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PRELIMINARY INVESTIGATION ON GRAPHENE AS SOLID LUBRICANT IN DRY TURNING

Simranpreet Singh Gill

Department of Mechanical Engineering, Beant College of Engineering and Technology, Gurdaspur – 143521, Punjab (INDIA)

ABSTRACT

The concept of dry machining has been realized in an effort to circumvent the environmental problems induced by cutting fluids. Graphene has been identified as a novel environmental friendly solid lubricant. In spite of intense research efforts on graphene for a copious of existing and future applications, its tribological potential as a solid lubricant in machining remains unexplored. In present study, rake faces near main cutting edge of carbide turning insert were polished and solution processed graphene as potential solid lubricant was applied. It was found that cutting forces and coefficient of friction at tool-chip interface reduced significantly while turning with inserts applied with graphene. However, the advantage obtained at lower cutting speeds was not sustained at relatively higher cutting speeds. The change in flank wear was marginal irrespective of cutting speed. The tribological role of graphene at tool-chip interface was identified and discussed.

Keywords – Graphene; dry turning; solid lubricant; tool wear; cutting force; friction coefficient

I. INTRODUCTION

The cutting fluids employed in machining processes have many advantages. Cutting fluids have been used for lubrication and cooling purposes in machining [1]. It is estimated that annual global consumption of metal cutting fluids comes out to be around 640 million gallons [2]. Cutting fluids help to dissipate the heat generated at cutting zone, enhance the tribological properties of tool-chip/work interface, prevent the development of built-up edge, assist the smooth transportation of chips, and attain superior tool life, dimensional tolerances and surface finish [3]. However, the cutting fluids have many harmful effects associated with them which are worth not to be ignored. Majority of these fluids are constituted of non– sustainable crude oil extracts which are environmental unfriendly harmful chemicals [4]. Many researchers have accentuated upon the problem of water and soil pollution caused by the use of mineral based cutting fluids [5, 6]. Reported data indicate that 80% of occupational skin diseases are caused by cutting fluids [7]. National Institute of Occupational Safety and Health (NIOSH) reported that over 1 million workers are under the influence of toxicology effects caused by cutting fluids [8]. In addition to occupational health hazards, the cost of storing and disposal of cutting fluid is 2 times higher than that of actual machining cost [8]. Also, the stern environmental policies all around the world have inspired the researchers to investigate the novel technologies to minimizing the use of cutting fluids or to completely shun them [3]. Therefore, it is important from the cost and health point of view to eradicate or substantially reduce the use of cutting fluids. In pursue of this ambition, the concept of dry machining has been comprehended recently.

Graphene is one of the recent revolutionary solid lubrication materials which is attracting enormous attention in the scientific community as an environmental friendly replacement of harmful synthetic lubricants. Literature survey shows that graphene has never been investigated as solid lubricant in any machining operation nevertheless its tribological advantages in laboratory conditions are well researched and documented [9-12]. In the light of the above discussion, the present study was planned to explore the tribological potential of graphene in dry turning. Carbide turning inserts were chosen as cutting tool. The rake face of the inserts were polished near the main cutting edge and graphene was applied to make the inserts self lubricating. Dry machining tests on hardened steel were carried out with these inserts. The machining performance was assessed in terms of tool wear, cutting forces and coefficient of friction at the tool–chip interface.

II. MATERIALS AND METHODS

The tool material selected for the present investigation was tungsten carbide insert which is the most extensively used cutting tool material in today's metal cutting industry. The commercially available square shaped tungsten carbide inserts of specification SPUN 12–03–08 (P25, Sandvik Coromant, ISO specification) were procured. The tool holder used for machining was ISO CSBPR–2525–M12 (Sandvik Coromant). The surface of insert on which the chips flows/rubs during cutting is the area on rake face near to main cutting edge (Fig. 1). Hence, in present study the area on rake face near to main cutting edge was considered for investigation.

