International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:12, No:2, 2018

Effect on the Performance of the Nano-Particulate Graphite Lubricant in the Turning of AISI 1040 Steel under Variable Machining Conditions

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Abstract—Technological advancements in the development of cutting tools and coolant/lubricant chemistry have enhanced the machining capabilities of hard materials under higher machining conditions. Generation of high temperatures at the cutting zone during machining is one of the most important and pertinent problems which adversely affect the tool life and surface finish of the machined components. Generally, cutting fluids and solid lubricants are used to overcome the problem of heat generation, which is not effectively addressing the problems. With technological advancements in the field of tribology, nano-level particulate solid lubricants are being used nowadays in machining operations, especially in the areas of turning and grinding. The present investigation analyses the effect of using nano-particulate graphite powder as lubricant in the turning of AISI 1040 steel under variable machining conditions and to study its effect on cutting forces, tool temperature and surface roughness of the machined component. Experiments revealed that the increase in cutting forces and tool temperature resulting in the decrease of surface quality with the decrease in the size of nano-particulate graphite powder as lubricant.

Keywords—Solid lubricant, graphite, minimum quantity lubrication, nanoparticles.

I. Introduction

METAL cutting results in the generation of a lot of heat due to the plastic deformation of work material, friction at the tool-chip interface and friction between the clearance face of the tool and work piece, which adversely affects the quality of the component produced [1], and hence, the quality of the work piece deteriorating [2].

The use of cutting fluids for heat dissipation [3] is a common practice but is not advisable in terms of cost, and environmental concerns, etc. Its use cannot be entirely eliminated but can be substituted by finding out alternate means and by using bio-degradable fluids [4]. Some other alternatives are by using cryogenic coolants [5], [6] or machining using the concept of Minimum Quantity Lubrication (MQL) by the application of powders mixed in water and other carrying mediums [7], [8] or by using environmentally friendly lubricants made from vegetable oils extracted from Rapeseed, Corn or Soya bean oil, esters etc., which has been found out to decrease the average temperature at the chip-tool interface [19].

With the advancement in tribology, the use of solid lubricants in machining has been observed during the past few years. It is found that solid lubricants could effectively control the temperature at the machining zone. Experiments also revealed the reduction in surface roughness value due to the use of solid lubricants [21]. Some of the common solid lubricants are graphite, molybdenum disulphide, tungsten disulphide and calcium fluoride which belong to a special class of materials known as lamellar solids [9], [20]. Several studies and researches related to the lubrication properties of Graphite [10], [11] have been carried out over the past few decades and investigated its use as a lubricating medium in various machining operations [22]. Shaji et al. and Venu Gopal et al. have used graphite as lubricant in grinding operations to reduce the heat generated at the grinding zone and found that graphite as lubricant proved to be better than conventional flood coolant in terms of decreased cutting forces, temperature and surface roughness values. It is also found [10] that with the use of graphite as lubricant, the tangential forces decrease and so the reduction in specific energy. Graphite powder, mixed with SAE 40 oil was also used for experimentation purpose as lubricant while machining hardened steel [20], which revealed better machining performance when compared to conventional cutting fluids and dry machining for the selected tool-work combination and cutting condition. One of the limitations of using dry graphite powder in the machining process is that the lubricant powder has to be sprayed continuously into the tool-work piece interface, which does not represent a viable lubrication alternative for industries. To nullify this problem, researchers [12]-[14], [25] are using vegetable oils and petroleum based oils like SAE 40 as a carrying medium to spray the lubricating powders into the tool – work piece interface, which is found to be a viable solution.

Rao et al. [9] have used solid lubricants and analysed the effect and behaviour of various machining parameters with respect to the particle size of the solid lubricant. Graphite particles with 50 micron, 100 micron, 150 micron and 200 micron sizes were used in the form of powder spray during the machining of hardened steel. It was observed from the results

