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Performance Evaluation of Cutting Fluids with Carbon Nano-Onions as Lubricant Additives

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Abstract

In machining of high precision automotive parts, the dimensional variation of the cutting process is very critical. The demand for high quality and fully automated production places a lot of emphasis on the cutting process, which has a major contribution to part quality. Cutting fluid has been a key factor to machining performance and a key contributor to increase the effectiveness of machining systems. In this way, cutting fluids play an important role in minimizing production time, cost, and energy in different machining operations. Maintaining and operating the cutting fluid supplies is a huge cost driver and an environmental challenge. Carbon onion nanoparticles have been successfully developed with high tribology performance and mixed in metalworking fluids (MWF) to improve the performance of the fluids. Even though the trend has been to use less MWF, which is dry or MQL whenever possible, MWF are still utilized in large volumes. The literature has reported several cases of very successful use of nanofluids in machining operations for various tough-to-machine materials. To enhance the coolant, nanoparticles such as carbon nano-onions are mixed in the oil and water-based MWF. The paper presents the results from several tests performed during the evaluation of the above nanoparticles in oil and water based cutting fluids in machining processes.

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Keywords: Nanofluid, coolant, cutting fluid, Carbon Nano-Onions

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Introduction

Cutting fluids play an important role in minimizing production time, cost, and energy in different machining operations. They are used in enormous quantities to cool, lubricate and remove chips in metal cutting. A fluid's cooling and lubrication properties are critical for decreasing tool wear, reducing the occurrence of build-up edge (BUE), and extending tool life. Cooling and lubrication are also important in achieving the desired size, finish and shape of the workpiece. Companies offer a multitude of cutting fluid formulations to help alleviate machining problems and increase productivity. However, it has

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been difficult and confusing trying to select the best fluid for any given application and often has required expensive trial-and-error approach.

Water based and oils are the common cutting fluids in the automotive industry. With the advancement of nanotechnology, the new generation of MWF, “nanofluids” have been developed with improved thermal conductivity and/or lubrication compared to the baseline coolants. Nanoparticles are being considered in MWF for various machining operations and are reported briefly in the literature as fluids that are more biodegradable and are safer for the operator. Some more recent results reveal that because of suitable nanofluid characteristics, the optimum utilization of them for lubrication and cooling purpose, can be beneficial in different machining operations because selection of specific cutting fluids is a common technique for improving machinability [1-4].

More specifically, MWF with carbon nano-onion (CNO) particles have been used successfully in some aerospace industries. Since the aerospace industry needs to verify that the nanofluid during machining does not influence negatively the part’s metallurgical characteristics, performance and reliability, the CNOs are not widely used in aerospace MWF. The MWF with CNOs cost more than conventional fluids, as much as 50% to 150% more depending on the concentration of nanoparticles. However, because the application of coolants is a significant part of the manufacturing cost (to 12-17% today), the challenge has been whether these nanoparticles can provide substantial returns on investment in applications other than the tough-to-machine materials to reduce the coolant cost per part. Since the cost of the nanoparticles was a significant portion of the cutting fluid cost itself, thorough investigation was necessary to verify the benefits of the above CNOs in MWF.

Since such nanoparticles have been reported as beneficial in MWF for tough-to-machine material, it was essential to identify and understand the cooling and lubrication characteristics of the CNO in MWF for wider workpiece material application. In order to evaluate the characteristics of the nanofluid, several parameters had to be considered: nanoparticle concentration, nozzle orientation, and fluid pressure. The traditional technique to optimize this process is the "trial and error" approach, yet it is very time consuming due to the requirement of a large number of tests. Even if the more reliable Taguchi optimization systematic approach is used, measuring cutting forces, temperature and/or tool wear as response variables is a large effort because we have a large variety of workpiece materials in the automotive industry. This was done by testing the CNOs in oil and water-based fluids versus the baseline coolant.

The aim of this paper is to assess the impact of CNOs technology on machining steel components. This report describes the findings about the CNO in MWF. Our main objective was to determine if the CNOs technology could improve tool life and/or part quality with respect to better surface finish and better dimensional accuracy without cost penalty for some of the automotive machining applications.

Background

The MWF is an important component of the machining system in many applications. Cutting fluids are used in a large proportion of metal cutting operations to improve tool life, surface finish, and dimensional stability, and to help clear chips from the cutting zone. For many materials cutting fluids are necessary to achieve acceptable part quality and tooling costs. However, cutting fluid acquisition, management, and treatment costs are a significant fraction of the overall operating expense in wet applications, and the fluids may also present an exposure risk to machine operators and require additional investment for enclosures, fire suppression, and air treatment.

Cutting fluids provide lubrication between the tool, chip, and workpiece, while they cool the part and machine tool and clear chips. They also help prevent edge buildup and part rust in most circumstances. When properly applied, they permit the use of increased cutting speed and feed rate. A cutting fluid’s cooling ability depends largely on the base fluid and the coolant volume. Chip flushing capabilities are determined by the operation geometry and the coolant application method. Lubrication is controlled by the chemical composition of the coolant and the application method.

The types of coolants which are effective for broad classes of work materials and operations, e.g. for turning aluminum alloys or milling steels, are generally understood. The selection of a cutting fluid for a specific application, however, is often determined by experience and limited performance testing, and typically represents one of the more arbitrary decisions in process design. This is unfortunate, since the cutting fluid type, application method, pressure, and flow rate have as strong an influence on tool life and surface quality as parameters such as the tool grade, cutting speed, and feed rate, all of which are normally carefully optimized during process design. As an integral part of the system, the available coolant options should be considered in addition to the tooling and feed and speed variables in process development.