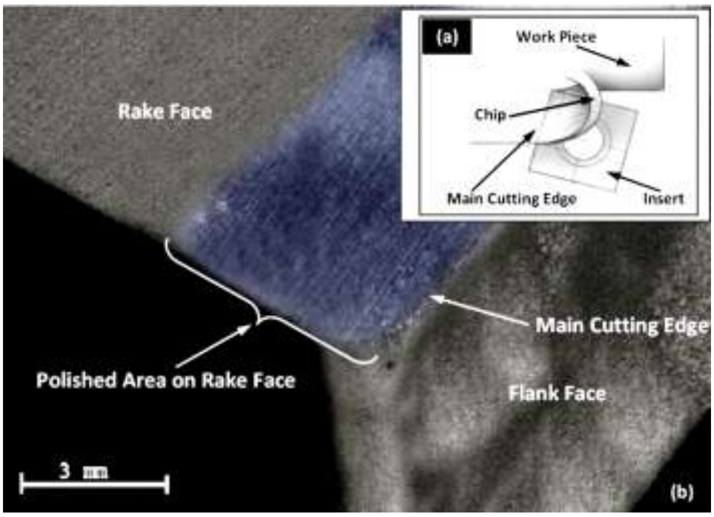

Fig 1. (a) Illustration of turning shows chip flowing on rake face of insert; (b) Rake face of insert showing polished surface.

It is imperative to note that graphene has never been used as solid lubricant in any machining operation to the best of author's knowledge. Hence, it was necessary to device the way to apply the graphene on the rake face of insert. Since, it was the first time graphene being used as solid lubricant in machining; it was decided to apply it on rake face as demonstrated by [9-11] in their study. The area near the main cutting edge was polished to obtain the roughness measure (RMS) of R_q = 14 to 16 nm (Fig. 1). Further the inserts were rinsed with hexane, and then ultrasonically cleaned in fresh alcohol to remove any contaminants specifically from rake face of insert. Solution processed graphene suspended in ethanol was procured commercially. This solution was spread on the polished rake face of the inserts and evaporated in protective environment to prevent graphene oxidation. The inserts so prepared were used for turning C 65 hardened steel on CNC turning machine (MSC-ZL25MC, Mori Seiki, Japan). To keep the cutting dry, no cutting fluid was used. Studies so far have shown that the cutting speed is the most dominate factor influencing machining output, followed by feed and depth of cut, in that order [13]. Hence, only the cutting speed was varied in four steps as 50m/min, 70m/min, 90m/min and 110m/min. All the cutting tests were performed at feed rate, f, of 0.1 mm/rev and depth of cut, a_p, of 0.2 mm and cutting time 5 min. For the purpose of comparison, conventional dry turning was also performed by similar inserts under similar cutting conditions but without applying graphene. Cutting forces were obtained with piezoelectric quartz dynamometer with provision of real time computerized data logging. Each experiment was repeated thrice to eliminate possibility of any experimental error. Raman's spectroscopy (laser of λ= 514 nm) was done on rake face of inserts to characterize the graphene present near main cutting edge after machining. Since the width of flank wear was not regular along the cutting edge, the maximum flank wear, VB_{max}, was measured using an inverted metallurgical microscope (DM ILM, Leica, Germany). The inserts were inspected under the scanning electron microscope (F-200 FEI, Quanta, Holland) to excavate the possible tribological mechanism on rake face of inserts.

III. RESULTS AND DISCUSSION

A. Flank wear

The variation of flank wear of the cutting inserts with and without graphene at different cutting speed is shown in Fig. 2. It is revealed that the inserts used with graphene as lubricant showed relatively small flank wear as compared to inserts used without graphene at all tested cutting speeds. It is important to mention that although there was smaller flank wear on inserts used with graphene, the advantage gained is not significant specifically at higher cutting speeds. It can be explained on the basis that the graphene was applied directly on rake face of inserts and not on flank face. Also, the graphene present on rake face cannot reach at the flank face as the chips flow away from the main cutting edge on the rake face during cutting. Hence, the improvement in flank wear reported could be because of reduced cutting forces which are discussed in the subsection B. Another prominent observation that can be obtained from Fig. 2 is that the improvement in flank wear was relatively more up to cutting speed of 70 m/min whereas after wards it decreased with the increase in cutting speed. This observation indicated the potential positive tribological role of graphene on rake face at lower cutting speeds. The reduced machining output in terms of flank wear at higher cutting speeds also indicates the marginal role of graphene as effective lubricant.

