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Original scientific paper

Nano MoS_2 Application in Turning Process with Minimum Quantity Lubrication Technique (MQL)

Şafak SERTSÖZ, Alaattin KAÇAL*

Abstract: In this study, nano-sized MoS_2 was mixed into coolant and was turned with GGG-70 spheroidal graphite cast iron. Surface roughness and tool wear were analyzed and effects of nano-MoS_2 on machinability were investigated. Cutting tests were carried out at 350 m/min cutting speed, 0.2 mm/feed rate and 4 mm cutting depth. Surface roughness (*Ra*) values and cutting tool wear obtained under dry cutting, conventional cooling, Minimum Quantity Lubrication (MQL) and 3 different nano-MoS_2 added MQL conditions were investigated. Highest average *Ra* value was obtained under dry turning conditions. Roughness value decreased at conventional cooling, MQL and nano MoS_2 added MQL conditions. A 37% reduction in *Ra* was obtained with respect to dry processing conditions. The lowest *Ra* 7 bar pressure, 160 ml/min flow rate and MQL + 1.5% nano-MoS_2 spray was measured at 0.99 µm.

Keywords: MQL; surface roughness; tool wear; turning

1 INTRODUCTION

Spherical graphite cast irons (SGCI) are widely used in production of machinery and automotive parts such as gears, cams and crankshafts. Machining methods are generally used to finalize parts produced from SGCI materials [1]. Significant heat is generated in all machining operations due to plastic deformation of workpiece, friction at tool-chip interface and friction between cutting tool cavity surface and workpiece. This heat generation can reach temperatures between 350 °C and 1000 °C and even varies between higher temperatures. Increasing demands for high productivity are put to machining at high cutting speeds and feed forward. Parameter selection in this direction naturally produces a high cutting temperature [2, 3]. The heat generated in machining process adversely affects quality of workpieces done (dimension accuracy and surface quality). At the same time, occurring heat causes impacts on workpiece, rapid wear of cutting tool and plastic deformation. Therefore, it is essential that heat generated in the machining process be removed quickly from cutting zone [4]. For this purpose, suitable coolants for the type of operation (turning, milling, grinding, etc.) are used. It is desirable to significantly improve both tool life and workpiece quality. Cutting fluids affect process performance in metal removal operations as a result of their functions of lubricating, cooling and removing chips during operation from operation area [5, 6].

In the use of conventional coolant in manufacturing processes (machine tool's own coolant system); negative effects of the use of cutting fluids reveal tendency of users to move away from cutting fluids. If they are not disposed of properly, they may damage working personnel, soil and water resources and cause significant losses for the environment. For this reason, environmental regulations must be observed in handling and disposal of coolants [2, 7].

