum quantity lubrication (known as MQL) [6]. Klocke and Eisennblatter (1997) state that MQL refers to the use of lubrication of only a minute amount-typically of a flow rate of 50 to 500 ml/hour which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition. This has been reported to reduce friction, cutting temperature and improve tool life due to its ability to penetrate into the chip-tool interface, this results in improving surface quality [7].

For more develop advanced machining processes for better surface quality using less lubrication, it is clear that a multi-pronged approach must be used, including innovation in technology. In this paper, authors will explore the development of nanolubrication in machining. It has been reported that, by introducing the nanolubrication system in machining process, the reduction of friction component could be achieved as it is working of billions of rolling elements in the tool chip interface and consequently produce much better surface quality [8]. Nanolubricant is defined as new engineering material consisting of nanomaterial-sized particles dispersed in base fluid. The nanolubricant is developed to sustain the high machining temperatures present in machining process, non-toxic, easy to be applied and effective in term of cost [9]. Over a decade, carbon onion has been successfully developed with high tribology performance. Carbon onion consist of concentric graphitic shells and it is one of the fullerene-related materials together with C60 and carbon nanotubes [10]. It has been proved that it can provide the similar lubrication with the graphite when tribologically tested at ambient air. It is expected to have good properties suitable for nanobrication system due to its unique structure. It also has been proved that it could be used as a solid additive to grease replacing MoS_2 in several commercially available lubricants for use in ambient air [11].

Following the review above, in this research work the surface quality improvement is investigated in end milling of AL2017-T4 alloy using carbon onion nanolubrication DLC coated cutting tool.

II. Experimental Set up and Procedure

The experimental set-up is shown in Fig. 1. The machine used in this study is a vertical-type machining centre (Sakai CNC MM-250 S3). The spindle has constant position preloaded bearings with oil-air lubrication with the maximum rotational speed of 5,000 min^{-1}. Two cutting tool type with similar geometry are used in this experiment; the ordinary end milling cutting tool (SLC-ALHEM2S8) and diamond like carbon coated tool (DLC-ALHEM2S8) with 8 mm diameter, shown in Fig. 2. A cutting process of a rectangular workpiece of duralumin AL-2017-T4 (85.1 HRB) prepared in 50 x 20 x 10 mm^3 is selected as a case study. Table 1 shows the mechanical properties of duralumin AL-2017-T4 while, Fig. 3 shows the workpiece and the tool paths used in the cutting tests. The slot-milling test was carried out, the tool moves in -X direction to cut a stroke of 50 mm. The cutting speed, feed rates and depths of cut used were selected based on the tool manufacturer's recommendation which are; 3,000 min^{-1} cutting speed, 100 mm/min feed rate, and 1.0 mm axial depth of cut.

To reduce the friction in the tool chip interface, the Alumicut lubricant type has been selected since it has a good lubrication quality characteristic. The two different types of lubrication modes used in this research are ordinary lubricant oil and 1.0%wt carbon onion nanolubrication concentration.

