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ORIGINAL ARTICLE

Assessment of the effect of borax and boric acid additives in cutting fluids on milling of AISI O2 using MQL system

Bilal Kursuncu[1] · **Ali Yaras**[2]

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Abstract The present study assesses the effects of eco-friendly cutting fluids prepared on cutting performance and tool wear in hard milling of AISI O2 cold work tool steel applying the minimum quantity lubrication (MQL) technique for sustainable manufacturing. Boron compounds such as boric acid (BA) (5% wt.) and borax (BX) (5% wt.) as additives were added to ethylene glycol (EG) of base fluid. For the purpose of comparison, commercial boron oil was utilized in addition to the dry machining as a benchmark using MQL method. The lowest surface roughness value (0.411 μm) was reached in the cutting fluid containing BA. Compared with the dry condition, the surface roughness value was determined to be improved as 52 and 38% in cutting fluids containing BA and BX, respectively. The highest tool life was measured as a cutting length of 3.15 m in the cutting fluid containing BX. According to the experimental results, a raise of tool life occurred in cutting fluids prepared using both BA and BX. Compared with dry condition, tool life was increased by 110% with cutting fluid prepared by BA and by 50% by cutting fluid prepared by BX. The cutting forces decreased with cutting fluids containing both boron compounds. After milling process, the wear type and mechanism of the cutting tool were analyzed by scanning electron microscopy (SEM) aided with energy dispersive spectroscopy (EDS). Furthermore, it has been found that the diffusion and abrasion are dominant wear mechanisms on cutting tools, all the cutting fluids studied. Consequently, the promising results were obtained by adding boron compounds, which are harmless and non-toxic to human and environmental health, to cutting fluid-based EG for improving machinability of AISI O2 cold work tool steel.

Keywords Minimum quantity lubrication · Hardmilling · Boric acid · Borax · AISI O2 · Tool wear · Cutting performance

✉ Bilal Kursuncu
bkursuncu@bartin.edu.tr; bilalkursuncu@gmail.com.tr

Ali Yaras
aliyaras@bartin.edu.tr; ayaras01@gmail.com

[1] Faculty of Engineering, Mechanical Engineering Department, Bartin University, 74100 Bartin, Turkey

[2] Faculty of Engineering, Metallurgy and Material Engineering Department, Bartın University, 74100 Bartin, Turkey

1 Introduction

The development of clean production methods has become very significant due to environmental factors nowadays. The clean production methods deal with the reduction of pollution caused by cutting or lubrication fluids utilized in various manufacturing processes [1]. The usage of cutting fluids in conventional metalworking systems is important to decrease the high temperatures and cutting forces that occur during process [2]. The cutting fluid minimizes the thermal or mechanical damage that occurs in the machining process because of its physical and chemical properties. The utilization of cutting fluid also serves to cooling as well as lubrication to reduce friction and removal of chips from cutting zone during the process. Thereby, it may be possible to positively affect the tool life and surface quality of machined surface. However, it should also be noted that the usage of cutting fluid, especially in cases of mineral-based oils, has some deleterious effects in terms of environmental/human health and process costs [3–7]. Therefore, researchers have focused on the utilization of environmentally friendly cutting fluids which are less harmful, biodegradable, less toxic, and have sufficient performance in machining process in recent years [8, 9].

Hard milling process is a widely used technology in the machining of high hardened, > 45 HRC [10], and strength materials [11, 12]. One of the most important disadvantages of this process is the formation of high amount heat in cutting zone as a result of the friction that occurs at the interface of the cutting tool and workpiece, the wear occurs on cutting tools. Consequently, the formed high heat causes an increase in temperature in the cutting zone and occurs rapidly wear in the cutting tool depending on diffusion and oxidation wear mechanisms. Due to tool wear, tool life is reduced and the quality of the machined surface is deteriorated. Therefore, keeping control of tool wear is critical to avoid undesirable catastrophic tool failure [13]. As a result, the parameters such as tool life, tool wear, cutting forces, surface roughness, which are very important in the machining industry, have been investigated by many researchers in the hard milling process [11, 14, 15].