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that the lubricating action of graphite with 50 micron particle size proved to be more effective which is attributed to its adhesion tendency. A number of research articles have reported that the addition of nanoparticles to the lubricant proves to be more effective in reducing the wear and friction [9], [11], [23]. In fact, the friction-reduction and anti-wear behaviour are dependent on the characteristics of nanoparticles, such as, their size, shape, and concentration. Chinas-Castillo and Spikes [24] investigated the effect of "particle-size process" using gold particles of 5 nm and 20 nm, which showed that the gold particles of 20 nm were more effective in reducing friction and wear, than that of the gold particles of 5 nm size. This reason being that the tiny 5 nm sized particles allow more asperities interaction than the 20 nm sized particles do. As such, Kabir et al. [15] have discovered an inverse relationship between the friction coefficient and the solid lubricant particle size. Similarly, Boric acid powder was used to conduct Pin on Disc (POD) experiment with particle sizes ranging from 350 microns to 100 nm. Ramana et al. [13] have compared the effect of particle size of boric acid powder used in the machining of hardened steel and concluded that nano sized particles as lubricant showed inverse phenomenon as compared to that when micron level particles are used. As the properties of materials change with respect to spatial dimensions from micron to nano size, the tribological performance of the solid lubricant used in metal cutting, has become questionable.

The present work is aimed to study the effect of solid lubricant assisted turning operations, using nano-particulate graphite powder as a lubricant and SAE40 oil as a carrying medium. Experiments were conducted on AISI 1040 steel using uncoated carbide tools; to compare the effectiveness of solid lubricant assisted machining under different operating conditions. For this, cutting forces and tool temperatures were measured online, while roughness was measured after the machining operations.

II. Experimental Work

The effect of nano-particulate graphite powder as lubricant during turning tests on the cutting forces, tool temperature and surface roughness is studied. Turning tests were conducted on AISI 1040 steel by using uncoated carbide inserts and by using SAE 40 oil as the carrying medium. Initially, experimentations were carried out to determine the optimum weight percentage of the nano-particulate graphite powder to be mixed in the carrying medium. The cutting forces were measured using a calibrated strain gauge dynamometer. The representative temperature was measured using an embedded thermocouple, which is placed at the bottom of the tool insert in the tool holder [16] and duly calibrated in a water bath with the help of a thermometer and a maximum of 2°C difference is noted over a range of 20°C to 98°C. A calibrated surface roughness tester (Talysurf) was used to measure the average surface roughness (R_a). A set of preliminary tests were carried out to determine the best lubricant flow using the principle of MQL so as to achieve a flow rate of 10 ml/min. of the lubricant onto the targeted area. The experimental set up developed to achieve the dispensing of the lubricant consists of a reservoir attached with a stirrer. Initially, SAE 40 oil and graphite powder were thoroughly mixed in a Magnetic Stirrer and poured into the reservoir. The stirrer was switched on when machining was carried out, so as to overcome the problem of agglomeration of the solid particles in the carrying medium. As per the literature available [17], [23], the L/D ratio of the work piece is maintained between 7 and 8 in order to avoid the phenomenon of buckling during machining.

III. Experimental Results

Initially, experiments were conducted to determine the optimal weight percentage of nano-particulate graphite powder to be mixed in the carrying medium SAE 40 oil. The different machining conditions considered were cutting velocity (96 m/min.), depth of cut (1 mm), and feed rate (0.1 mm/rev). The sample weight percentages considered were 0.25%, 0.5%, 2%, 4%, 6% and 8% in 60 ml of SAE40 oil. Experimental observations revealed that with a 0.5 weight percentage of the graphite powder, the cutting forces, tool temperature and surface roughness showed better results than that obtained with increased weight percentages.

Fig. 1 represents the feed force which clearly shows that the feed force increases with the increase in depth of cut. As observed in Fig. 1 (a), when the depth of cut is increased from 0.25 mm to 1.0 mm with the feed rate and cutting velocity kept at 0.05 mm/rev and 61.5 m/min, respectively, the feed force increases from 61.4 N to 73.3 N measured for a particle size of 70–90 nm, which shows an increase from 64 N to 76.3 N measured for a particle size of 5-10 nm. The average feed forces measured for all the particle sizes in terms of increase in particle sizes considered is 67.55 N, 66.8 N, 65.60 N and 64.83 N, respectively. It can be inferred that as the feed rate increases from 0.05 mm/rev to 0.125 mm/rev, and simultaneously, the cutting velocity increases from 61.5 m/min to 234 m/min., the feed force increased by 1.88 times for a particle size of 70-90 nm and by 1.95 times when 5-10 nm graphite particle size is used.

Below are the results with respect to the increase in Feed Force.