The most common MWF are the neat or cutting oils and water-based fluids [1]. Water based fluids include emulsifiable oils, semi-synthetic fluids, and synthetic fluids. Cutting oils are mineral, animal, vegetable, or synthetic oils used without dilution with water. They are more effective as lubricants than coolants [5]. They are used extensively in grinding and honing operations, where they permit higher metal removal rates with better finish and less surface damage than water-based fluids [6]. Due to their limited cooling capabilities, they are not used in high speed machining and restricted to relatively low speed operations such as broaching, tapping, gear hobbing, and gun drilling, and in machining nickel alloys and other hard metals.

Water-based fluids are dilute emulsions or solutions of oils in water, which provide less lubrication but better cooling and chip clearing abilities than neat oils [1]. The concentration is typically between 5% and 20%, with lower concentrations (less than 10%) being most common in general-purpose machining. Water cools 2-3 times faster than mineral oils and can retain more than twice the amount of heat. They are used extensively in higher speed operations and large recirculating systems.

The effectiveness of MWF depends to a large extent upon the method of their delivery into the cutting zone. There are four basic methods of applying coolant: low pressure flood application, high pressure flood application, through-tool application, and mist application [1]. Regardless of the method used to apply coolant, sufficient volume must be supplied to provide adequate cooling and chip clearing action.

For approximately two decades, nanotechnology has been slowly introduced in MWF for machining operations. Typical MWF are nanoscale colloidal suspensions holding solid nanomaterials [7-9]. The published research indicates that nanofluids are especially effective in grinding and small hole drilling [5,6,10-12]. The nanofluids are obtained by suspending nanoparticles in the range of 1-100 nm in water based or oil cutting fluids. Even and stable suspension of the particles is important to the performance of the fluid. Solid nanoparticles are designed with higher thermal conductivity and as they are added in the fluid, the overall thermal conductivity of the nanofluid is improved [13,14]. More specifically, the thermal conductivity of water based cutting fluid is significantly lower than that of water. By adding a small amount of nanoparticles the thermal conductivity could increase to that of water or even higher [15]. The density is one of the factors that affects the heat transfer properties of the nanofluid. The simplest method for calculating the density of a nanofluid is [14]:

$$\rho_{nf} = \varphi\, \rho_s + (1 - \varphi)\rho_f \qquad (1)$$

Where ρ is the density, ϕ is the volume concentration, and the subscrips "nf" and "f" are the nanofluid and base fluid, respectively.

The specific heat capacity (that determines the ability to store energy in the form of heat) of nanofluids is affected by the density and the specific heat of the nanoparticles and base fluid. There are several models and most of them relate to the density model above [13,16]. It has been found by many researchers that the specific heat of nanofluids decreases with increasing nanoparticles' volume fraction although the nanofluids have significantly higher specific heat than the base fluid [17]. Another very important parameter is the thermal conductivity of nanofluids. Since the rate of heat transfer through the solid nanoparticles is much higher than the base fluid, the nanofluids with small amounts of nano-particles have significantly better thermal conductivity (50 to 100%) than the base fluids [18]. In addition, the thermal conductivity increases with increasing volume fraction and with reduced the particle size. Therefore, the heat transfer coefficient for the nanofluids is higher than the baseline fluids [14,18].

The properties of the nanofluids are determined by the characteristics of the nanoparticles. For example, carbon nanotubes, and Al_2O_3 are used for their superior thermal properties, while others, such as graphite and boric acid, are better for improving the lubricity of the cutting fluid. Graphite has been found the best candidate for cutting fluids because it provides both cooling and lubrication. However, carbon nanotubes and graphite do not disperse readily in water based fluids compared to oils and they require special techniques for suspending them to form a stable dispersion. The enhancement from the nanoparticles in MWF could vary from 20% to 300%.

Therefore, the current knowledge of the nanofluid improvement cannot be generalized; each nanofluid must be evaluated for the specific metal cutting application to determine the enhanced performance and cost benefit that is depended on the cutting tooling cost and productivity improvements.

Over the past twenty years, CNOs were successfully developed with high tribological performance. Mechanisms by which CNOs can reduce friction and wear were investigated in greater detail [19,20]. Computer simulations suggest that the lubrication of CNOs between two surfaces is caused by rolling–sliding of the nanoparticles. Our objective was to determine the financial impact and the effects on quality that CNOs in MWF will have. This helps us understand the impact of CNOs particles on the cutting process with respect to part quality and tool life. Carbon onion consists of concentric graphitic shells and can be made by various processes. The CNO particles considered here are about 5-10 nm in diameter and are made by detonation synthesis, a process that transforms carbon powder into nano-onions [21]. The structure consists of a hard diamond-like core with an outer shell of amorphous carbon and graphene that should provide similar lubrication to graphite.

By design, the nano-onion structure has the ability to absorb liquids and release them when under the pressure of cutting [22]. In doing so, the liquid is released in the ideal location which is between the loaded metal-to-metal interface of the tool and the workpiece. Furthermore, during machining, the nano-onions are exposed to shearing forces created by the cutting action. This process results in graphene, also known as single layer graphite, breaking off (or exfoliating) and becoming distributed throughout the coolant. The shearing amplifies the number of nano-particles in the coolant which increases the lubricious characteristics of the coolant. The cooling characteristics are superb since the graphene is a very good conductor.