In terms of sustainable manufacturing in hardmilling process: there are various methods used such as dry machining, machining with conventional, and cryogenic cooling, MQL at the present time [16–18]. Dry machining is the environmentally friendly as well as extremely low cost in terms of cooling. However, the adverse effects of dry machining in hardmilling process are much greater in the case machining of high strength and high hardness materials by conventional cutting tools [19, 20]. There are numerous studies to overcome these problems in literature using hard thin-coated cutting tools under dry machining [21, 22]. For this reason, MQL method in hardmilling process of metal and composite materials is generally preferred because of superior advantages such as technological, environmental, and economic aspects [11, 12, 23, 24]. Ginting et al. [25] compared the conventional and MQL methods in the machining of the AISI 4340 steel and observed a reduction in manufacturing cost with lower power consumption and machining time compared to the conventional method in the cutting process. Sohrabpoor et al. examined the effects of AISI 4340 stainless steel on the cutting performance of conventional, dry, air cooled, and MQL systems. After the turning, the most effective method was found to be MQL in terms of tool wear and surface roughness [26]. In another study, the influence of the MQL method on the cutting performance of the AISI 1040 steel with uncoated carbide tools studied and determined a raise in cutting performance due to the temperature decrease in the cutting zone [43]. In the MQL technique, the drops directly contact with the cutting zone and a thin tribofilm layer forms on cutting tool surface which helps to reduce the friction and the formed heat in the cutting zone [11, 13, 27]. This method is preferred because it is comparable, if not better, than the cutting performance obtained by conventional flood cooling [28–30]. Another innovative aspect of the MQL method, the amount of used cutting fluid is rather low compared to conventional methods. While the cutting fluid used in the conventional methods is 1200 l/h [31], it can be decreased to 50 ml/h [32] in the MQL system. M. Rahman et al. indicated that, when compared to the cutting performance, the 25,260 ml/h cooling fluid used in end milling process using the conventional flood cooling method was reduced to 8.5 ml/h by the MQL technique [33].

In recent years, a great number of studies have been carried out in which different nanoparticles are added to the cutting fluid in order to increase the efficiency of the MQL system in the metalworking process [34, 35]. It is desirable that the cutting fluids utilized in the MQL system have the following characteristics for high-performance cutting operation. These characteristics are biodegradable, high lubrication, and high stability [2]. In the MQL system, vegetable and synthetic oils are often preferred because of their biodegradability [36–38]. On the other hand, solid particles which have high thermal conductivity such as Al_2O_3, MoS_2, and graphite are added to the cutting fluids to enhance in terms of cutting performance [39]. In addition, the nanoparticles fill the gaps in the cutting zone to prevent material loss [40–45].Especially, BA is used as a solid lubricant in machining processes since it is cheaper than other lubricants and effective to wear and friction nowadays. It is known that this effect is due to the formation of a protective film layer in the cutting zone of the nanoparticles [46, 47].

The aim of this study is to investigate the influence of the boron compounds-added cutting fluid in the MQL system on wear resistance of the protective layer on the cutting tool. The innovative aspect of the work is that the cutting fluids obtained with the additives utilized in the milling of the AISI O2 steel using the MQL system for the first time. At the light of obtained findings, it can be stated that the boron compounds can be used effectively in the various cutting fluids in the milling of the AISI O2 cold work tool steel by MQL system, and alternative to cutting fluids due to their low-cost and non-toxic properties.