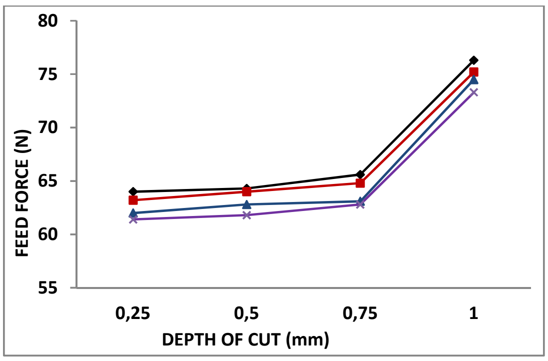

Fig. 1 (a) Feed Force at F: 0.05 mm/rev

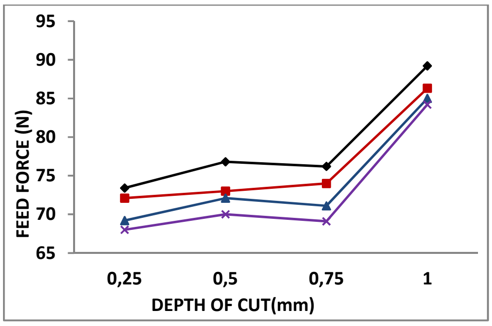

Fig. 1 (b): Feed Force at F: 0.08 mm/rev

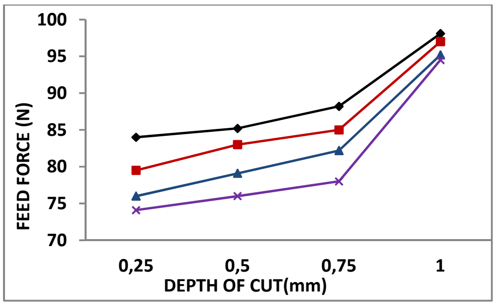

Fig. 1 (c) Feed Force at F: 0.1 mm/rev

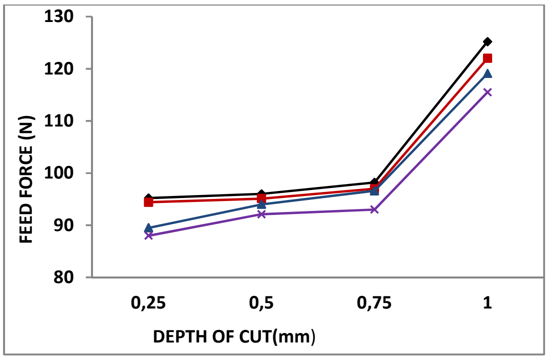

Fig. 1 (d) Feed Force at F: 0.125 mm/rev

Similar trends are visible when the main cutting forces are measured (Figs. 2 (a) and (b)). With the feed rate at 0.05 mm/rev and cutting velocity at 61.5 m/min, and when the depth of cut is increased from 0.25 mm to 1.00 mm, it can be observed (Fig. 2 (a)) that the main cutting force increases. It can be inferred that as the feed rate is increased from 0.05 mm/rev to 0.125 mm/rev, and simultaneously the depth of cut is increased from 0.25 mm to 1.0 mm, the main cutting force increases by 2 times when 70-90 nm graphite particle size is used and by 0.22 times when 5-10 nm graphite particle size is used as lubricant.

Below are the results with respect to the increase in Main Cutting Force. The change in the thrust force is represented in Fig. 3 (a) and (b) with respect to the increase in depth of cut. When the feed rate is increased from 0.05 mm/rev to 0.125 mm/rev, and simultaneously the cutting velocity from 61.5 m/min to 234 m/min., the feed force increases. It shows an increase by 0.18 times when the average thrust force is considered, when the particle size is decreased from 70-90 nm to 5-10 nm.