It has been easy to compare two different coolants under the same machining and tooling conditions by keeping all the variables in the machining system constant. In this case, it is important to understand the failure modes and wear conditions of cutting tools since tooling and coolant costs have a large influence on the cost of a machining process. A common performance metric for machinability testing is the measurement of flank wear and BUE (built up edge) as shown in Fig. 1. The wear of the flank surface due to rubbing against the workpiece is one very characteristic source of cutting wear due to friction and heat generation as illustrated in Fig. 2. All other parameters during machining being equal, the degree of flank wear and edge degradation are good indicators of the performance of the coolant that is being evaluated. This was done by testing the proposed nanofluid versus the current production coolant as a baseline and measuring the flank wear at the end of the tool change interval only to find out how the relative flank wear, BUE, and edge deterioration compare as well as part quality characteristics such as surface finish.

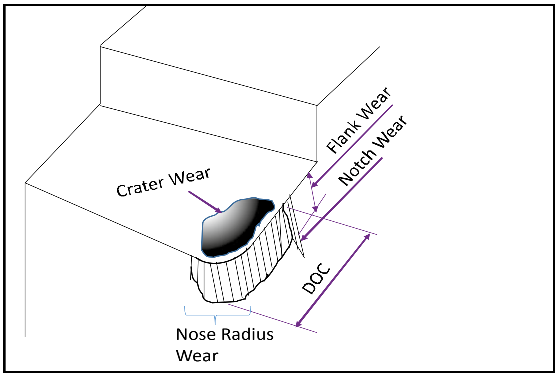

Fig. 1. Illustration of the tool insert geometry for OP.10 and OP.20 used for and types of wear that occur.

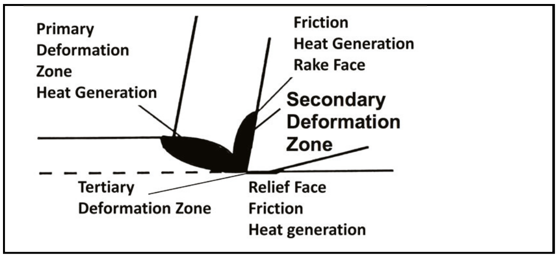

Fig. 2. Heat generation zones at the tool-workpiece and tool-chip interfaces.

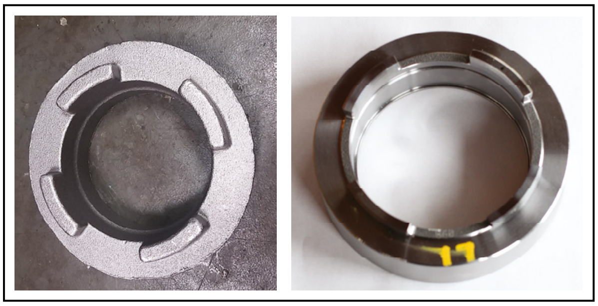

Fig. 3. As-forged and finish machined gears.

Experimental Plan

Three different cutting tests were performed using CNOs in the MWF:

1. The machining of the transmission input and idler/transfer gears (see Figure 3) are considered using several identical cells with CNC lathes. The gears are made from 5120 hot as forged steel material (20MnCrS5 per ZF7B) about 30HRC. Both gears were about 100 mm OD by 30 mm width. The cells for machining both gears had two operations with several sub-operations as given in Tables 1 and 2. The gears were clamped in a three-jaw chuck in a Murata MW200 twin spindle lathe.

Table 1. Machining process for input gear.

OP 10	Tool 1 - OP 10 Rough Gear Face & OD, CNMG-433
OP 10	Tool 3 - Finish Gear Face and OD, DNMG-432
OP 10	Tool 5 - Rough & Finish Bore, CNMG-432
OP 20	Tool 1 - Rough Gear Face & Interrupt OD, CNMG-433
OP 20	Tool 3 - Finish Gear Face and Interrupted OD, NR3031
OP 20	Tool 5 - Rough & Finish Bore, CNMG-432
OP 20	Tool 9 - Finish ID Groove, Grooving insert

Table 2. Machining process for idler gear.

OP 10	Tool 1 - Rough Gear Face & OD, CNMG-433
OP 10	Tool 2 - Finish Gear Face and OD, DNMG-432
OP 10	Tool 3- Rough Pocket, DNMG-432
OP 10	Tool 5 - Rough Pocket, DNMG-432
OP 10	Tool 7 - Finish Hub and Pocket,
OP 10	Tool 9 - Finish Bore, DNMG-432
OP 20	Tool 1 - Rough End Face, CNMG-433
OP 20	Tool 3 - Rough Bore, CNMG-433
OP 20	Tool 5 - Finish Bore, DNMG-432
OP 20	Tool 7 - Finish Pocket, NR3031
OP 20	Tool 9 - Finish Face, CNMG432

The current production water soluble coolant was considered the baseline cutting fluid supplied at 140 psi flooding of the tool-part interface area. The CNO particles were dispersed in the baseline coolant to form the nanofluid (at about 1 Vol.%) that was evaluated against the baseline coolant. Several identical cells were used to machine the two gears. The testing of the coolant performance was based on 100 parts. Tool life was determined with the baseline coolant as the point at which tools were near to failure, i.e. the flank wear for several tools reached the end of tool life, the point when the tool no longer performed satisfactorily. Two machining cells were used for the input gear and four cells for the idler gear. Half of the cells had the baseline coolant and the others the nanofluid.

