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Investigate the Possibility of Using Carbon Onion Nanolubrication with DLC Cutting Tool to Reduce the Machining Power Consumption

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***Abstract*— Due to rapid consumption of world's fossil fuel resources and impracticality of large-scale application and production of renewable energy, the significance of energy efficiency improvement of current available energy modes has been widely realized by both industry and academia. In the CNC machining field, the key solution for this issue is by increasing the effectiveness of the existing lubrication systems as it could reduce the power required to overcome the friction component in machining process. For more improvement, introducing the nanolubrication could produce much less power consumption as the rolling action of billions units of nanoparticle in the tool chip interface could reduce the cutting forces significantly. In this research work, the possibility of using carbon onion nanolubrication with DLC cutting tool is investigated to reduce the machining power consumption. Carbon onion nanolubrication has been successfully developed with high tribology performance and mixed with ordinary mineral oil. The proper sonification method is used to provide a way to mix and suspend the particles thoroughly and efficiently. Furthermore, Diamond-like carbon (DLC) cutting tool is used and expected to play significant role in reducing friction and cutting forces and increasing abrasion resistance. The results showed significant reduction of the cutting force and the working power compared with the other conditions of using carbon black and normal lubrication systems.**

***Keywords*— carbon onion nanolubrication, machining power consumption, DLC cutting tool**

I. Introduction

In a developing country, economic growth is associated by the technology improvement particularly from the manufacturing industries. In machining processes, the improvement of saving money and sustainability performance can be done by reducing energy and power consumption. The cost of power used over a ten-year period is about 100 times higher than the initial purchase cost of these machine tools [1]. According to US Energy Information Administration, the fabrication of metal products consumed 47 billion kWh in 2008, which equivalent to 5% of the total industrial electricity consumption [2]. Moreover, the cost of power, materials, and waste have an impact on economic effectiveness [3]. Production companies can save up to 15% of their energy and power consumption just as easily by lubricating the machining areas with better lubricants. Turning to better lubricants pays off and it immediately lowers both energy use and direct expenses. It is fast, easy and requires minimal investment. Companies that recognize this make the switch with wonderful results [4].

Lubricants are meant to reduce the friction in the tool chip interface during machining. But not all lubricants are alike. High-quality and fully synthetic variants, for instance, reduce the friction better than normal mineral oils. As soon as the friction in machining has reduced, less energy is converted to friction heat. Beside that the amount of existing cutting force during machining will be reduced as well. Cutting force is very significant in order to achieve high accuracy and productivity and it could provide the basis information for process planning as well as to minimize the production cost and time [5, 6]. This lowers the operating temperature and the vibration levels, takes less energy to drive the machine and produces a greater output. The amount of energy that production companies can save using high-quality lubricants turns out to be between 5 and 15%. Sometimes, however, this is much more, depending among other things on the type of machine and how heavily cut it is used [7].

Making the upgrade to better lubricants is very essential for less energy in machining. High-quality lubricants are more expensive to buy, but much cheaper in use. Considering the current high energy costs and energy taxes, the use of quality lubrication usually pays for itself within very short time even if you look only at the lower energy bill. Moreover, the lubricant is used up to 5 times less frequently. The effect can be measured objectively by determining the difference in the energy use of the machine in operation before and after the upgrade with a clamp meter or the ampere-meter on the installation. This way, companies lower more than just their energy bills. They also save on pollute the environment much less with used lubricants. An important ISO 14001 target.

For more develop advanced machining processes for less power consumption and pollution using less lubrication, it is clear that a multi-pronged approach must be used, including innovation in technology [8]. In this paper, authors will explore the development of carbon onion nanolubrication to

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be used in machining, as it is working as billions of rolling elements in the tool chip interface [9]. Nanolubricant is defined as new engineering material consisting of nanomaterial-sized particles dispersed in base fluid. The nanolubrication system is developed to sustain the high machining temperatures present in machining process, non-toxic, easy to be applied and effective in term of cost [10]. Over a decade, carbon onion and carbon black nanoparticle has been successfully developed with high tribology performance. They are consist of concentric graphitic shells and it is one of the fullerene-related materials together with C60 and carbon nanotubes [11]. It has been proved that it can provide the similar lubrication with the graphite when tribologically tested at ambient air. Besides, 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 [12].