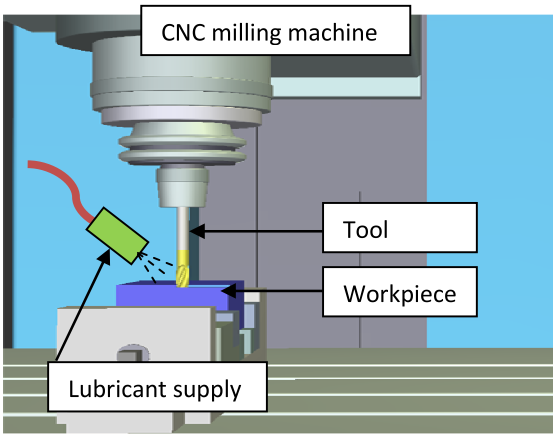


Fig 1 Experimental set-up

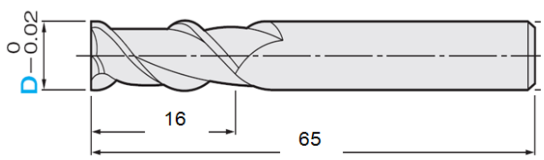


Fig 2 The tool geometry

The ordinary lubricant oil is used with the ordinary end milling cutting tool (SLC-ALHEM2S8), while the carbon onion nanolubrication is used with the both of ordinary end milling cutting tool (SLC-ALHEM2S8) and diamond like carbon coated tool (DLC-ALHEM2S8) as shown in Table 2. The nanoparticle-oil were prepared by adding Carbon onion nanoparticles (1% wt) with an average size of 5-20 nm to the mineral oil followed by sonication (240 W, 40 kHz, 500 W) using Sono Bright ultrasonic device for 30 minutes in order to suspend the particle homogeneously in the mixture. Carbon onion nanoparticle has been produced by heat-treatment of carbon black (Cabot R250 from Cabot Corporation) in a resistance heated furnace using a graphite crucible under a Helium atmosphere. The nano onions were obtained by inductive heating at 2000°C for 15 minute duration and were used without further treatment (e.g. purification). Figure 4

ISBN: 978-988-19252-2-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

shows the TEM picture of carbon onion at average size of 5 to 20 nm.

TABLE 1
THE MECHANICAL PROPERTIES OF DURALUMIN AL-2017

Mechanical properties	Value
Hardness, Vickers	118
Ultimate tensile strength	427 MPa
Tensile yields strength	276 MPa
Modulus elasticity	72.4 GPa
Poisson ratio	0.33
Fatigue strength	124 MPa
Shear Modulus	27 GPa
Shear Strength	262 MPa

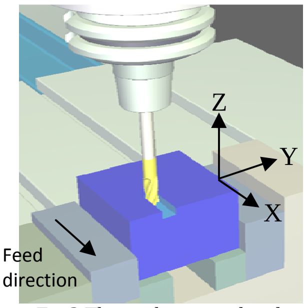


Fig 3 The workpiece and tool paths

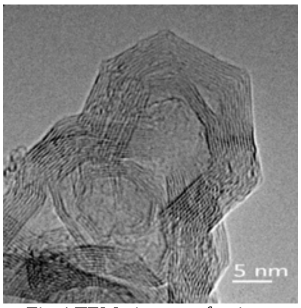


Fig 4 TEM pictures of onion-carbon [7]

To ensure the consistent lubrication supply into the systems, it was properly spur on the top of workpiece during machining. After the machining, the surface roughness (Ra) is measured using the Nanofocus roughness tester with µsufr Software following the ISO 11562 with 0.5 mm cut off distance. The surface roughness has been measured three times after every single machining run under 1000X magnification and the average has been calculated.

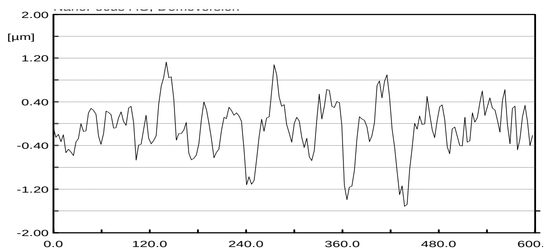
III. RESULTS

The slot-milling test was carried out to investigate how to improve the surface quality of the machined duralumin AL-2017-T4 using DLC cutting tool and carbon onion nanolubrication system. Figure 5 (a), (b) and (c) shows examples of measured surface roughness at different machining modes using ordinary lubrication and ordinary cutting tool. The average measured surface roughness at three different measurements has been calculated for all modes of lubrication and it was summarized in Table 2. While the measured and average of the roughness data are plotted in Fig. 6. As can be seen in Fig. 6, the surface roughness in mode 3 with carbon onion nanolubrication and DLC has shown the smallest value followed by mode 2, while the largest surface roughness can be seen in mode 1, of ordinary cutting tool in conjunction with ordinary lubrication. The interpretation of the results has been supported by the results in Fig. 7.