2 Material and Method

2.1 Preparation of cutting fluids

Boric acid (H_3BO_3) and borax decahydrate ($Na_2B_4O_7 \cdot 10H_2O$) used in the experiments were supplied from the Eti Maden in

Table 1 Some properties of chemicals used in experiments

Chemical	Property	Value
Boric acid	Specific weight	1.51 g/cm^3 (20 °C)
	Molecular weight	61.83 g/mol
	Melting point	450 °C
Borax	Specific weight	1.71 g/cm^3 (20 °C)
	Molecular weight	381.37 g/mol
	Melting point	741 °C
Ethylene glycol	Molecular weight	62.07 g/mol
	Density	1.1130 g/cm^3
	Viscosity	20.9 cp (20 °C)

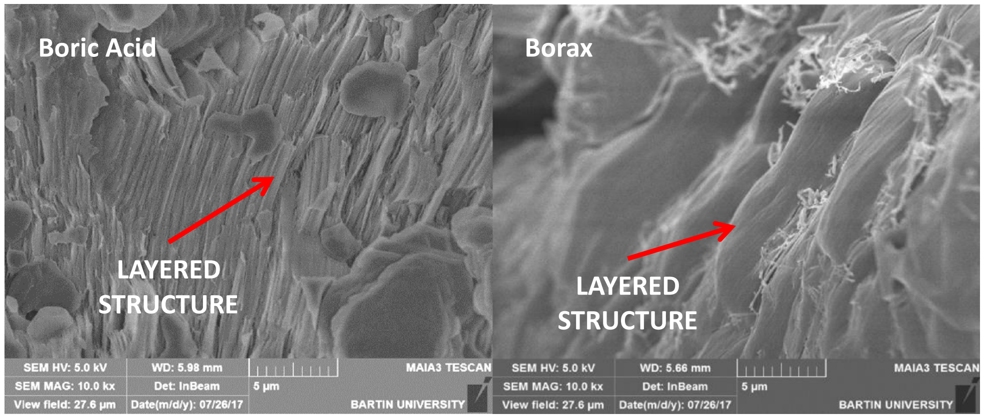

Fig. 1 SEM images of boron compounds

Turkey. Analytic grade ethylene glycol ($C_2H_6O_2$) and commercial boron oil (Houghton Sitala D 201.03) were purchased from Merck and a company, respectively. Some properties of abovementioned chemicals are given in Table 1.

The cutting fluids containing boric acid (5% wt.) and borax (5% wt.) were prepared using desired volume of ethylene glycol (EG), separately. Commercially boron oil (5% *v*/*v*) is prepared by diluting with distilled water. Prepared cutting fluids were stirred for homogeneity by a mechanical stirrer for 10 min. at 300 rpm and room temperature. SEM images of both boron compounds used in the preparation of cutting fluids are represented in Fig. 1. As seen from Fig. 1, it is clear that BA and BX have layered structures. Moreover, these compounds are lubricant materials due to their relatively high load-carrying capacity and low steady-state coefficient of friction [48].

2.2 Workpiece material

The chemical composition of the workpiece material used in face milling tests is shown in Table 2. AISI O2 cold work steel is widely used in manufacturing of dies and molds [49]. Workpiece material dimensions are specified as 150 mm × 100 mm × 80 mm. Three different holes were drilled on the workpiece so that it could be rigidly connected to the dynamometer.

2.3 Machine tool, cutting tools, MQL system, cutting tests

Sintered carbide cutting tools with the code (R390-11 T3 08M-KM H13A) supplied from SANDVIK company. These cutting tools are coated TiN hard coating by another company. The R390-025A25-11L coded tool holder to which the cutting tools mounted is 25 mm in diameter and has two flutes. Although the tool holder has two flutes, only one mouth was connected to the cutting tool to eliminate run out problem. Falco VMC 855-B CNC three-axis vertical machining center was used for face milling experiments. The experimental set-up is seen in Fig. 2.

Table 2 Chemical composition of AISI O2 cold work steel (% wt) [49]

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

In the milling test, as the MQL system (Werte Mikro STN 25), with a lubricating range of 0.0021–0.028 ml, operating at a pressure range of 4–6 bar was used.

