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USE OF NANO HEXAGONAL BOR NITRIDE (HBN) ADDED CUTTING FLUID IN MILLING OF HARD TO CUT MATERIALS

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In machining processes, MQL method is substantially preferred in terms of sustainable production because of lower usage of cutting fluid and better cutting performance in comparison with traditional techniques. On the other hand, it is also critical that the cutting fluid used is not hazardous to human and environmental health. In the present study, we aimed to investigate the cutting performance of AISI O2 steel in the presence of the cutting fluid containing various amounts of environmentally friendly Nano hexagonal boron nitride (Nano h-BN) based ethylene glycol (EG) by minimum quantity lubrication (MQL) method. Nano h-BN at 1% and 2% percentage by volume was added to the ethylene glycol and sonication was carried out for one hour for both prepared cutting fluids. Based on the experimental results using prepared cutting fluids, the highest cutting tool life was obtained in tests using 2% h-BN containing cutting fluid with 2.4 m cutting length. The improvement in tool life was approximately 46% using 2% h-BN containing cutting fluid compared to using 1% h-BN containing cutting fluid in milling tests. 2% h-BN containing cutting fluid compared to dry conditions in terms of tool life, the increase was approximately 78%. The improvement in surface roughness value measured on milled surface of workpiece material was approximately 60% using 2% h-BN containing cutting fluid compared to dry conditions. Compared to using 1% h-BN containing cutting fluid the improvement in surface roughness values was approximately 46%. A reduction in the cutting forces measured by the increased h-BN ratio in the prepared ethylene glycol based cutting fluid has occurred. As a result of SEM images and EDS analysis of worn tools, it was observed that the dominant wear mechanism was abrasion in all applied tests.

Key words: Minimum quantity lubrication, hardmilling, hBN, 2D structure, AISI O2, tool wear, cutting performance

1. Introduction

The machinability feature of a material is evaluated in terms of tool life, cutting force and surface roughness [1]. In addition, the characteristic of the cutting fluid significantly influences the cutting performance as it removes the heat generated in the cutting zone [2]. Especially at high cutting speeds, the failure of the cutting fluid to penetrate between the workpiece and the tool causes the heat not to be removed effectively

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during the process [3]–[7]. Furthermore, the cost of the cutting fluid corresponds to about 5% of the total process cost in some applications and the safe disposal of these fluids is a very important issue [8], [9]. Therefore, in recent years, researchers have been focused on alternative methods such as minimum lubrication technique (MQL) to both reduce the amount of the cutting fluid used and to improve cutting performance [10], [11].

MQL method can be defined as the process of spraying the liquid at a certain pressure and speed into the cutting zone in the literature [12]. MQL method is intensively preferred in cutting processes as it is low cost and sensitive to human and environmental health [13], [14]. Compared to conventional and dry machining, it provides significant contributions to tool life, cutting forces and surface roughness due to reducing heat between tool and workpiece [15]. In the MQL method, it is known that the addition of inorganic additives such as h-BN, MoS2 and graphite to the cutting fluid improves the cutting performance. Among these additives hexagonal boron nitride (h-BN), has a lamella structure where boron and nitrogen atoms are linked by covalent bonds. In addition, due to the easy separation of the basal plane, h-BN has lubricating properties. h-BN, similar to graphene in terms of physical and chemical properties; it is preferred as an alternative to other solid lubricants due to its inert, environmentally friendly and high temperature endurance [12] [13][18][19][20][21].

In spite of numerously researches on the cutting performance of AISI O2 [22][23][24], the number of studies is limited related to the machinability of AISI O2 using MQL method. Moreover, no literature was existing on used the cutting fluid containing nano h-BN as lubricant by MQL method. On that sense, the study is thought to fill the deficiency of literature due to innovative approach. This research will reveal the cutting performance of AISI O2 steel in terms of tool lifetime, tool wear, cutting force and surface roughness in the presence of the cutting fluid containing different nano h-BN concentration by MQL method.