The cutting tools for each process were selected through extensive testing when the process was optimized with the baseline coolant. The different single point inserts utilized for all the idler gear operations are shown in Figure 4. Since the tools for both operations are changed at the same time, the number of gears processed between tool changes is determined by the tool with the lower tool life. The cutting conditions (speed and feed) for each of the operations was optimized based on the cycle time requirement. Tools from each cell were collected at the end of the tool life and the tool wear characteristics were measured at the flank and rake faces using a tool maker microscope. Generally, the inspection was done to determine whether the nanofluid minimized the flank wear and prevented unwanted tool failure modes such as catastrophic fracture, gross plastic deformation, and crater wear.

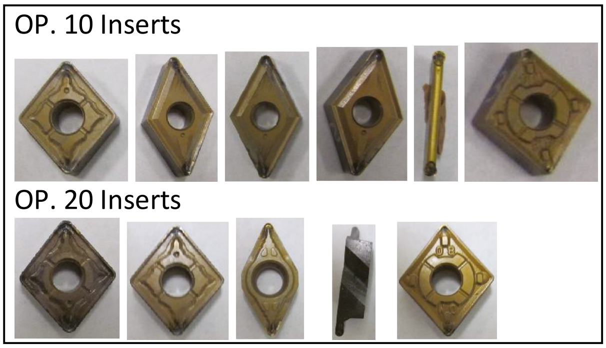

Fig. 4. Illustration of the tool insert geometry for OP.10 and OP.20 used for the idler gear.

2. The gear cutting (Hobbing) operation for manufacturing A1 and B1 ring gears was selected for evaluating the CNOs blended in the baseline mineral oil (forming the nanofluid) at a specified concentration of 0.5 Vol%. The material for the helical ring gears is steel alloy SAE J1268-8630H (34-42 HRC). The process involves the use of a special type of milling machine to progressively cut the gear teeth into the workpiece. The machines were programmed for four tool passes each (between regrinds) with A1 gear and six passes for B1 gear using the baseline oil lubricant. The tool wear and part quality were monitored and checked after a specified number of passes. Because the cutting tool or hob has many cutting edges (as illustrated in Figure 5 for a generic hob), the flank wear was measured for about 20 teeth at various locations of the tool. The maximum flank wear threshold for this type of tool was setup at 0.12 mm in order to allow for so many regrinds while removing about 0.3 mm per regrind from the rake face of the tool. The test objective was to find the number of

passes per regrind using the nanofluid since the baseline oil lubricant was already utilized in current production. The tool life was increased one pass at a time, the wear was measured, the tool reground, and reused.

Fig. 5. Illustration of a generic hob.

3. Milling and drilling tests were performed to evaluate the nanofluid. Three MWF's were used for comparison: (1) a water-based semisynthetic coolant, (2) Molybdenum disulfide (MoS2) nanoparticles were blended in the baseline coolant, and (3) baseline coolant blended with CNOs at 2% Wt. MoS_2 nanoparticles in size ranges from 20 to 100 nm make a hard, brittle material that is cheap and readily available on the market. They are applicable in machining applications [23]. 25 mm wide slots were milled with a solid carbide end mill. The cutting forces on the spindle and machine tool axes were measured during milling 16 rectangular steel blocks. The slot width and surface roughness were also measured.

A 12.98 mm diameter carbide drill with through spindle coolant was evaluated by drilling through a 25.4 mm thick plate as many holes as possible until the point of the drill failed. 462 holes were drilled in a 900 X 230 mm plate (11rows by 42 holes per row) with 18 mm distance between centers. A new drill was used with each coolant test. The drills were tested at three different cutting conditions: 100%, 110%, and 120% of the drill manufacturer recommended cutting peripheral speed and feed per revolution. They were tested to failure without measuring the flank wear to minimize the testing time and effort. It was assumed that the drill wear rate for the drill making the largest number of holes, was the lowest and reflected the optimum coolant. The relative thrust force was also recorded through the machine tool monitoring system as another coolant performance indicator. The material used for the above tests was 4120 steel heat treated to Rc 28/32.

4. Results

4.1. Input Gear

The graph in Figures 6 illustrates the flank wear comparison for the various turning tools in Op. 10 for the input gear. The average value together with the minimum and maximum wear is shown by the bar graphs. The flank wear for these three inserts with the nanofluid was not significantly lower than that of the base coolant. However, the tool life of the tools used with the nanofluid was extended to 250 parts without catastrophic failure of any of the tools.

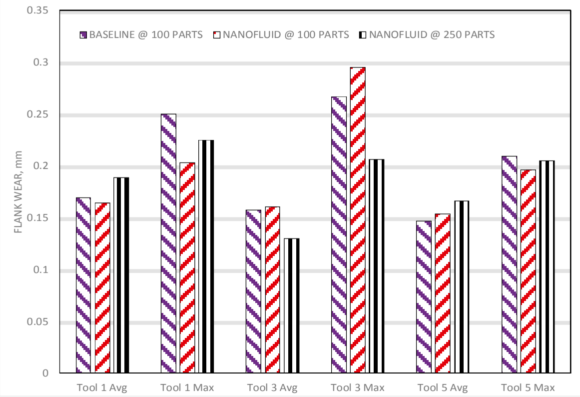

Fig. 6. Flank wear for Tools in Op 10 for Input gear.