After milling tests, a stereo zoom microscope (Vision SX45) supported by computer software was used to determine the tool life of sintered carbide cutting tools. After each cutting pass, the tool holder was taken off the CNC machine, and the wear amount measured on the cutting tool through the image obtained by the microscope software was measured. SEM (MAIA3 TESCAN) in combination with EDS was used in order to analysis of the wear mechanisms of the cutting worn tools.

The surface roughness R_a value was measured at seven different points on the workpiece surface after each cutting pass (150 mm) using Mitutoyo Surftest SJ-310 stylus-type instrument.

Fig. 2 Experimental setup

Table 3 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 of cutting fluid	50 ml/h

Kistler multicomponent dynamometer up to 10 kN type 9257B was used for measuring cutting forces. For multicomponent force measurement, Kistler 5070 multichannel charge amplifier was used, and for data analysis and visualization software (Kistler DynoWare) was used. The cutting force components *Fx*, *Fy*, and *Fz* were measured using this system.

Cutting parameters used in face milling tests were determined by considering the manufacturer's catalog and previous scientific publications [49] are given in Table 3.

3 Results and discussion

3.1 Tool lifetime and wear analysis

TS ISO 8688-1 standard [50] has been used to determine tool life of cutting tools. The sintered carbide cutting tool is considered to have completed its tool life when the notch wear length reaches 0.25 mm. After face milling tests, the tool life obtained with different coolant combinations is shown in Fig. 3. According to the results obtained, the lowest tool life was obtained with dry conditions. The tool life achieved as a result of milling applied in cutting fluid containing only EG has increased somewhat with respect to dry condition and commercial cutting fluid. The highest tool life was also obtained with BX-added cutting fluid. As a result of the milling tests with a cutting fluid containing EG and BX, it can be said that the increase in tool life is due to the high thermal conductivity of BX [3, 4, 46]. Similarly, it has been observed that the cutting fluids containing BA increases the tool life. When the cutting fluids prepared were evaluated in terms of tool life, it was observed that the addition of both boron compounds had a positive effect because of the high thermal conductivity coefficient of the boron element.

In order to determine the wear type of the cutting insert with the highest tool life, SEM with EDS feature was used. As abovementioned, the highest tool life was reached to cutting fluid containing BX. It is thought that the notch wear type that occurs at the wear zone is due to the oxidation, and diffusion wear mechanisms (Fig. 4) [51]. As it is known, there are fluctuations in the cutting forces obtained due to the intermittent milling process. This force fluctuates and the stress accumulates in the cutting zone, causing chipping wear type. Another drawback in the wear zone is the formation of built-up-edge (BUE) and EDS analysis confirms this situation.

3.2 Surface roughness

Surface roughness is an important indicator in determining the quality of the machined surface and varies with increasing tool wear [11]. In this study, surface roughness values were calculated as the average of the values obtained during the tool life of the cutting tool from machined surface at the end of the surface milling tests applied with four different cutting fluids shown in Fig. 5. Compared to the surface roughness values as a result of milling tests applied in dry conditions, commercial, and only EG-containing cutting fluid, it is clearly seen that there is no significant difference between them. The lowest value was obtained with a cutting fluid prepared with BA. This state may be attributed to the boron compounds added to EG enhance surface roughness values of workpiece machined surface by lubricating effect of boron element [48, 52].