2. Material and Method

2.1. Preparation of cutting fluids

Analytical grade nano h-BN as additive was provided from the Bortek company in Eskişehir/Turkey. The ethylene glycol ($C_2H_6O_2$) used as the base fluid in the experiments was obtained from a commercial company. First, nano h-BN was added to the ethylene glycol solution to prepare solutions of 1% and 2% with a total volume of 800 ml. Then, the obtained suspension was sonicated for 1 h to ensure homogeneity of the solution.

2.2. Materials and Methods

AISI O2 cold work tool steel was used in milling tests which has a high dimensional stability in heat treatment, cracking resistance and abrasion resistance [25]. It is widely used in the manufacture of different materials in industry such as dies and molds production. The chemical composition of workpiece material shown in Tab. 1.

Table 1. Chemical composition of AISI O2 cold work steel (wt. %) [23]

C	Si	Mn	P	S	Cr	V
0.88	0.29	2.07	0.024	0.09	0.26	0.08

2.3. Machine Tool, Cutting Tools, MQL System, Cutting Tests

Sintered carbide cutting tools with R390-11 T3 08M-KM H13A coded from Sandvick were used in milling operations. Sandvick R390-025A25-11L coded with a diameter of 25 mm was selected as tool holder. Although there are two places where the cutting tools can be attached on the tool holder, experiments were performed with a single cutting tool. The devices used in milling tests can be summarized as follows (Fig. 1);

- All milling tests were performed on Falco VMC 855-B CNC 3-axis CNC machining center.
- Werte Micro STN 25 was used as MQL system.
- In order to measure the amount of wear occurring on the flank surface of the cutting tool during milling tests, Vision SX45 stereo zoom microscope was used. A computer software was used to measure the amount of wear on the flank face of cutting tool.
- Mitutoyo Surftest SJ 310 was used to measure the roughness values on the workpiece machined surface after milling operation.

- Cutting forces were measured by Kistler Multi-Component Dynamometer up to 10 kN Type 9257B.

Figure 1. Experimental setup

The work flow chart of the tests can be summarized as follows; AISI O2 cold work tool steel of 150mm* 80mm*80mm was supplied as workpiece material. On this workpiece, three holes were drilled for fixing on the dynometer. Then, according to the manufacturer's catalog and previous studies in the literature, cutting parameters were determined. In order to prepare the nano cutting fluid to be used in the MQL system, percentage by volume 1% and %2 h-BN was added to the commercially available ethylene glycol. Then, one-hour sonication was performed to ensure homogenous distribution of the h-BN in the cutting fluid. Then, the milling process started with the specified cutting parameters. After every 150 mm cutting length, the tool holder was removed from the CNC machine and the amount of cutting tool wear was measured on the flank face of cutting tool. In addition, roughness values were measured from seven different locations of the milled surface of the workpiece material and the average of these values was calculated as roughness value. Surface roughness values were measured at each pass up to 0.45 m cutting length. The cutting force values for each pass are transported by DynoWare, a computer program of the dynamometer, with a value of 1000 values per second. After each pass, the amount of wear from the microscope image obtained from the flank surface of the cutting tool was measured. According to ISO 8688-1: 1989 standards, when the amount of wear occurring on the flank face of cutting tool reaches 0.25 mm length, the cutting tool is considered to have completed its tool life. SEM images and EDS analyzes were investigated in order to determine the wear mechanisms occurring in the worn area of cutting tools for both conditions.

Table 2. Cutting conditions

Cutting speed, V_c	100 m/min
Feed rate, f_z	0.05 mm/tooth
Axial depth of cut, a_p	0.5 mm
Radial depth of cut, a_e	15 mm
Pressure	5 bar
Flow rate	50 ml/h