The flank and crater wear maps of rough and finish inserts for Op. 10 with the baseline coolant are shown in Figure 7. The flank wear land was uniformly distributed along the cutting edge and around the corner radius as illustrated. In some cases, the corner wear for the finish inserts was somewhat higher than the cutting edge as expected due to shallower depth-of-cut. The major wear mechanism was abrasive wear. 20 to 30% of the finishing inserts #3 and #5 had notch wear as illustrated in the photo (Fig. 7). The depth of notch was generally larger than the flank wear. The contribution of crater wear was not as significant as the notch wear on tool life. There were also a few inserts with edge micro-chipping. The tool life with the nanofluid was extended from 100 to 250 parts without any major concerns. The inserts with the baseline coolant were failing randomly when the tool life was extended above 100 parts. The tools with nanofluid had significant flank wear after 100 parts but the wear did not increase as drastically as with baseline coolant. Furthermore, the micro-chipping or notch phenomena after 250 parts was not much worse than those after 100 parts. It seems that the nanofluid is very effective with worn inserts and it works well under higher cutting pressure at the tool-workpiece interface. In addition, it was observed that the tool with the baseline coolant had significantly more buildup than the tool with nanofluid; this is possibly another reason why the nanofluid extended the tool life to 250 pieces. This was evidenced by occasional material attached on the back of the otherwise smooth chips. The chip formation is illustrated in Fig. 8 for the three tools in Op. 10. Tool #1 generated continuous ribbon-type chips with both coolants; the ribbon was very uniform with nanofluid and more random and problematic with baseline coolant. Tools #3 and #5 generated continuous chips with baseline coolant and shorter chips with nanofluid. Build-up-edge at the face of the tool was much more pronounced with the baseline coolant than the nanofluid. The formation of BUE indicates excessive friction at the interface between tool and workpiece that results in higher temperatures. The lack of coolant and lubricant could farther promote the BUE and was obvious with the baseline coolant because the chips were not as smooth as those with nanofluid.

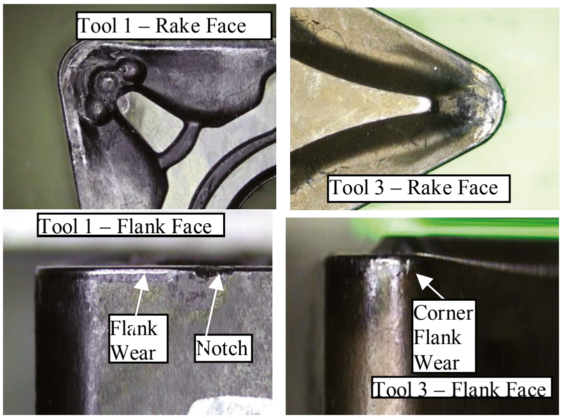

Fig. 7. Crater and Flank wear for Tools 1 and 3 in Op 10 for Input gear.

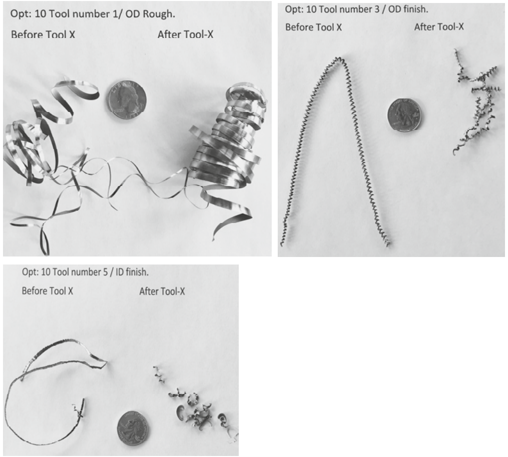

Fig. 8. Comparison of chip formation with baseline and nanofluid coolants in Op 10 for Input gear.

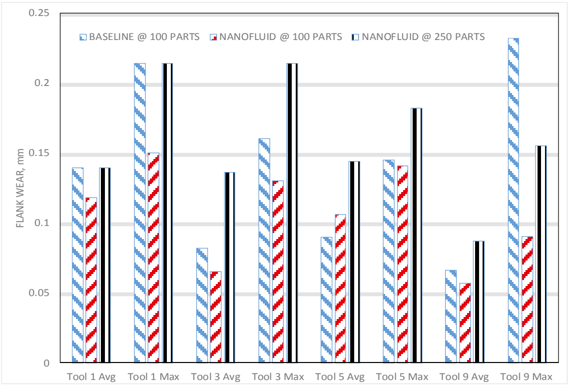

Fig. 9. Flank wear for Tools in Op 20 for Input gear.

The flank wear of rough and finish turning inserts for input gear Op. 20 with both coolants is shown in Fig. 9. The average and maximum values of flank wear is shown by the bar graph. The flank wear for tools #1 and #9 was higher with the baseline coolant than the nanofluid. The other two tools had equivalent flank wear with both coolants at 100 parts. The grooving tool #9 had three times greater wear with the baseline coolant than the nanofluid. The wear for two of the four inserts increased when the tool life with the nanofluid was extended to 250 pieces. An interesting observation was noted with the grooving tool because the wear at 250 pieces with the nanofluid was only 2/3 of that of the baseline coolant at 100 pieces. The grooving tool probably has higher localized cutting forces because both tool edges (both sides of the insert) were in contact with the workpiece. In this case, the flood coolant was not as effective as necessary for the ID grooving operation. It seems that the chip prevented the baseline coolant from reaching the rake face in the cutting zone; on the other hand, the nanoparticles in the nanofluid improved the lubrication and the cooling characteristics in this more difficult operation.