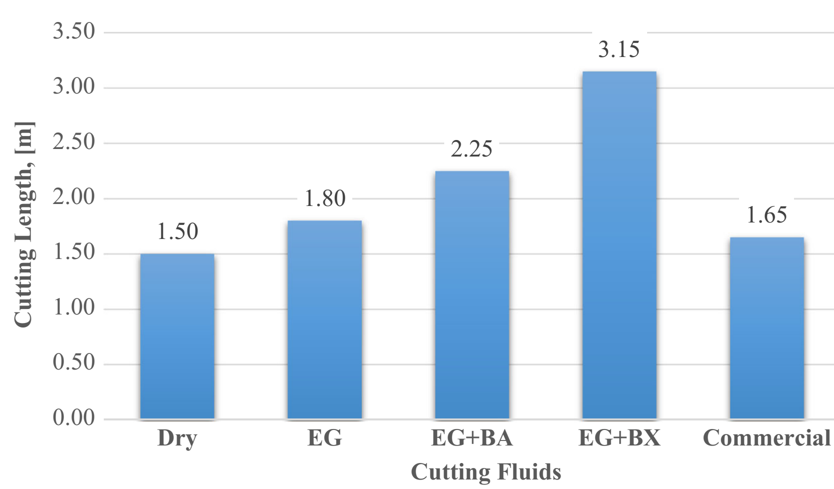

Fig. 3 Comparison of cutting tools' lifetime

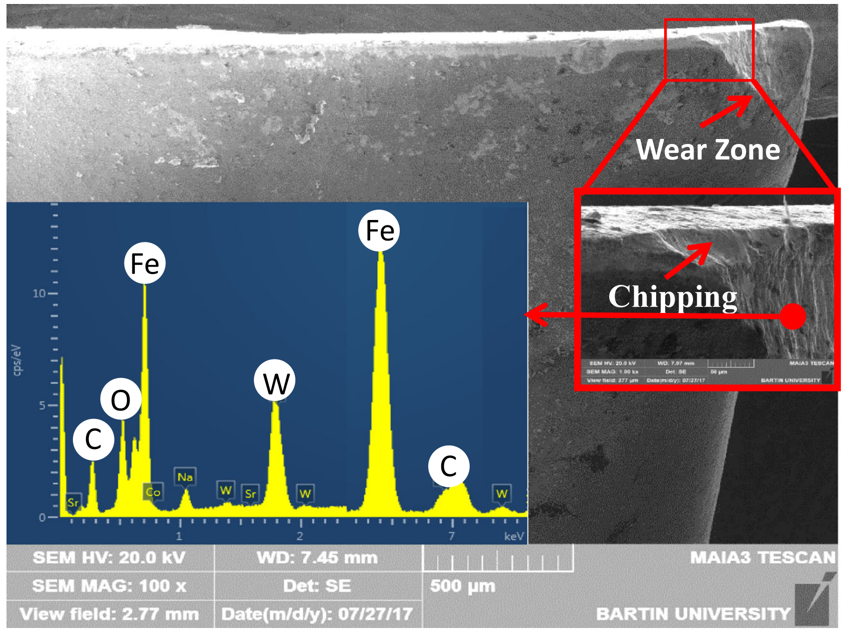

Fig. 4 SEM image and EDS analyses of the worn carbide cutting tool

3.3 Cutting forces

Cutting force waveforms of F_R obtained at the end of the surface milling tests applying different cutting fluids and under MQL conditions are shown in Figs. 6 and 7. These values in the graphs are the values in the 10th pass of the milling tests applied with each cutting fluid. Cutting forces in the machining are directly related to wear of the cutting tool, and as the amount of wear increases on the cutting tool, the cutting forces increase [53]. As is known, in consequence of the intermittently of the milling process, fluctuations occur in the cutting force values obtained [54]. Compared to dry conditions, commercial boron oil, and cutting fluid-only EG (Fig. 6a–d), it can be said that the reduction of the friction coefficient because of the protective layer formed between the workpiece and the tool causes decrease in the resultant cutting forces-based EG cutting fluid than the others [55]. Similarly, it is clearly seen that BA and BX have positive effect on cutting forces because of additives boron compounds in based-EG cutting fluid (Fig. 6b, c). It was observed that cutting forces were reduced with all cutting fluids used.