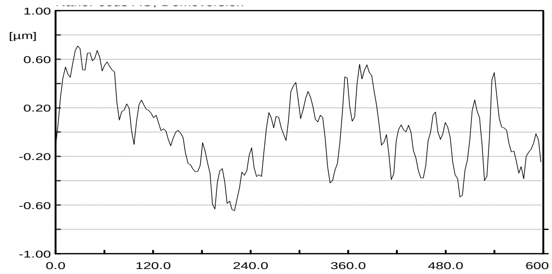
Figure 7 shows the stereoscopic photographs for three-dimensional views of machined surface for mode 1, 2 and 3, respectively.

TABLE II
THE AVERAGE OF MEASURED SURFACE ROUGHNESS

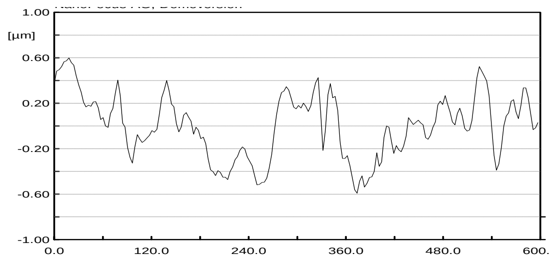
Machining mode	Lubrication	Tool	Average Measured Surface roughness R_a (µm)
Mode 1	Ordinary lubricant	Ordinary cutting tool	0.380
Mode 2	1.0 %wt of Carbon onion	Ordinary cutting tool	0.251
Mode 3	1.0 %wt of Carbon onion	DLC coated tool	0.233



a. Mode 1 (ordinary lubricant combined with ordinary tool)



b. Mode 2 (1.0%wt carbon onion combined with ordinary tool)



c. Mode 1 (1.0%wt carbon onion combined with DLC coated tool)

Figs 5 Roughness profile of machined surface.

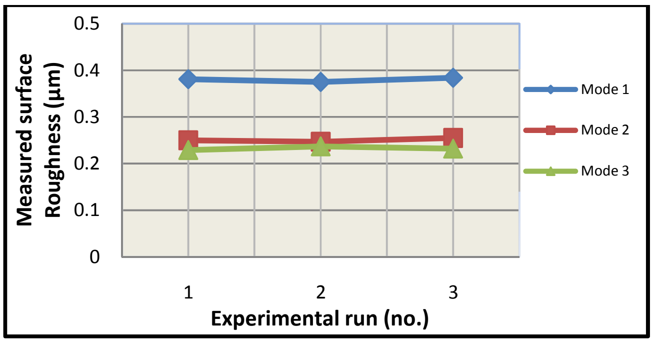
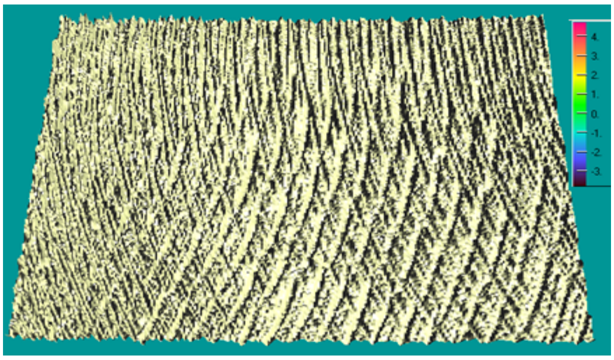


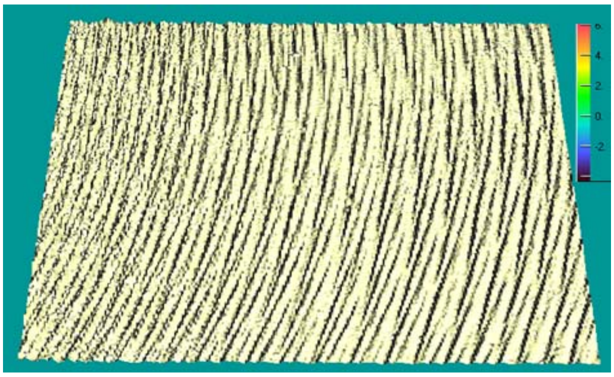
Fig 6 Measured surface roughness at all modes