The flank wear maps of the grooving insert for Op. 20 with the baseline coolant is shown in Figure 10. The flank wear land was uniformly distributed along the cutting edge and around the two corners as illustrated. About 50% of the inserts used with the baseline coolant had a micro-chipping at one of the two corners as shown in Figure 10. However, very few of the inserts used with nanofluid had micro-chipping. Furthermore, none of the groove inserts with nanofluid at 250 pieces tool life had any micro-chipping. The nanoparticles are very effective under higher cutting pressure at the tool-workpiece interface. Even though the coolant application is the same for the nanofluid as for the baseline, the CNO particles greatly help the grooving operation. The nanoparticles seem to control the temperature at the cutting edge, resulting in less tool wear and more stable performance. In addition, the chips produced (see Figure 11) with the nanofluid were shorter and better managed because they had less chance to tangle around the part or cutting tool in a way that might result in catastrophic failure. Good chip control could extend the tool life.

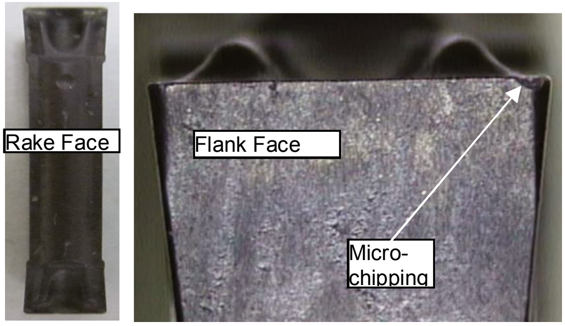

Fig. 10: Flank wear for Tools 9 in Op 20 with baseline coolant for Input gear.

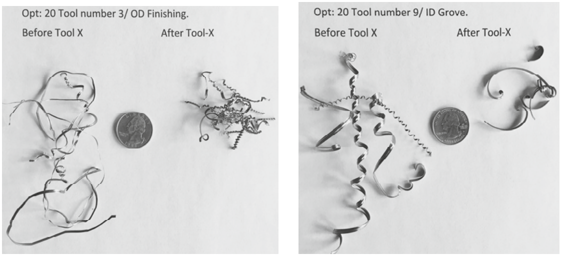

Fig. 11. Comparison of chip formation with baseline and nanofluid coolants in Op 20 for Input gear

The surface roughness for three surfaces requiring good finish quality were measured and the comparison is given in Fig. 12. The Ra and Rz surface finish parameters are provided. From the results, with use of CNO in the coolant, the surface roughness values were reduced for the OD and ID surfaces compared with the case of using baseline coolant. This can be attributed to the tribological properties of CNOs, which reduces the coefficient of friction and BUE at the tool–chip interface during the machining process. However, the results on the face of the gear did not show any reduction of roughness with the nanofluid. In this case, the nanofluid was not effective because the nanoparticles probably could not effectively penetrate the tool-workpiece interface.

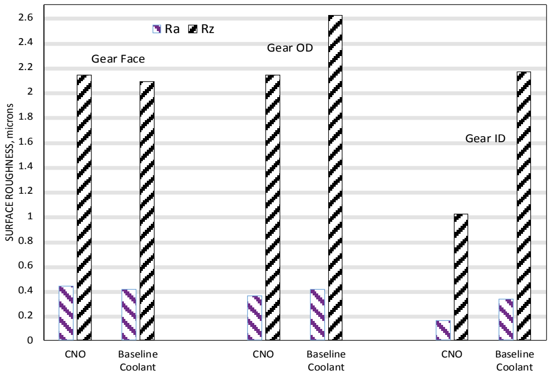

Fig. 12. Surface roughness for three surfaces in the Input gear.

4.2. Idler Gear

The comparison of the nanofluid with the baseline coolant for the idler gear did not show a significant reduction in flank wear with CNO nanofluid. Several of the turning tools exhibited micro-chipping and in some cases, large chipping at the cutting edge or corner of the insert was observed with both coolants. Even though the number of inserts with micro-chipping or small fracture at the edge was larger with the baseline coolant, and because some inserts with nanofluid had similar macro-cracks, it was decided that the nanofluid could not extend the tool life above the 100 parts. The result indicated that the cutting conditions were aggressive in order to meet the required cycle time and the nanofluid did not help enough to increase the tool life to the next level.

4.3. Ring Gear

The CNOs were added to the baseline oil to form the nanofluid. The tooling for the A1 gear did not show any significant flank wear in both hobbing machines until the 6th pass and it stayed at that level through the 11th pass with the CNO oil lubricant. The average and maximum of the flank wear of about 20 teeth in the hob is shown in Figure 13. We don’t have any further information about the 12th pass and beyond. In addition, the gear quality did not change with the number of passes. Since the flank wear threshold was 120 microns, the maximum wear had not yet been reached and the number of passes could extend further. Also, now the tools only had an average of 0.12 mm removed on regrind, as opposed to 0.3 mm before the start of the trial with nanofluid to remove the wear and other micro-chipping from the flank and cutting edge for all the teeth of the hob. The nanofluid resulted in more than 150% improvement in tool life.

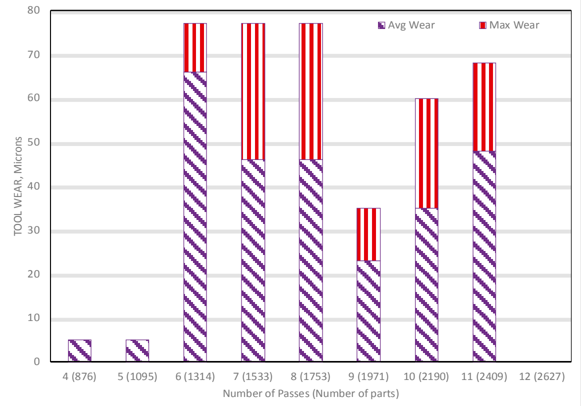

Fig. 13. Flank wear for Hobbing tool with ring gear A1

The hob for the B1 gear was optimized with the baseline oil. The flank wear after six passes was about 0.08 to 0.12 mm that is the wear threshold. After 6 passes with the nanofluid, little to no wear had occurred (see Fig. 14) in all the four hobbing machines, and the number of passes was further increased to 7 and 8. The flank wear at the end of the 11th pass was below 60 microns for the four hobs.