Graphs of the F_R cutting force fluctuations obtained after surface milling using the other prepared cutting fluids except for dry condition comparisons are shown in Fig. 7a–d. Accordingly, it can be said that the BA and BX elements added to the EG have a positive effect on the cutting forces as a result of decreasing the coefficient

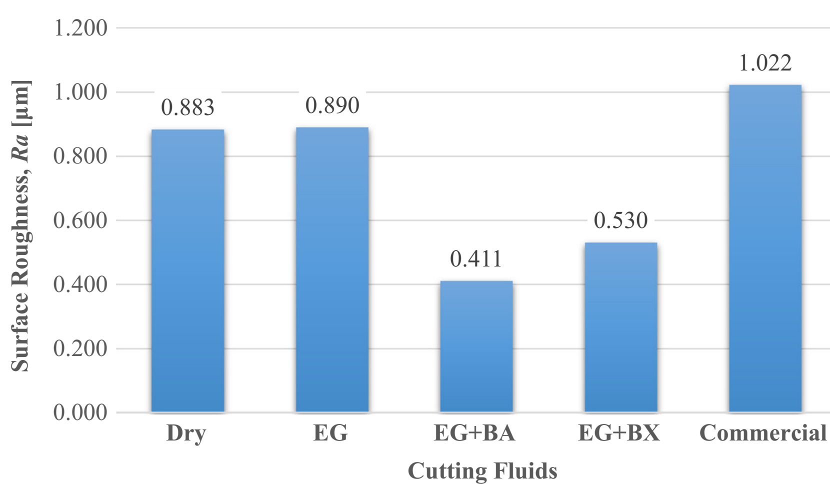