3. Results and Discussion

3.1. Tool lifetime and wear analysis

The tool life of the cutting tools is determined according to the ISO 8688-1 standard. According to this standard, it is determined that the cutting tool is worn when the wear length of the flank face of the cutting tool reaches 0,2 mm. The fig. 2 shows the tool lifetimes obtained after the face milling operations, which are applied in three different conditions. Accordingly, in dry conditions, the tool life is lower than other conditions due to the high temperature that occurs in the cutting zone. Milling with cutting fluid prepared with EG containing 1% h-BN showed an increase in tool life of approximately 22% compared to the dry condition. In the milling operations, the highest tool life was obtained by processing with cutting fluid containing 2% h-BN. In milling using cutting fluid containing 2% h-BN, tool life increased approximately 78% compared to dry condition. Similarly, in terms of tool life of cutting fluid containing 2% h-BN, the increase in tool life was approximately 46% when compared to cutting fluid containing 1% of h-BN. It can be said that, in the milling process applied with cutting fluid containing h-BN, the increase of tool life is provided by reducing the friction coefficient of the h-BN nanoparticles in the cutting zone [2,3].

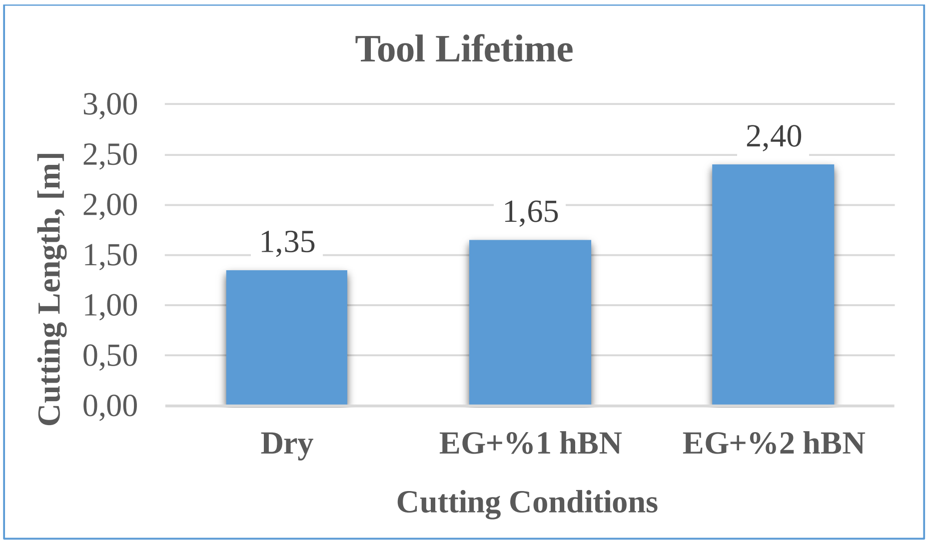

Figure 2. Comparison of tool life under different cutting conditions.

3.2. Surface Roughness

Ra surface roughness value is often used when determining the surface quality of a part [27]. In the milling process, many parameters affect the surface roughness value, some of them; tool geometry, feed rate, cutting fluid, cutting speed, tool wear [28]. In this study, the influence of the cutting fluid used in the MQL method on the roughness value of Ra was investigated. The surface roughness values, shown in fig. 3 were determined as the average of the measured values from the 7 different parts of the machined workpiece surface, up to a cutting length of 0.45 m, after every cutting length of 0.15 m. Thanks to the lubricating effect of h-BN the surface roughness value was reduced by approximately 20% measured after milling tests with cutting fluid containing 1% h-BN compared with the values measured in dry conditions. The improvement in surface roughness value was approximately 60% using 2% h-BN-containing cutting fluid compared to dry conditions. Smooth workpiece surface obtained with EG solution with 2% h-BN. It can be said that the improvement in surface roughness value is due to the lubricating effect of h-BN in the cutting zone [22] [26].