Furthermore, Diamond-like carbon (DLC) cutting tool is traditionally expected to play multiple roles for less energy; such as, reducing friction, cutting temperatures and cutting forces and increasing abrasion resistance. DLC coatings are often used to prevent wear due to its excellent tribological properties. DLC is very resistant to abrasive and adhesive wear making it suitable for use in applications that experience extreme contact pressure, both in rolling and sliding contact . DLC is often used to prevent wear on razor blades and metal cutting tools, including lathe inserts and milling cutters. Following the review above, the experimentation have been carried out in this research work to investigate the possibility of using carbon onion nanolubrication with DLC cutting tool to reduce the machining power consumption.

II. Experimental Details

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 similar geometry of two flutes Tungsten carbide (WC) tool were used in this experiment with 8 mm diameter; in which end milling ordinary cutting tool (SLC-ALHEM2S8) and diamond like carbon coated tool (DLC-ALHEM2S8), shown in Fig. 2.

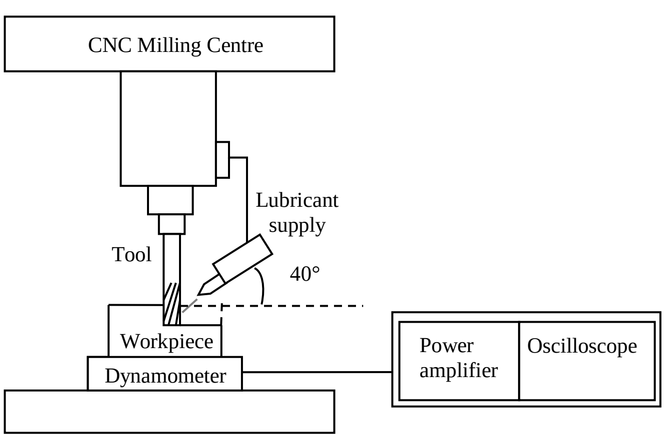

Figure 1. Schematic diagram of experimental set up

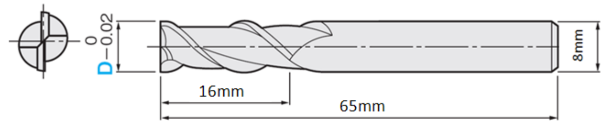

Figure 2. The tool geometry

A cutting process of a rectangular workpiece of duralumin AL-2017-T4 (85.1 HRB) prepared in 50 × 20 × 10 mm^3 by using new tool for each experiment 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 are 75.408m/min cutting speed, 0.0167 mm/tooth feed rate and 1.0 mm axial depth of cut, selected based on the tool manufacturer's recommendation.

TABLE 1. THE MECHANICAL PROPERTIES OF DURALUMIN AL-2017-T4

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

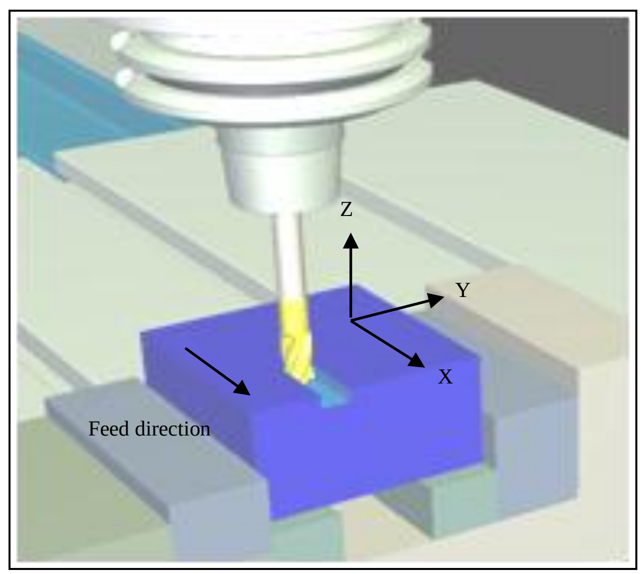

Figure 3. Workpiece and tool path used in the cutting test

Alumicut type has been selected as lubricant since it has a good lubrication quality characteristic for working with aluminum in reducing coefficient of friction during machining process. It appears in clear form with 6.9 pH values and it was formulated especially for non-ferrous workpiece. Alumicut would adhere to eliminates galling, gouging, and tearing of material, plus stops metal chip pile-up on tools extending tool life considerably. The ordinary lubricant, carbon black nanolubricant and onion carbon nanolubricant has been