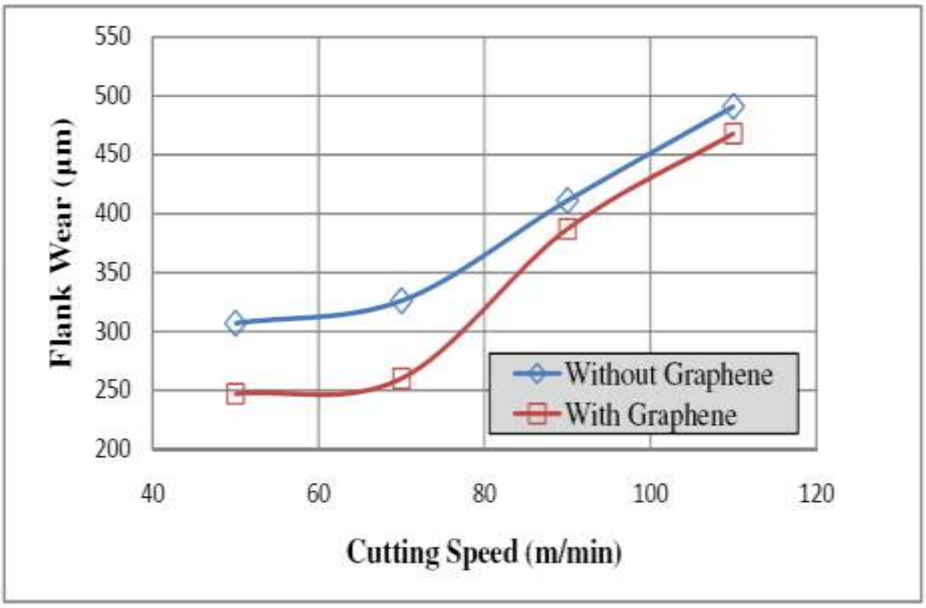

Fig 2. Flank wear of turning inserts with and without graphene as solid lubricant in dry cutting at different cutting speed (depth of cut 0.2 mm, feed rates 0.1mm/r, cutting time 5 min).

B. Cutting Forces

Cutting forces may provide a better understanding of the machining process as they relate directly to the cutting conditions and tool condition during machining. Fig. 3 illustrates the main cutting force, Fz, radial thrust force Fy, and axial thrust force Fx as a function of cutting speeds reported by cutting inserts used with and without graphene. It is found that the cutting force Fx, Fy, and Fz components were significantly reduced when cutting by inserts used with graphene under the same cutting conditions up to cutting speed of 70 m/min. However when cutting speed was raised to 90 m /min and beyond, all the cutting force components increased sharply as evident from Fig. 3. This trend is in contrary with standard perception that cutting forces generally decreases with the increase in cutting speed as high speeds result in high cutting temperature thus reduced forces due to thermal softening of the workpiece material. Even in present study, the same trend was reported for inserts used without graphene as clear from Fig. 3. However in case of inserts used with graphene, the significant reduction in cutting forces at lower cutting speeds might be due to lubricating effect of graphene present on rake face of insert. But at higher cutting speeds the graphene might have removed from the tool-chip interface resulting in higher friction and therefore sharp increases in cutting forces. At the highest tested cutting speed of 110 m/min all the three cutting force components increased almost equal to the respective cutting force component reported during machining with inserts without graphene. This observation is in line with flank wear pattern recorded at different cutting speeds as discussed in section A above. It is evident that when cutting speed was increased beyond 70 m/min for inserts with graphene, the flank wear also increased sharply and consequently cutting force components also followed the same pattern. It can be concluded that graphene definitely has positive impact on machining output but to make it a sustainable solid lubricant in dry turning, we will have to find out the ways to keep it on the tool-chip interface for longer times at higher speeds and forces.

C. Coefficient of Friction

The average coefficient of friction at the tool–chip interface was calculated by using the following formula [14]:

$$\mu = \tan(\beta) = \tan(\gamma_0 + \arctan(Fy/Fz))$$

where β is the friction angle, γ_0 is the rake angle, Fy radial thrust force, Fz is the main cutting force. Fig. 4 shows the average coefficient of friction at the tool–chip interface for inserts used with and without graphene as a function of cutting speed.

It is clear from the graph that the coefficient of friction at the tool–chip interface for inserts used with graphene was significantly low as compared to inserts used without graphene under the same cutting conditions at lower cutting speeds. However, the difference was not significant at higher cuttings speeds tested. It is evident from Fig. 4 that cutting speed has obvious effect on the coefficient of friction at the tool–chip interface for inserts used without graphene. The reduction in coefficient of friction at higher cutting speeds for inserts used without graphene might be due to dominant thermal softening effect over strain hardening. It is interesting to note that coefficient of friction for inserts used with graphene increased drastically when the cutting speed was raised from 70 m/min to 90 m/min. This observation is in good agreement with the trend of cutting forces observed for inserts used with graphene as discussed in subsection B above.