Even though we don’t have the total number of passes with the nanofluid (CNOs in the oil), the number of passes per tool has been increased by at least 100%. The nanofluid reduced the flank wear with a uniform wear across all the teeth that led to lower depth of regrind for the teeth as in hobs for A1 gear. The results with the ring gears indicated that the additive of the CNOs in the oil at 0.5 Vol% drastically improved the cooling and the lubricity characteristics of the baseline oil when hobbing steel alloy gears at 34-42 HRC hardness. In addition, a large amount of coolant was applied at the cutting zone and the nanoparticles were very effective in minimizing the tool wear and micro-chipping at the cutting edges.

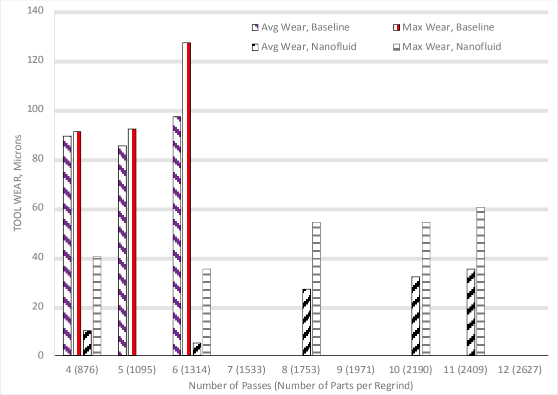

Fig. 14. Flank wear for Hob used for ring gear B1.

4.4. Milling & Drilling Tests

The machine tool relative cutting forces for the end-milling process as provided by the controller are shown in Figure 15. There is no significant force change across three different water-based coolants including the nanofluid (baseline + CNOs). This result was expected because the cutting is not continuous in milling, but rather is periodically interrupted as cutting edges enter and leave the part. Therefore, increased cooling and lubrication were not as effective as in continuous cutting (i.e. turning, drilling, etc.). The slot width quality and the surface roughness measurements in two directions are provided in Fig. 16. The average value and the variation of slot width among the 16 milled blocks were smaller with CNO coolant. Likewise, the surface roughness was lower with the CNO coolant. In addition, the chip formation was more consistent with the CNO coolant, and resulted in somewhat better dimensional control and surface finish.

The drills performed well with all the three cutting fluids at 100% of the recommended cutting conditions and this tool life test was terminated after 200 holes. Unfortunately, the flank wear was not measured among the drills. The peripheral speed and feed were

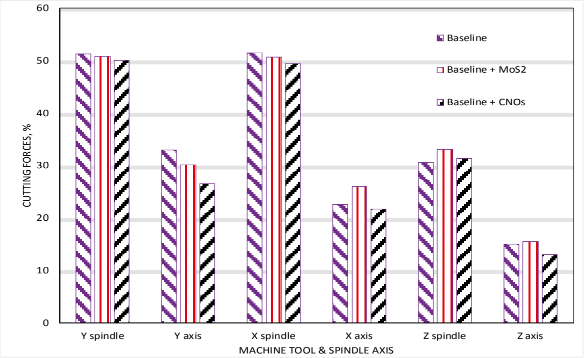

Fig. 15. Cutting forces from milling with three different MWF.

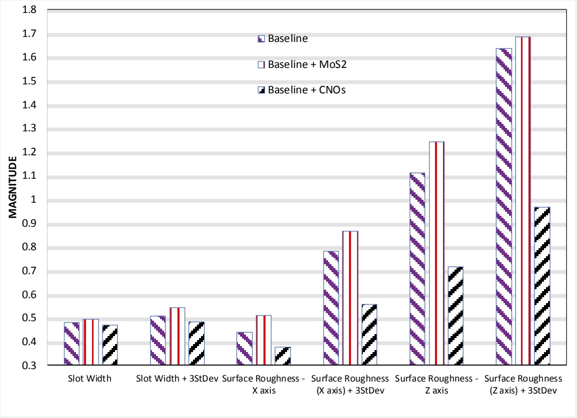

Fig. 16. Slot width and surface roughness from milling with three different MWF.

increased by 10% and the test was repeated. Again, no one drill failed at 200 holes and the test was stopped.

A third test was performed with the cutting conditions increased by 20%. In this case, the drill with the baseline coolant made only 11 holes and with the baseline coolant plus MoS_2 made 144 holes before they failed within the last hole. The drill with the baseline coolant and the CNOs made 252 holes and the test was terminated because the drill was worn. The comparison of the tool life from the above tests is shown in Figure 17. The relative thrust force as the tool was run to a failing point is compared in Figure 18. The thrust force during drilling was very consistent among the three coolants as long as the tool wear was not excessive. We can assume that the thrust force changed proportionally to the feed changes in which case a 10% increase in feed should increase the thrust force by about 10% since the contribution of the speed is negligible. In this case, it was observed that the 10% increase in feed resulted in about 10% increase in force that increased further with tool wear to 20% after 200 holes. However, when the feed and speed increased by 20%, the thrust force increased proportionally by about 20% but the tool wear increased drastically due to 20% higher speed. When the cutting conditions increased by 20%, the force increased with number of holes by 40% and 64% at the end of the drill life, respectively, for the baseline and baseline plus MoS2 coolants. The force for the drill with the CNOs coolant increased by about 44% while drilling 252 holes without a strong indication of failure. This drilling test showed that the CNO particles improved the lubricity characteristics of the water based coolant. In addition, the coolant was applied through the drill and the nanoparticles were very effective at the cutting zone to minimize wear.