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adopted as three different of lubricant modes. Ordinary lubricant is referring to the common Alumicut without additional substance while carbon black and onion carbon nanolubricant have been prepared in three different concentrations which are 0.5% wt, 1.0%wt and 1.5% wt. followed with sonification using Sono Bright ultrasonic vibration (240 V, 40 kHz, 500 W) for 30 minutes to homogenously mix the solid nanoparticle with oil. The three main different lubrication modes with different concentration and different type of cutting tool were used in this research to investigate how to reduce the power consumption during machining. The nano particle concentrations are selected based on the limitation with lubrication delivery system in such that the nozzle is clogged when the nanoparticle concentration is higher than 1.5 wt%. The clogging issues would arise after several experimentation due to the geometrical design and small nozzle diameter (<1mm). Hence, the improvement of the delivery system is taken into consideration in future research. To ensure the consistent lubrication supply, it was delivered at the flow rate of 10 ml/min at the 45⁰ direction from horizontal plane into the cutting zone by utilizing the machine's built-in lubricant delivery system during machining. In this research, the nozzle angle is set at 45°, which is the recommended angle from our previous research [13].

Carbon onions and carbon black are defined as quasi-spherical nanoparticles consisting of fullerene-like carbon layers enclosed by concentric graphitic shells. They possess the properties different from other carbon nanostructures as graphite due to their highly symmetric structure and excellent in term of tribological properties. In this research, carbon onion nanoparticles were produced by heat-treatment of carbon black (Cabot R250 from Cabot Corporation) in a resistance heat furnace using a graphite crucible under a Helium atmosphere. The carbon onions were obtained by inductive heating at 2000⁰C for 15 minute duration and were used without further treatment (e.g. purification). Figure 4 shows the TEM picture of carbon onion at average size of 5 to 20 nm.

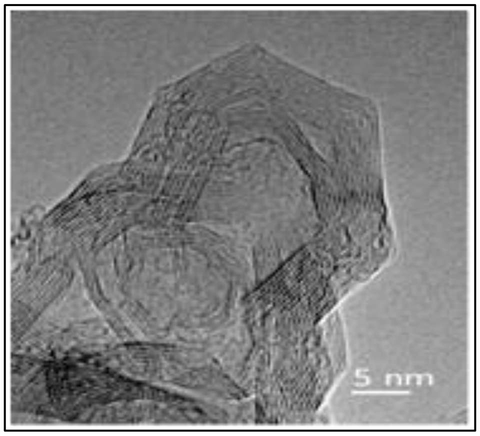


Figure 4. TEM picture of carbon onion [13]

On the other hand, the cutting force is measured using the Kistler three-axis dynamometer (type 9067). The measured cutting force signals (X and Y directions) are captured with the Keyence NR-600 with Wave Logger Pro Software and the sampling frequency is set so that 20 points per one spindle revolution can be obtained. This captured force signal is filtered with low-pass filters (10 Hz cutoff frequency). In this case, the dynamometer is measuring Fx and Fy forces which are considered as the resultant of all the fluctuating tangential (Ft) and radial (Fr) forces. In this case, cutting force (Fc) has been calculated based on the measured Fx and Fy which is equal to $F_c = \sqrt{F_x^2 + F_y^2}$.

III. Results and discussions

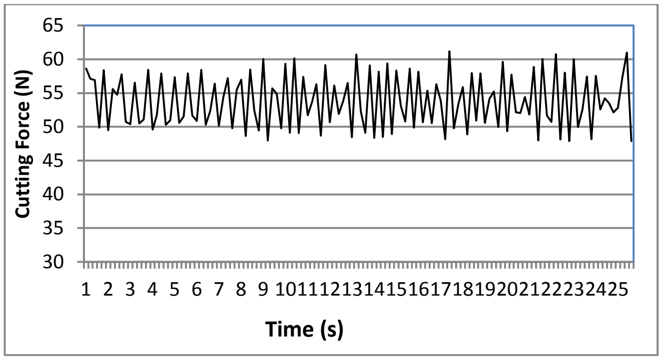
The slot-milling test was carried out for machining duralumin AL-2017-T4 using different cutting tools and lubrication systems. Figures 5 and 6 show examples of measured cutting forces using different cutting tools and lubrication modes. The cutting force values has been averaged in Table 2, while, the cutting force changes at different cutting tools and nanoparticle concentration are shown in Fig.7. As can be seen in Fig.7, the smallest cutting force with 33.9% reduction is obtained at 1.5%wt of onion carbon with DLC coated tool. As a consequence of the cutting force change, the specific energy and the power consumption should be investigated as well. The specific energy and the power consumption at the cutting tool could be obtained as follows [5].