ISBN: 978-988-19252-2-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

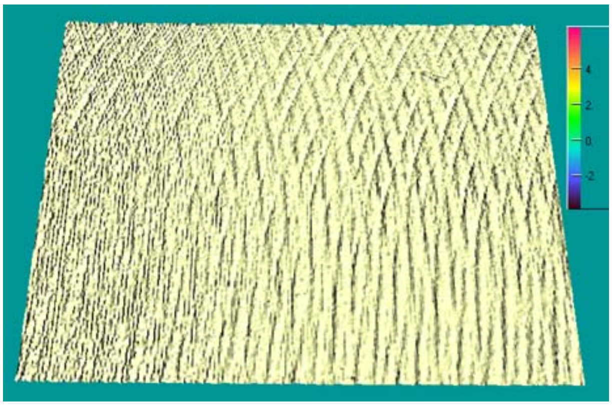
From these photos, it is clearly shown that the parameter set up at mode 3 (DLC coated tool in conjunction with 1.0%wt carbon onion concentration) would produces the lowest surface roughness compared with mode 2 and mode 1. From the results, it has been found that the reduction of surface roughness using carbon onion nanolubrication with DLC tool is 7.17% compared to mode 2 and 38.68% compared to mode 1. This evidence may suggest that the ordinary cutting process could be improved by using either onion carbon nanolubrication or the usage of DLC coated cutting tool or using both together.



a. Mode 1 (ordinary lubricant combined with ordinary tool)



b. Mode 2 (1.0%wt carbon onion combined with ordinary cutting tool)



c. Mode 3 (1.0%wt carbon onion combined with DLC coated tool)

Fig 7 Stereoscopic photographs for three-dimensional views of machined surface.

IV. Discussion

In this research work, both DLC coated and normal cutting tool has been used with two different modes of lubrication, the normal lubricant and carbon onion nanolubrication to investigate the surface quality improvement of CNC end milling machined duralumin AL-2017-T4. From the results, it is clearly seen that mode 3 where DLC coated tool used in conjunction with 1.0%wt carbon onion concentration is producing the best surface quality followed by mode 2 (1.0%wt carbon onion with normal cutting tool) and mode 1 (normal lubricant with normal cutting tool). This may attributed to the friction at the tool rake face while chip is flowing over a tool leading to localized region of intense shear at the secondary zone as shown in Fig. 8. If the coefficient of friction in the tool chip interface is greater than 0.5, the sticky friction would result and flow would occur only within the workpiece but not at the tool-workpiece interface leading to poor surface quality. Using the DLC coated cutting tool in conjunction with lubrication system to the tool chip interface will reduce the coefficient of friction leading to better surface quality.

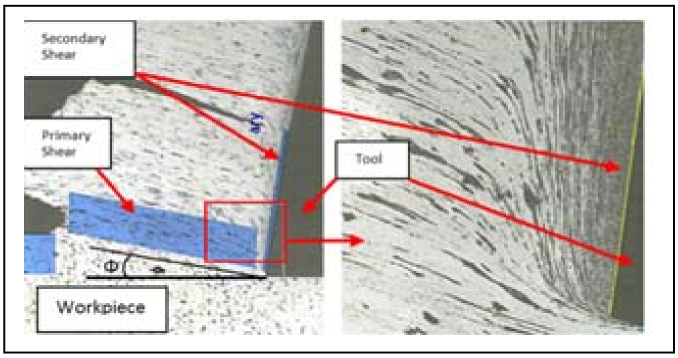


Fig 8 Shear mechanism in cutting zone [1]

However, introducing of the carbon onion nanolubrication system would show much less friction and much better surface quality. This is mainly attributed to the tribological properties of both DLC coated surface and carbon onion which can reduce the coefficient of friction in the interface between the cutting tool and workpiece during machining as it is acted as billions of nano-scale quasi-spherical structure rolling elements in the tool chip interface as shown in Fig. 9. The outermost shell of the carbon onion is scarcely contains defects as no dangling bonds exist on the surface of carbon onion when carbon atoms perfectly arranged. Besides, this suggest that the improvement of the surface quality has been resulted from the lesser tool wear and reduction of cutting temperature due to the reduction of coefficient of friction at the cutting zone during the machining process.