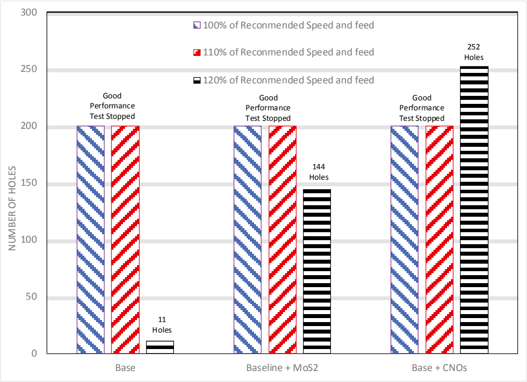

Fig. 17. Tool life comparison when drilling with three different coolants.

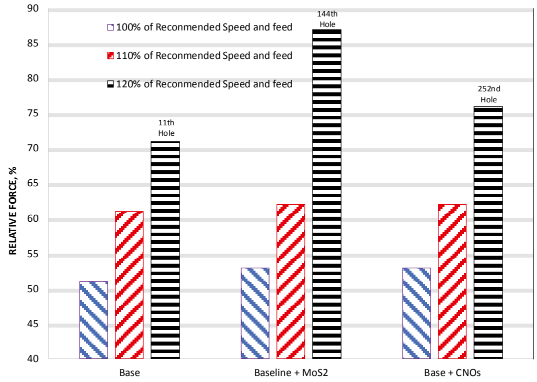

Fig. 18. Cutting forces when drilling at different cutting conditions and three different coolants.

5. Discussion

Our goal was to assess the impact of CNO technology in the coolants on machining automotive steel components. The CNO technology has been used successfully for tough-to-machine materials, including titanium, super alloys, and hardened steels. The literature and our communication with aerospace manufacturers indicated that the nanotechnology is delivering substantial improvements in tool life, surface finish, and dimensional accuracy, while permitting higher production rates and productivity with tough-to-machine materials. Their results indicate a machining cost reduction of 15% to 25% for tough-to-machine materials.

In our effort, water based and oil MWF with CNOs were evaluated for several applications including turning, gear hobbing, milling and drilling of heat treated steel parts. The results from the turning tests indicated that the tool life can be increased as much as 150% assuming the cutting conditions are optimized to avoid catastrophic failure of the tools. In addition, our tests indicated that the nanoparticles are effective if they are dispersed properly in the water based coolant and the nozzle orientation and pressure are adjusted for each operation to make sure the nanoparticles are reaching the cutting zone (tool-chip and tool-workpiece interfaces). The surface finish indicated some small improvements even though the surface appearance was much better with the nanofluid. It did reduce the BUE for several of the tools.

The results from the hobbing process for the ring gears indicated that the CNO particles were very effective in the oil lubricant. The results followed the trend discussed in the literature for tough-to-machine materials when using nanofluids. Hence, in this application the addition of CNOs in the cutting oil outperformed and resulted in a cost benefit for production.

The results from the milling tests indicated that the milling cutting forces did not reduce with CNO coolant compared to baseline water based coolant. However, the slot width and surface roughness were better with the CNOs additive. The drilling results indicated an increase in tool life and productivity potential when adding CNOs particles to the water based coolant. However, a cost analysis was not performed for such a short test.

The cost of coolants with CNOs could be significantly higher than the cost of the base coolants without CNOs. For example, in one case the cost of the oil fluid was about $13 per gallon, while the cost of the same oil blended with 0.05 Vol% CNOs was about doubled. However, the concentration of CNOs utilized in the base fluid could vary significantly depending on the application. The concentration generally varies from 0.01 to 0.05 Vol%. The tooling cost, regrind cost, number of regrinds, and the uptime of the machine lost to change tools will affect the break-even point for tool life that could vary from 10 to 50% or even 100%. For example, when the tool cost and the tool change time are low (i.e. a gear hob may cost $1,500 with a tool change time of 30 min and low cost to regrind), it would require a tool life increase of at least 50-100%. However, when the tool cost and the tool change time are high (i.e. a gear broach tool may cost $50,000 with a tool change time of 1 hours and 4 hours to regrind it), will require only 10 to 30% increase in tool life to break-even.

6. Conclusions

Carbon nano-onion particles dispersed in oil or water-based coolants are ideal for tough-to-machine material such as heat treated gears because it improves the lubricity and cooling effects of the baseline cutting fluid.

Tests showed a cost saving when machining steel gears with CNO water-based or oil cutting fluids. It seems that the CNOs performed well as long as the cutting conditions are optimized.

Tool life and productivity improvements were shown for drilling heat treated steel material with CNO water-based cutting fluid. In addition, the cutting forces were lower with the nanofluid as expected for a continuous cut of heat treated steel. However, no significant change in cutting forces was observed in milling the same heat treated material because it was an interrupted cut.

The CNOs in the MWF improved the appearance of the surfaces of a part and in some cases the surface finish over the baseline cutting fluids.

Finally, CNOs in the MWF can impact the cutting process and should perform better in some operations than others. The cost benefit was not always obtainable and it depended on the operation, cutting tool and workpiece materials, and the cutting conditions. The cost benefit should be reviewed case by case and coolant testing is often necessary for validation purposes. We can say it is likely CNOs will significantly benefit the tough-to-machine materials.

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