$$E_c = \frac{F_c v_c}{f d_a d_r} \qquad (J/mm^3) \qquad (1)$$

$$P = F_c V_c \qquad (Watt) \qquad (2)$$

Where; E_c is the specific energy (J/mm^3), F_c : the cutting force (N), v_c: the cutting speed (m/min), f: the work feed (mm/min), d_a: the axial depth of cut (mm), d_r: the radial depth of cut (mm), P: power (Watt), F_c: cutting force (N) and V_c is cutting speed (m/s). The averaged specific energy and power consumption for both ordinary and DLC coated cutting tool are shown in Tables 3 and 4 and plotted in Figs. 8 and 9, respectively.

As can be seen in Figs. 8 and 9, the smallest specific energy and power consumption is obtained at the same condition for the smallest cutting force, 1.5%wt of onion carbon with DLC coated tool. This is mainly attributed to the reduction of the friction coefficient of friction at the tool chip interface.



a) Ordinary lubricant

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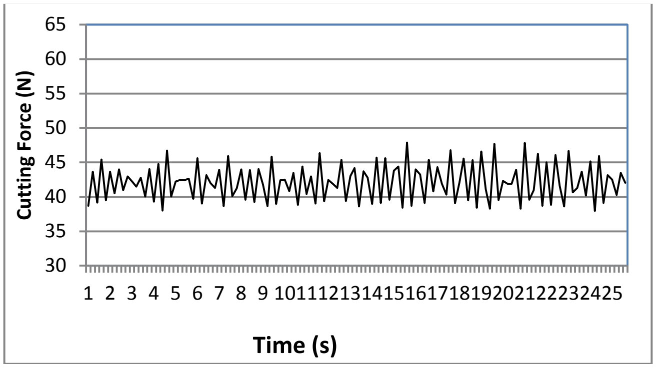
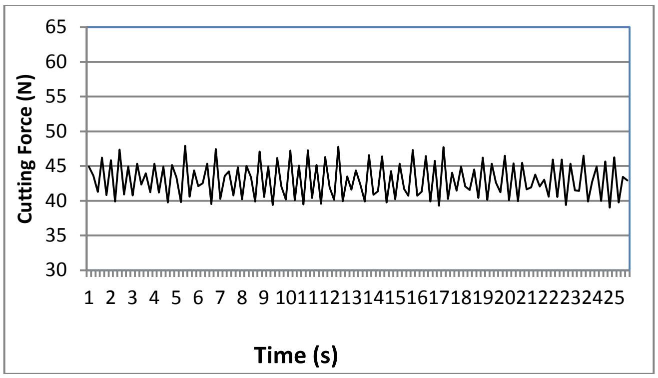
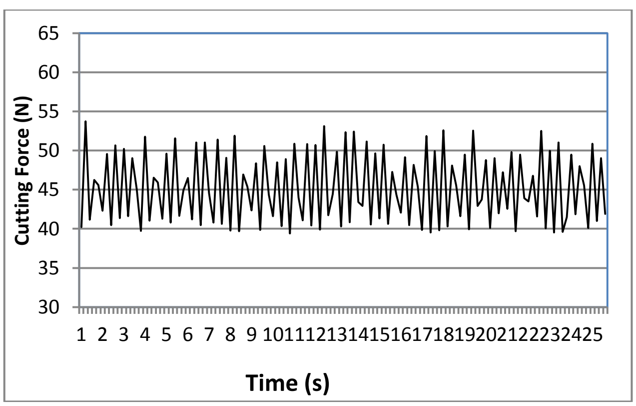