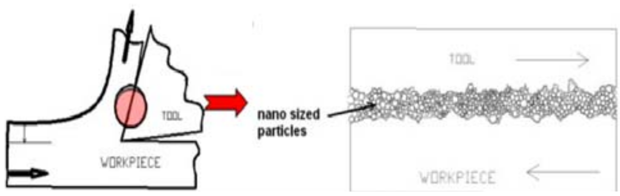


Fig 9 Rolling element in the tool chip interface [12]

ISBN: 978-988-19252-2-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

V. Conclusion

In this study, the investigation of the surface quality improvement of CNC end milling machined duralumin AL-2017-T4 when using DLC coated tool and carbon onion nanolubrication system has been conducted. Based on the results obtained, the usage of DLC coated tool in conjunction with carbon onion nanolubrication produced the best surface quality, 38.8% surface roughness reduction compared with the case of using ordinary lubrication. This is mainly due to the tribological properties DLC coated tools and the carbon onion. Besides, the carbon onion is acting as billions of nano-scale spherical structure rolling elements in the tool chip interface makes the coefficient of friction is significantly reduced.

Acknowledgements

Authors would like to acknowledge the JASSO and AOTULE Summer program 2011, Tokyo Institute of Technology, Japan for providing the equipment and facilities to this research.

References

[1] Trent, E.M. and P.K. Wright, *Metal Cutting*. Fourth ed. 2000: Butterworth-Heinemann.
[2] Fukui, H., J. Okida, N. Omori, H. Moriguchi, and K. Tsuda, *Cutting performance of DLC coated tools in dry machining aluminum alloys.* Surface and Coatings Technology, 2004. 187(1): p. 70-76.
[3] Lathkar, G.S. and U.S.K. Bas, *Clean metal cutting process using solid lubricants,*, in *in:proceeding of the 19th AIMTDR Conference*. 2000, Narosa Publishing House IIT Madras. p. 15-31.
[4] Suresh Kumar Reddy, N. and P. Venkateswara Rao. *Enhancement of machinability of AISI1045 steel using molybdenum disulphide as a solid lubricant*. in *2006 ASME International Mechanical Engineering Congress and Exposition, IMECE2006, November 5, 2006 - November 10, 2006*. 2006. Chicago, IL, United states: American Society of Mechanical Engineers.
[5] Dilbag, S. and P.V. Rao, *Performance improvement of hard turning with solid lubricants.* Int J Adv Manuf Technol 2008. 38: p. 529-535.
[6] Yassin, I.N., M.Hamdi, M.Fadzil, and M.Z. Norhirni, *Investigation into New Development of Minimal Quantity Lubricant (MQL) System in High Speed Milling of H13*, in *UK-Malaysia-Ireland Engineering Science Conference 2011 (UMIES 2011)*. 2011: Faculty of Economics & Administration, University Malaya, Kuala Lumpur, Malaysia.
[7] Klocke, F. and G. Eisenblätter, *Dry Cutting.* CIRP Annals - Manufacturing Technology, 1997. 46(2): p. 519-526.
[8] Reddy, N.S.K. and M. Nouari, *The influence of solid lubricant for improving tribological properties in turning process.* Lubrication Science, 2011. 23(2).
[9] Deshmukh, S.D. and S.K. Basu, *Significance of solid lubricants in metal cutting*, in *22nd AIMTDR*. 2006.
[10] Hirata, A., M. Igarashi, and T. Kaito, *Study on solid lubricant properties of carbon onions produced by heat treatment of diamond clusters or particles.* Tribology International, 2004. 37: p. 899-905.
[11] Street, K.W., M. Marchetti, R.L.V. Wal, and A.J. Tomasek, *Evaluation of the tribological behavior of nano-onions in Krytox 143AB.* Tribology Letters, 2004. 16: p. 143-149.
[12] Yan, J., Z. Zhang, and T. Kriyagawa, *Effect of nano-particle lubrication in diamond turning of reaction-bonded SiC.* International Journal of Automation Technology, 2011. Vol.5(No.3): p. pp. 307-312.

ISBN: 978-988-19252-2-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)