Fig. 5 Comparison of surface roughness

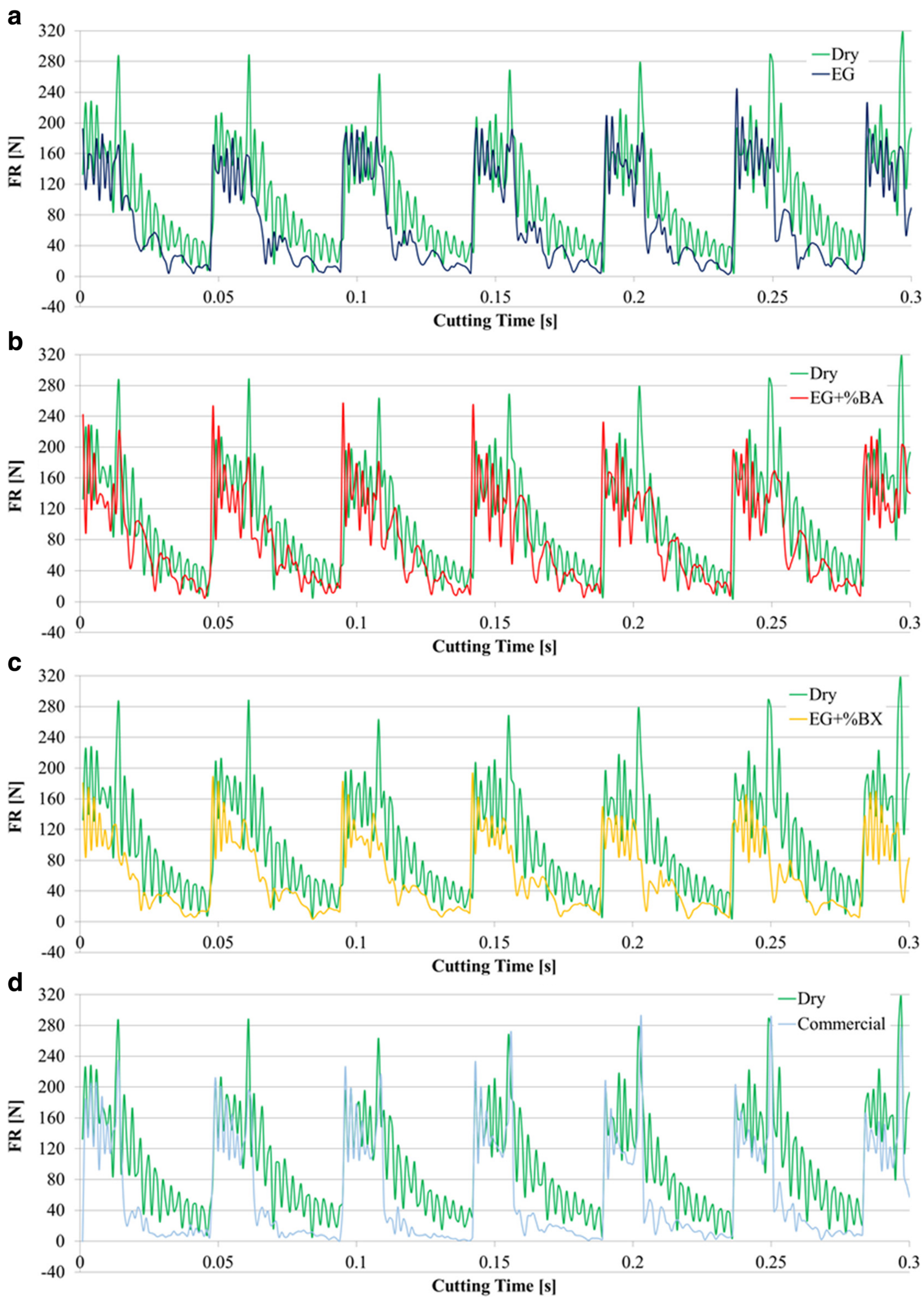

Fig. 6 Comparison of F_R cutting force fluctuations obtained with dry conditions and EG-based cutting fluids

of friction in the cutting zone due to the high-thermal conductivities of the boron compounds and their lubricating properties [39, 48, 52]. It is seen that the cutting forces obtained with additives BX and BA