b) 1.5 %wt onion carbon

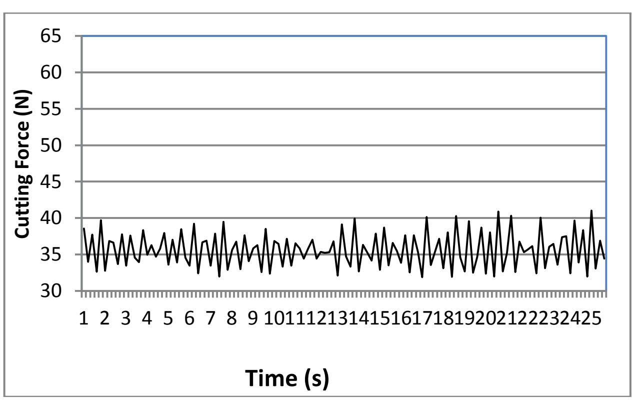


c) 1.5 %wt carbon black

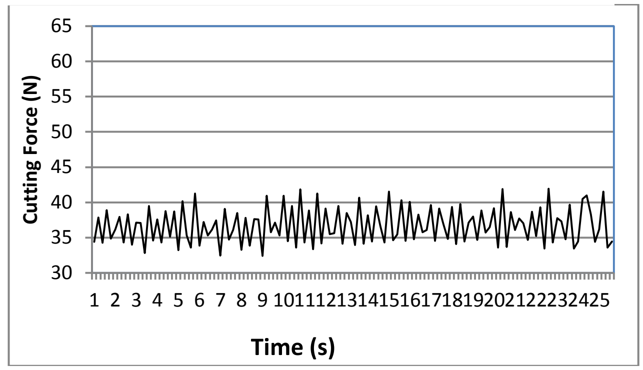
Figure 5. Examples of measured cutting force using ordinary cutting tool with different types of lubrication modes



a) Ordinary lubricant



b) 1.5 %wt carbon onion

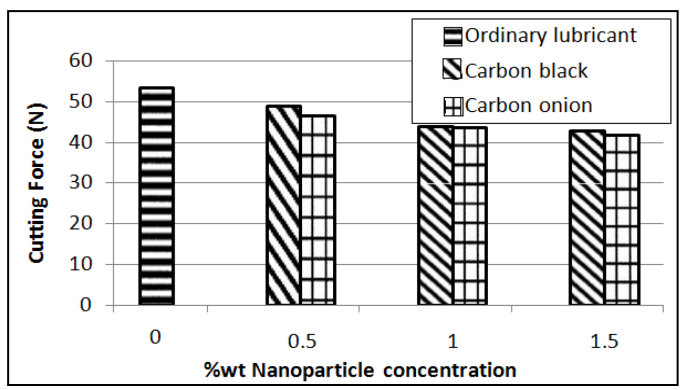


c) 1.5 %wt carbon black

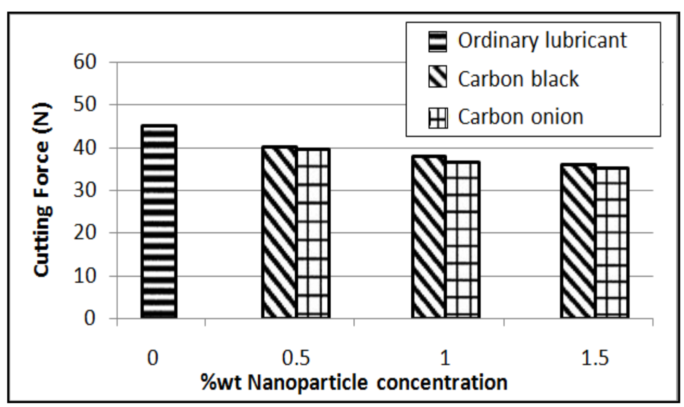
Figure 6. Examples of average measured cutting force using DLC coated cutting tool with different type of lubrication modes

TABLE 2. THE AVERAGE OF MEASURED CUTTING FORCE

Type of tool	% weight concentration	Measured cutting force (N)		
		Ordinary lubricant	Carbon black	Carbon onion
Ordinary cutting tool	0	53.51	-	-
	0.5	-	48.98	46.58
	1.0		43.97	43.64
	1.5		42.81	41.74
DLC coated cutting tool	0.0	45.25	-	-
	0.5	-	40.22	39.78
	1.0		38.14	36.59
	1.5		36.08	35.37



a) Ordinary cutting tool



b) DLC Coated cutting tool

Figure 7. Averaged measured cutting forces using ordinary cutting tool and DLC coated cutting tool