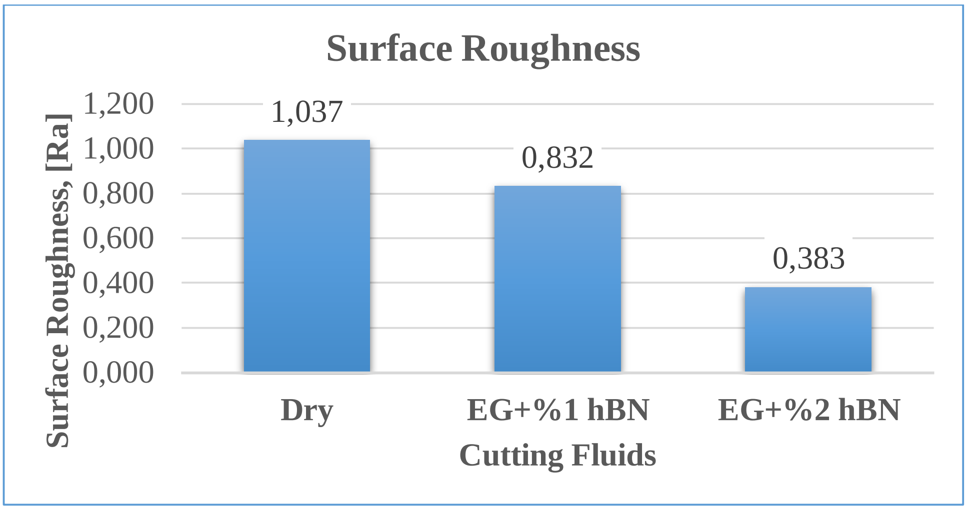

Figure 3. Comparison of surface roughness under different cutting conditions.

3.3. Cutting forces

Fig. 4. shows the resultant cutting force F_R value fluctuations measured at the same cutting length with different cutting conditions. Accordingly, a reduction in cutting forces has occurred with the addition of nano sized h-BN into the cutting fluid. This can be said to be caused by the reduction of the friction in the cutting zone by the lubricating effect of h-BN. In addition, when the cutting tool is outside the workpiece, it is seen that the vibration is less in the milling operations with the h-BN containing liquid.

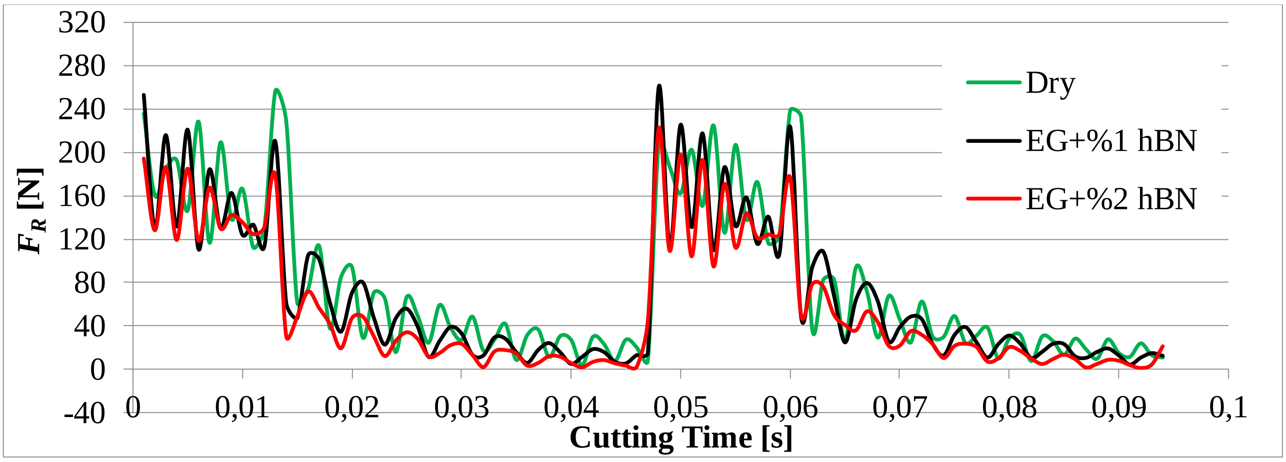

Figure 4. Fr cutting force fluctuations according to cutting time with using different cutting fluid.