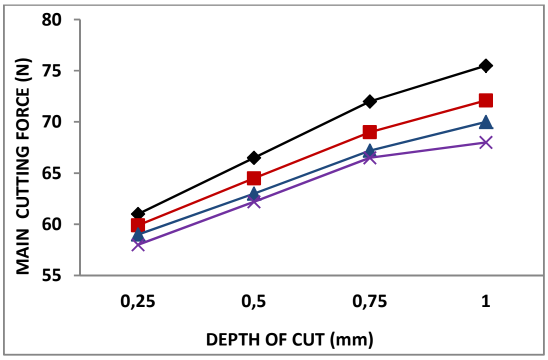

Fig. 2 (a) Cutting Force at F: 0.05 mm/rev

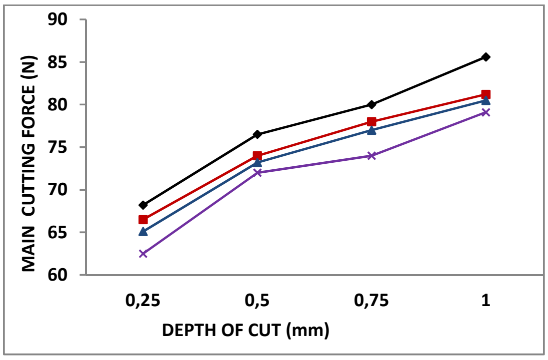

Fig. 2 (b) Cutting Force at F: 0.08 mm/rev

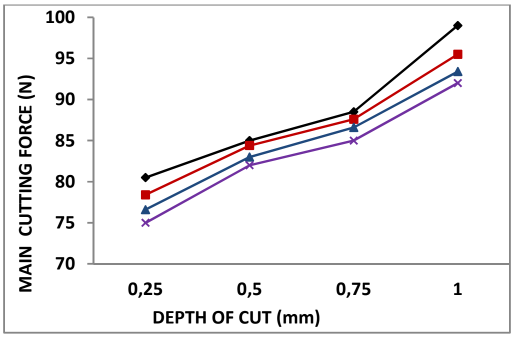

Fig. 2 (c) Cutting Force at F: 0.1 mm/rev

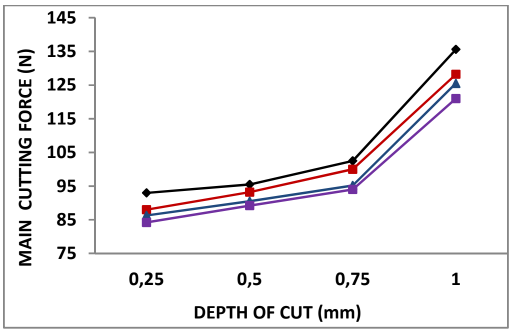

Fig. 2 (d) Cutting Force at F: 0.125 mm/rev

Below are the results with respect to the increase in Thrust Force.