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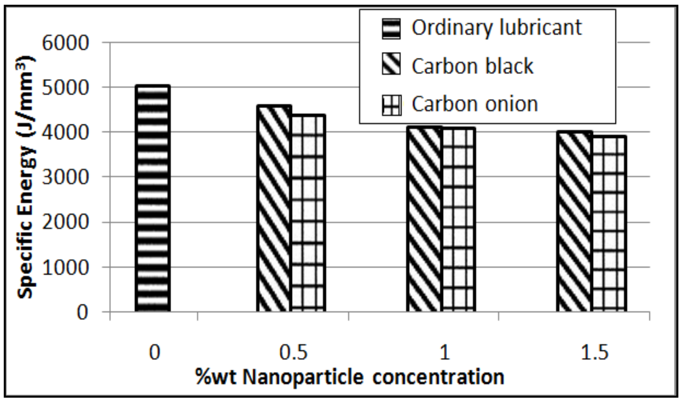
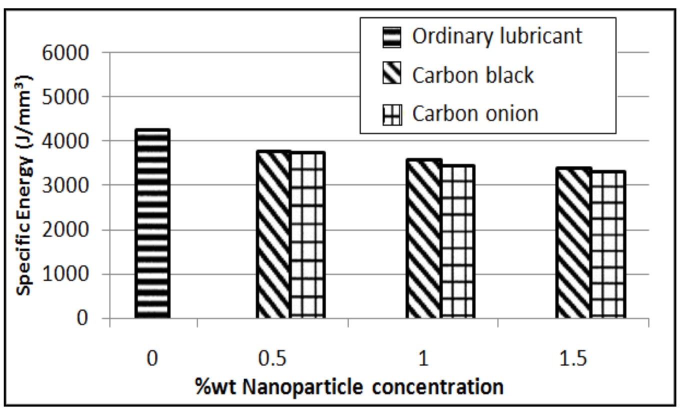
TABLE 3. THE SPECIFIC ENERGY

Type of tool	% weight concentration	Specific energy (J/mm^3) Ordinary lubricant	Carbon black	Carbon onion
Ordinary cutting tool	0.0	5045.13		
	0.5		4618.03	4391.74
	1.0		4145.66	4114.55
	1.5		4036.29	3935.41
DLC coated cutting tool	0.0	4266.35		
	0.5		3792.10	3750.61
	1.0		3595.99	3449.85
	1.5		3401.76	3334.82



a) Ordinary cutting tool

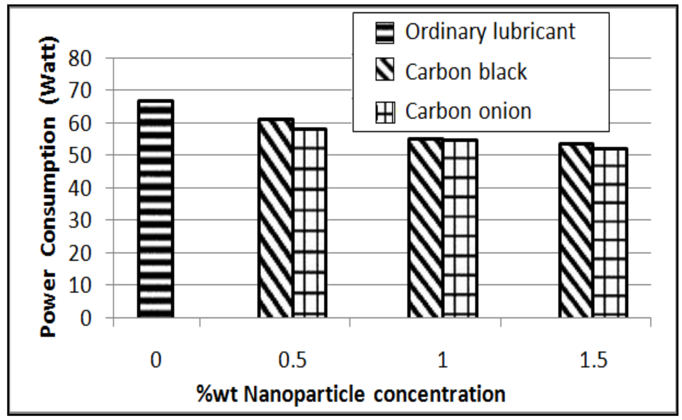


b) DLC Coated cutting tool

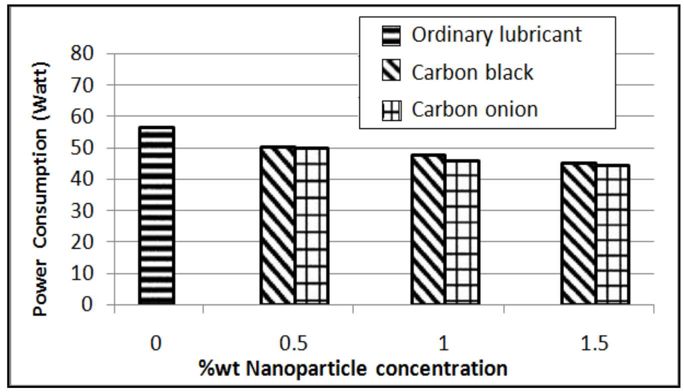
Figure 8. The change of specific energy using ordinary cutting tool and DLC coated cutting tool