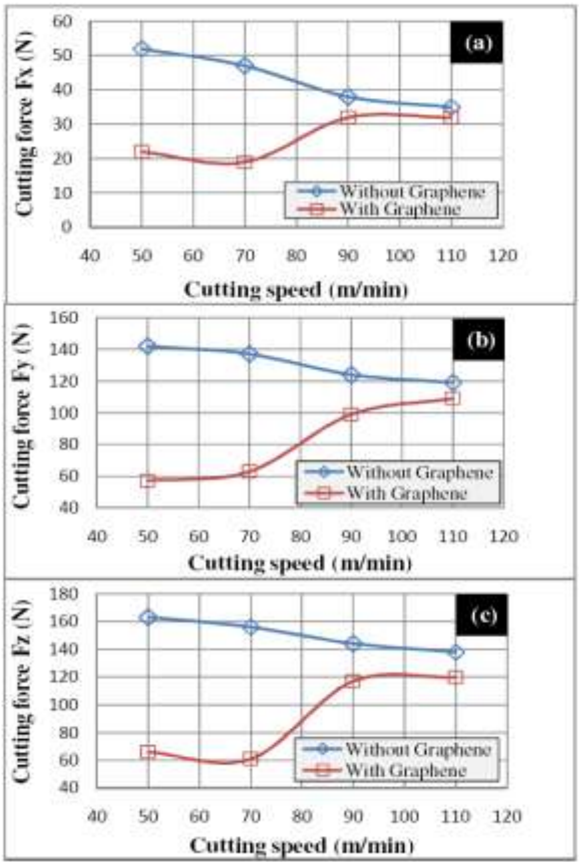

Fig 3. Effect of cutting speed on the cutting forces for turning inserts with and without graphene as solid lubricant at different cutting speeds, (a) axial thrust force Fx; (b) radial thrust force Fy; and (c) main force Fz (depth of cut 0.2 mm, feed rates 0.1mm/r, cutting time 5 min).

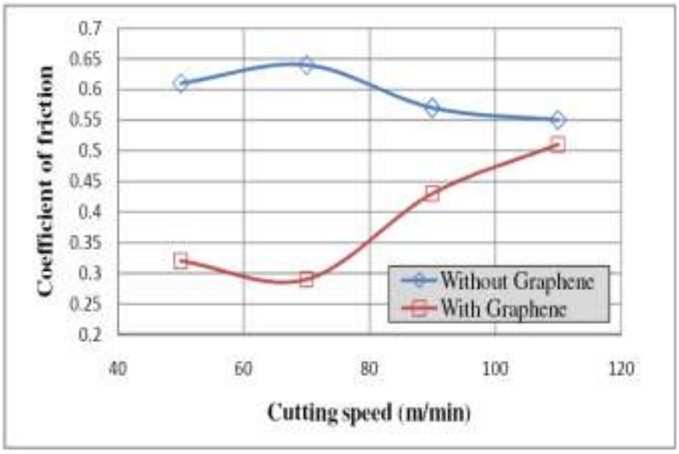

Fig 4. Coefficient of friction between the tool–chip interface for turning inserts with and without graphene as solid lubricant at different cutting speeds (depth of cut 0.2 mm, feed rates 0.1mm/r, cutting time 5 min).

IV. CONCLUSION

The major outcomes of the present study are listed as follows:

1. The application of graphene on rake face of insert does not contribute in reducing the flank wear of tool. A little improvement reported in flank wear by using inserts with graphene on rake face may be due to reduced cutting forces.
2. The application of graphene on tool-chip interface was found out to be effective in reducing tool wear, coefficient of friction and cutting forces but at lower cutting speeds. Although there was reduction in tool wear, coefficient of friction and cutting forces at higher cutting speeds also, but the difference was not significant.
3. It was found that the effectiveness of graphene on tool-chip interface drastically decreased to almost negligible when main cutting force increased beyond ~60N.
4. Great potential of graphene as environmental friendly solid lubricant in machining was identified. Hence sincere research and development efforts are required to be made to make its use sustainable in machining as solid lubricant.

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