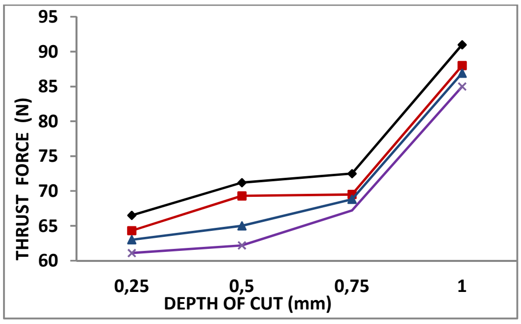

Fig. 3 (a) Thrust Force at F: 0.05 mm/rev

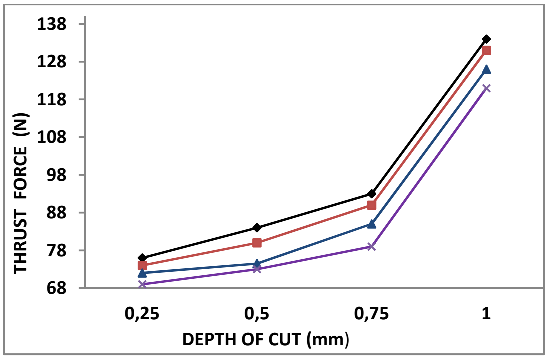

Fig. 3 (b) Thrust Force at F: 0.08 mm/rev

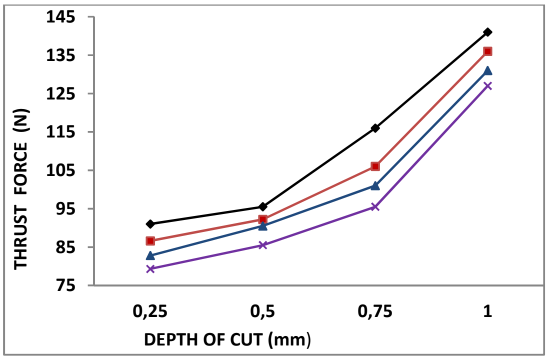

Fig. 3 (c) Thrust Force at F: 0.1 mm/rev

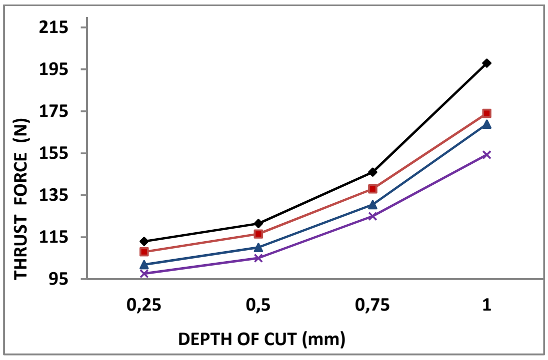

Fig. 3 (d) Thrust Force at F: 0.125 mm/rev

The increase in the forces, when the particle size is decreased at the nano level attributes to the conceptual model developed by Ramana et al. [14], which explains about the agglomeration of particles at the chip – tool interface leading to the sticking and interlocking of the solid lubricant particles. This may be due to more of the smaller graphite particles present in the wear track than the larger particles. Since graphite powder has higher dry friction coefficient than SAE 40 oil, it can be viewed that greater percent of graphite powder would be present in the sliding contact area. The sticking and interlocking phenomena increases frictional resistance and hence leads to increased frictional forces.

The effect of variation of particle size of the solid lubricant on the tool temperature is presented in Figs. 4 (a) and (b). During machining, maximum amount of heat generated is at the tool-chip interface due to the flow of chip on the rake face of the tool. The lubricating medium used in the experimentation is expected to decrease the temperature by reducing the rubbing action at the tool-chip interface. It can be summarized that when the feed rate is increased from 0.05 mm/rev to 0.125 mm/rev and simultaneously the cutting velocity from 61.5 m/min to 234 m/min, the increase in the temperature is from 36.2 °C to 210.6 °C for a particle size of 70-90 nm and from 44.2 °C to 225.2 °C for a particle size of 5-10 nm. This clearly shows an increase by 0.08 times when the average temperature is considered in terms of the decrease of particle size from 70-90 nm to 5-10 nm. Below are the results with respect to the increase in Tool Temperature.