TABLE 4. THE POWER CONSUMPTION

Type of tool	% weight concentration	Power consumption (Watt) Ordinary lubricant	Carbon black	Carbon onion
Ordinary cutting tool	0.0	67.25		
	0.5		61.56	58.54
	1.0		55.26	54.85
	1.5		53.80	52.46
DLC coated cutting tool	0.0	56.87		
	0.5		50.55	50.00
	1.0		47.93	45.99
	1.5		45.35	44.45



a) Ordinary cutting tool



b) DLC Coated cutting tool

Figure 9. The power consumption using ordinary cutting tool and DLC coated cutting tool

As can be seen in the results in Figs. 7, 8 and 9, using DLC coated tool would reduce the cutting force, specific energy and power consumption on ordinary lubricant. However, carbon onion nanolubricant is producing much less cutting force, specific energy and power consumption compared with ordinary lubricant and carbon black nanolubricant. The usage of DLC coated cutting tool in conjunction with carbon onion nanolubrication will produce much less coefficient of friction leading to more power saving. This is mainly due to the tribological properties of DLC coating on the tool surface. The DLC coatings are often used to prevent wear due to its excellent tribological properties. DLC is very resistant to abrasive and adhesive wear making it suitable for use in applications that experience extreme contact pressure, both in rolling and sliding contact. At the same time, the carbon onion is having superior lubrication properties, highly stable, high mechanical strength and wear resistance [11] which consequently lead to a better machining process.

During cutting, the chip is flowing over a tool, leading to localized region of intense shear occurring due to the friction at the rake face, known as secondary shear as shown in Fig. 10 [14]. If the coefficient of friction in the interface is greater than 0.5, sticky friction will result and the chip flow will only occur along the workpice. As the consequence, the deformed chip thickness will increase leading to decrease the cutting ratio and shear angle and increase the shear length. Furthermore, the force (F_c), specific energy and power consumption needed to remove the chip will increase significantly, as shown in Fig. 11 [15].

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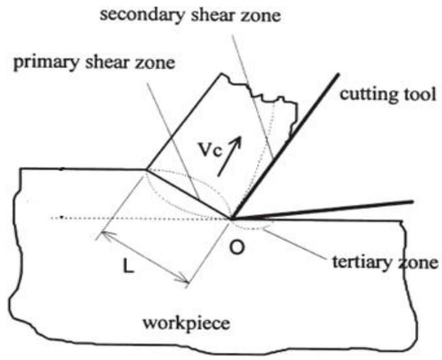

Figure 10. Shear zones in metal cutting [14]

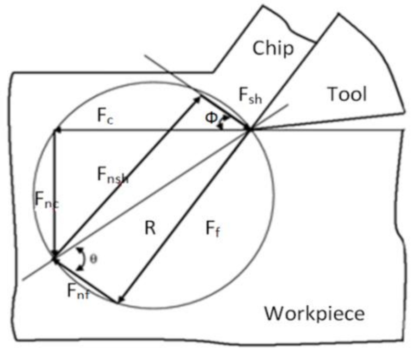

Figure 11. Cutting mechanisms [15]

Applying the lubrication system to the tool chip interface will reduce the coefficient of friction and hence leads to lower cutting force with less power consumption. However, introducing nanolubrication will give lesser cutting force, specific energy and power consumption. This is mainly attributed to the nanoparticles in the mineral oil, which act as a combination of rolling and sliding bearings at the tool chip interface. This, in turn, reduces the coefficient of friction significantly. Therefore, the cutting force is obtained to be lower in the nanolubrication system compared to the pure oil without nanoparticle lubricant. The reduction of cutting force leads to a reduction of specific energy and power required during the machining process. Besides, the carbon onion nanoparticle is acting as billions of nano-scale structure rolling elements in the tool chip interface makes the coefficient of friction is significantly reduced as shown in Fig. 12 [16].

Figure 12. Rolling elements in the tool-chip interface [16]

IV. Conclusion

In this study, the possibility of reducing the machining power consumption in CNC end milling duralumin AL-2017-T4 using DLC coated tool and carbon onion nanolubrication is investigated. Based on the results obtained, the usage of carbon onion nanolubricant in conjunction with DLC coated cutting tool is reducing the cutting force, specific energy and power consumption by reducing the coefficient of friction between the tool-chip interface. This is mainly attributed to the excellent tribological properties of the DLC coated tools. In addition the carbon onion nanoparticle is acting as billions of nano-scale structure rolling elements in the tool chip interface makes the coefficient of friction is significantly reduced.

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