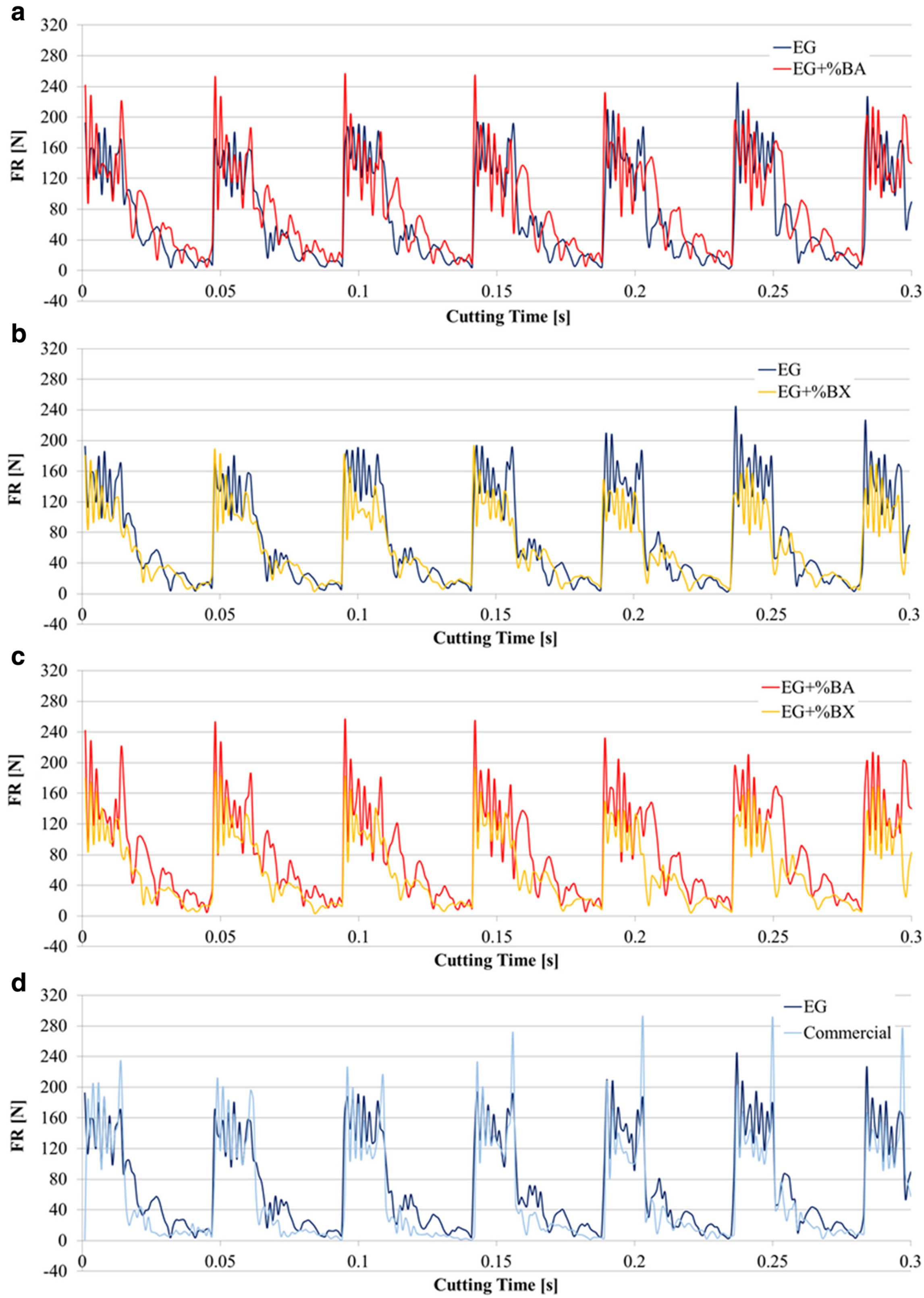

Fig. 7 Comparison of F_R cutting force fluctuations obtained EG-based cutting fluids

compounds to EG are lower than those acquired by cutting fluid added with BX when they are compared with each other in terms of cutting forces obtained after milling applied with cutting fluids.

4 Conclusions

In present study, the influence of EG cutting fluids containing both boron compounds additives on the cutting performance on milling of AISI O2 cold work tool steel was examined using the MQL system.

It is considered that the prepared cutting fluid forms a protective layer on the cutting tool during the process and accordingly the tool life is increased. Furthermore, the cutting force values are less than dry conditions since the protective film maintains the sharpness of the cutting tool. Based on the lubricating effect of the cutting fluids prepared with both boron compounds, it can be clearly stated that the surface roughness of the workpiece surface reduced.

The following conclusions have been reached after this study:

- With boron compounds added to the cutting fluid, the tool life of the sintered carbide cutting tools is increased. The highest tool life (3.15 m) was achieved after milling with BX-added cutting fluid. Compared with dry conditions, tool life was increased by 110% with cutting fluid prepared by BA and by 50% by cutting fluid prepared by BX.
- A smoother workpiece surface was obtained with the tests applied with boron-added cutting fluids. The lowest surface roughness value (0.411 μm) was attained with BA added cutting fluid. Surface roughness value improved by 52% with cutting fluid prepared by BA and about 38% by cutting fluid prepared by BX when compared with the value obtained in dry condition.
- The cutting force values decreased with used cutting fluids. Relatively low cutting forces have been obtained in tests made with boron compounds-added cutting fluids.

The results illustrated that boron-added cutting fluids perform better than commercially available cutting fluids under MQL system. Boron compounds will be a good alternative to conventionally cutting fluids because of their properties of biodegradable, non-toxic, and low cost to the environment and human health. In subsequent work, the effect of different boron compounds on cutting performance can be examined in the machining of different hard-to-cut materials.

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