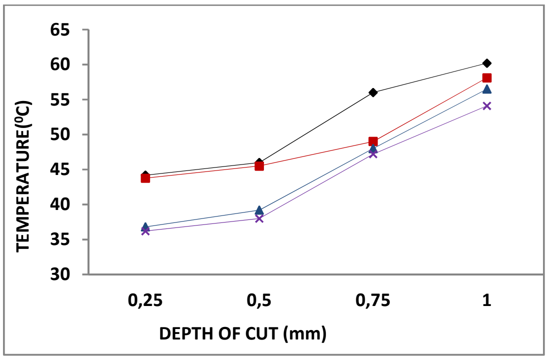

Fig. 4 (a) Temperature at F: 0.05 mm/rev

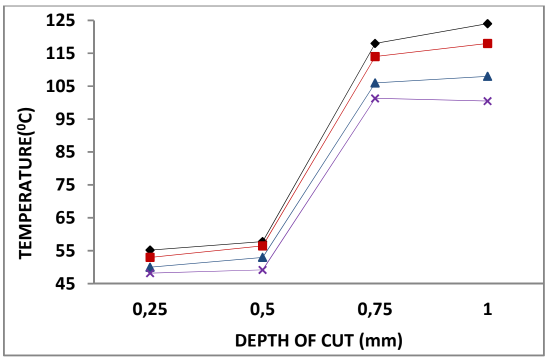

Fig. 4 (b) Temperature at F: 0.08 mm/rev

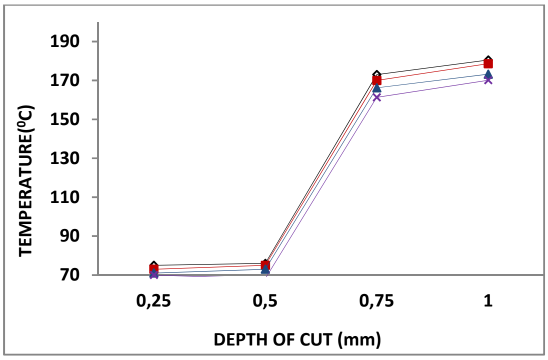

Fig. 4 (c) Temperature at F: 0.1 mm/rev

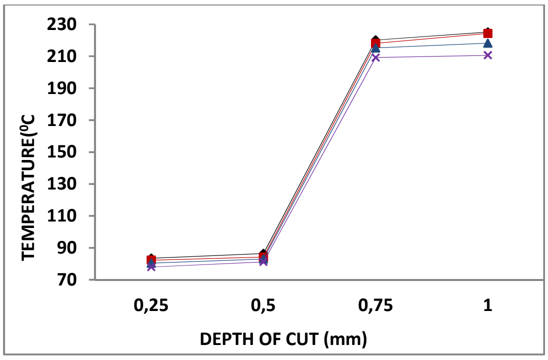

Fig. 4 (d) Temperature at F: 0.125 mm/rev

Syam Sundar et al. [18] found that with the increase in temperature, the thermal conductivity ratio of nano–fluids increases; a reciprocal of the present findings. This can be attributed to the decreased stochastic motion of the nano–particles rather than the thermal conductivity. The increase in temperature can also be attributed to the fact that due to the agglomeration of particles in the chip tool interface more amount of heat will be retained at the chip–tool interface, thus leading to higher tool temperature. Another reason for the increase in the temperature is due to the increase in the force components during machining. Increase in cutting forces leads to the increase in the power consumption, which in turn is converted into heat energy along the primary (shear plane) and secondary (tool-chip interface) shear zones. Fig. 5 shows the values of surface roughness of the machined surface which were measured off-line after the machining process is completed. When the depth of cut is increased from 0.25 mm to 1.0 mm, the surface roughness value increases by 0.12 times for a particle size of 70-90 nm and by 0.17 mm for 5–10 nm particle size. In general, poor surface finish is obtained with the use of reduced particle size of the lubricant. This can be attributed to the increase in the cutting forces and tool temperature at the cutting zone. The increase in the temperature leads to tool wear in terms of its geometry which in turn leads to tool chatter resulting in deteriorated surface quality.

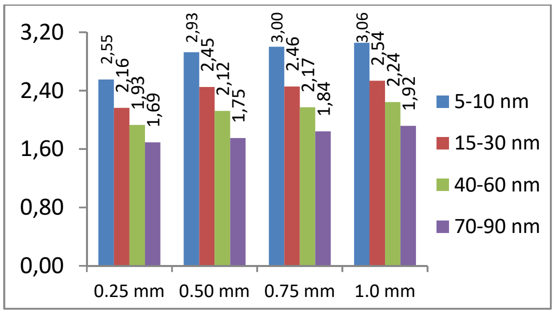

Fig. 5 Results with respect to the change in Surface Roughness

IV. Conclusion

The investigation of this study indicates that the input parameters - feed rate, cutting speed, depth of cut and size of the nano-particulate graphite powder are the primary influencing factors which affect the cutting forces and tool temperature. The level of surface roughness with the change in the input parameters is also indicated. The experimental work provides an impetus to develop analytical models, based on the experimental results to predict the general trends of work piece surface roughness, tool temperature and the cutting forces generated.

The experimental data gives an insight of the effect of nano-level variation in the particle size of graphite powder on the machining of AISI 1040 steel.

- The optimum percentage of the nano-particulate graphite powder is found to be 0.5%.
- The force components viz. longitudinal feed force, main cutting force and thrust force increased with the decrease in the particle size of the lubricant from 70 – 90 nm to 5–10 nm. This can be attributed to the increase of frictional resistance due to agglomeration of more quantity of nano particles at the tool–chip interface as the lubricant size decreases.
- The tool temperature also increased with the decrease in the particle size which emphasizes the decrease in lubrication performance in its nano dimensions. This leads to the conclusion that more heat is generated at the tool–chip interface due to greater rubbing action increases the tool temperature.
- The surface finish of the work material deteriorated. This can be attributed to the increase in cutting forces and tool temperatures and rubbing action at the tool–chip interface.

The experimental work reveals an inverse phenomenon in the nano regime of the solid lubricant particle size used when compared to the behaviour of solid lubricant particle size in the micron level. Hence, it can be concluded that when graphite powder is to be used as a solid lubricant in the machining of hardened steel, the size of the particles should be in the micron level and with the increase in the weight percentage of nano level graphite powder, there is an increase in the cutting forces, tool temperature, and ultimately, the deterioration of the surface roughness.

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