3.4. Wear Analysis

Fig. 5. shows the SEM photograph of the worn cutting tool after milling operation in dry condition. According to the photograph taken from the wear zone, due to the high temperature at the cutting zone, the workpiece material adhered to the cutting tool and the BUE was formed. Seizure zones were also formed on the flank surface due to high temperatures. It is seen by EDS analysis that the coating material is deformed in the seizure zone. As a result, the dominant wear mechanisms in the dry milling process were abrasion and adhesion.

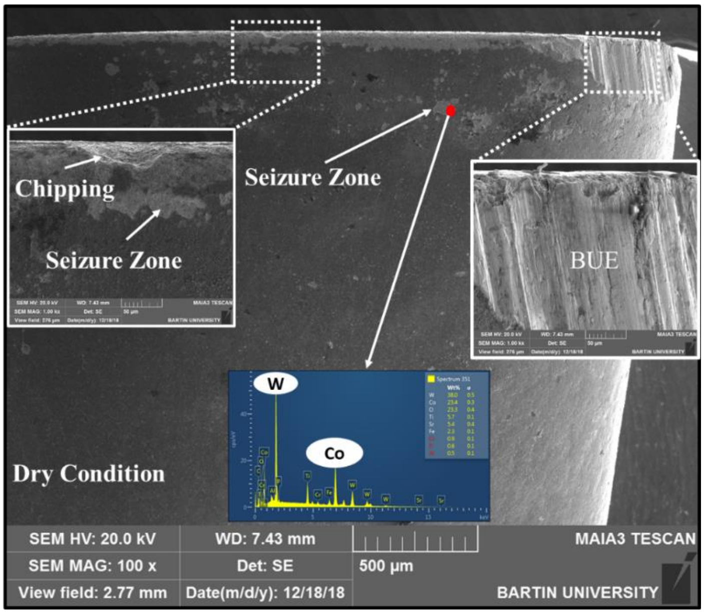

Figure 5. Worn cutting tool SEM image under dry condition

Figure 6 shows the SEM image of the worn cutting tool after milling in MQL conditions with 1% h-BN containing cutting fluid. After milling with cutting fluid containing 1% h-BN, BUE formation was not observed in the wear zone compared to dry conditions. Chipping was observed in the wear zone due to intermittent cutting. Seizure zone formation has also occurred in the use of 1% h-BN including cutting fluid as in the case of dry milling. The reason for the Seizure zone formation is that the chips at high temperatures adhere to the flank surface of cutting tool and the adhered chips break away with the coating layer in the progressive cutting stages. According to the results obtained from the EDS analysis applied to the worn cutting tool, it was observed that the thin hard film coating was removed.

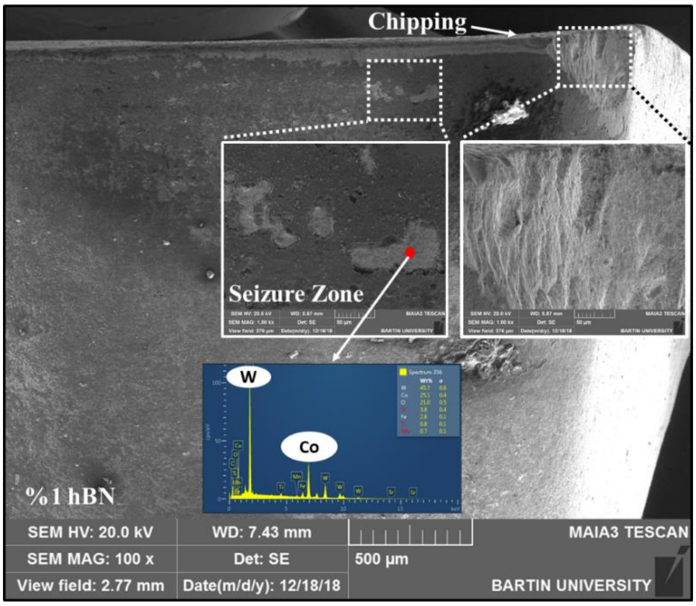

Figure 6. SEM image of worn cutting tool using %1 h-BN added cutting fluid

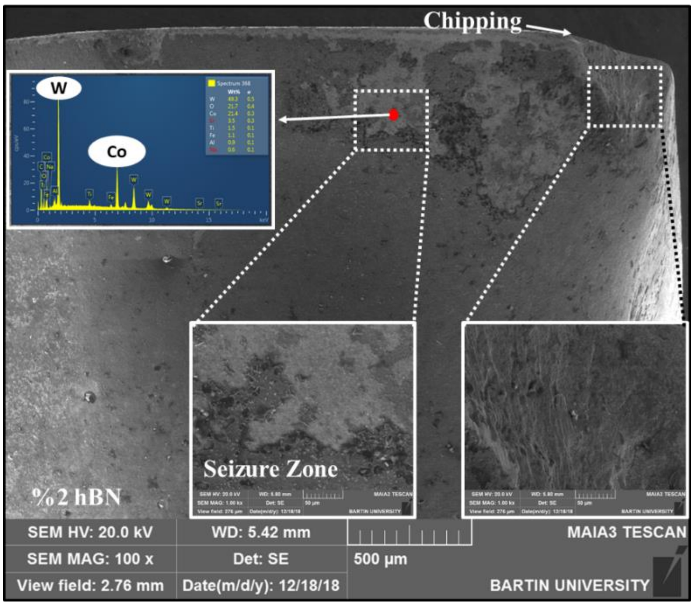

Figure 7. SEM image of worn cutting tool using %2 h-BN added cutting fluid

Figure 7 shows the SEM image of the worn cutting tool after milling in MQL conditions with 2% h-BN containing cutting fluid. Similar to the milling process using 1% h-BN added cutting fluid, the BUE in the wear zone was not observed due to the temperature in the cutting zone is reduced with using cutting fluid. Seizure zone formation was also seen this worn tool similar to worn tools that occur under different conditions. According to EDS analysis taken from Seizure zone, it is observed that the coating material is deformed.

4. Conclusions

In this study, the use of an innovative cutting fluid in milling of AISI O2 workpiece as an alternative to cutting fluids which are highly harmful to the environment and human health and used in high amounts in the manufacturing sector have been investigated. Nano-size h-BN was added to ethylene glycol and used as cutting fluid in milling operations of AISI O2 with MQL system. The findings obtained from the study can be summarized as follows;

- The highest cutting tool life was obtained by using 2% h-BN added cutting fluid. The increase in cutting tool life was approximately 78% compared to dry conditions. Similarly increase in cutting tool life was approximately 46% compared to using %1 h-BN added cutting fluid. According to the values obtained after milling for three different condition, cutting tool life increased with the effect of h-BN used in cutting fluid.
- In terms of surface roughness, the best workpiece surface quality was achieved after milling with h-BN containing 2% h-BN. The improvement in surface roughness value was approximately 60% using 2% h-BN-containing cutting fluid compared to dry conditions. The surface roughness value was reduced by approximately 20% in the milling process with h-BN containing 1% h-BN compared with the dry condition. As a result, as the amount of nano h-BN used in the coolant increased, the workpiece surface roughness values were improved.
- In the milling of AISI O2 steel with using MQL system, the cutting forces are reduced by the use of cutting fluid and by the increase in the amount of h-BN in the cutting fluid. The lowest resultant cutting force values were obtained in the milling process using cutting fluid containing 2% h-BN. In addition, the use of h-BN reduced the vibration of the workpiece and in this way, surface roughness values were improved.
- Dominant wear mechanisms have been found to be adhesion and abrasion for both condition. Seizure zones have been observed due to high temperature for both condition on flank face of cutting tools. In dry milling operations, BUE has been observed in the wear zone due to higher temperature than milling operation using cutting fluid.

According to the findings, it was observed that the nano h-BN added cutting fluid, which is harmless to the environment and human health, increased the cutting performance in milling AISI O2 steel. In further studies, the effect of prepared nano h-BN added cutting fluid on the cutting performance in the machining of hard to cut materials can be examined.

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