When machining costs are considered, it is known that cutting fluids cost much more than cutting tools [8]. In this case, the issue that should be considered with precision is to shape high-strength materials in a short time with desired sensitivity without damaging the environment by using alternative methods of metal removing and machining processes. Minimizing the use of coolant also provides economic benefits by saving lubricant costs and cycle time for workpiece/tool/machine cleaning. In recent years, trends in both manufacturing industry and academic studies have shown an increase in less or no use of coolant [9]. MQL is also a method developed for this purpose [2]. MQL is basically spraying a small amount of oil mixture with compressed air at cutting point so that cooling lubrication is carried out with very little lubricant. When MQL is applied, it is seen that lubricant quantity and performance are significantly saved. Production times on machine tools can be reduced by up to 30% and cutting tool life can be increased with MQL [10]. In addition, waste and recycling costs after machining are greatly reduced. A cleaner, healthier and safer working environment is achieved. It is seen that MQL is used effectively in cutting operations such as turning, milling, reaming and drilling. When availability of coolant to cutting edge is considered, two types of applications as external and internal stand out in MQL systems. In the external case, lubrication is applied around cutting tool by means of spray tip. It is recommended to apply this system in standard operations (turning, milling, drilling). In the internal feed, oil is transported through spindle system of the machine and channels in the machining point [11, 12]. Attanasio et al. tried to investigate benefits of minimum amount of lubrication for reducing cutting tip wear. As a result of performed tests and SEM analysis, they showed that applied MQL can increase tool life [9]. Chinchanikar and Choudhury discussed use of coolant in hard turning (55 HRC) of coated carbide cutters. They stated that MQL's contribution to turning is more pronounced, especially at a cutting speed of 150 m/min [13]. In wet, MQL and dry study performed with AISI 420B stainless steel, it was stated that lubrication technique does not significantly affect tool wear [14]. In their study, Shokoohi et al. evaluated application of environment and user-friendly MQL system in turning AISI 1045 steel in terms of surface roughness, consumed power and chip formation and obtained successful results [15]. Khan et al. evaluated effects of MQL using vegetable oil on AISI 9310 steel in terms of surface roughness. MQL gave positive results compared to other cooling conditions. Chip-tool interface temperature decreased [16]. Results of the research on the effect of MQL on cutting zone temperature, tool wear and surface roughness in the processing of AISI 4340 steel material also provided benefits for improving tool wear [3]. Hwang & Lee conducted a research on MQL and wet turning processes of AISI 1045 steel. Cutting force and surface roughness were measured according to cutting parameters. Mathematical equations and optimal cutting parameters were proposed using experimental results and regression analysis [17]. Carou et al. experimentally investigated intermittent turning of UNS M11917 magnesium alloy under different machining conditions. At different machining conditions, they determined cutting speed, cutting depth, feed rate as well as dry machining and MQL method conditions. They reported that use of MQL slightly caused worse surface roughness at high rates of feed [18]. In Leppert study effect of cooling on cutting zone and lubrication on rough surface were investigated in production of coolers and pipes. Dry cut and MQL results were compared [19]. Settineri presented a study to machine nickel-based super alloys in MQL or dry conditions in his study. Significant agreement was found between MQL results and tribological and adhesion/toughness tests [20]. Hadad and Sadeghi investigated effects of MQL nozzle position and cutting parameters (such as cutting speed, cutting depth, and feed rate) on turning performance of test parameters. The results provided a model for average temperature formations and temperature zones of MQL during turning. This model can also be used in other turning operations [21]. Padmini et al. focused on vegetable oils in turning of MQL application of AISI 1040 steel. Nano molybdenum disulfide ($nMoS_2$) with coconut (CC), canola (CAN) and sesame (SS) oils were prepared at different solutions for use in nano cutting fluid. They found that 0.5% CC + $nMoS_2$ performs better compared to other lubrication conditions. When compared with dry method turning, it was observed that cutting force decreased by 37%, temperature by 21%, cutting tip wear by 44% and surface roughness by 39% [22]. In some studies related to MQL, it is seen that nanoparticles such as hBN, SO_2, CuO, SiO_2, Al_2O_3 are used [23-25].

When the above mentioned studies are evaluated, it is seen that there are many studies about minimum lubrication and cooling process. In these studies, cutting fluid type, flow rate, pressure, nozzle type, insertion angle, material, cutting parameters, processing processes and more recently additive materials to coolants are discussed. This study was planned based on the assumption that minimum lubrication in turning GGG 70 material and nano MoS_2 powders added to fluid will have a positive effect on machinability. Solid lubricity of MoS_2 is an important element that can support the hypothesis. Actual manufacturing conditions and environment were taken as basis for planning and conducting experiments. In addition, when determining materials and equipment, principles of using in manufacturing industry and easy access are followed. Surface roughness and cutting tool wear were determined as evaluation criteria.

2 MATERIALS AND METHODS

It is aimed to prevent tool wear and bad surface properties that may occur when turning at high chip volumes in a crane manufacturing sector where GGG70 material is used intensively. For this purpose, nano-sized MoS_2 was mixed into the MQL and coolant; effect of MQL on tool wear and roughness of the turned surface was evaluated in turning GGG-70 spheroidal graphite cast iron. In Fig. 1, the experimental procedure is schematized.

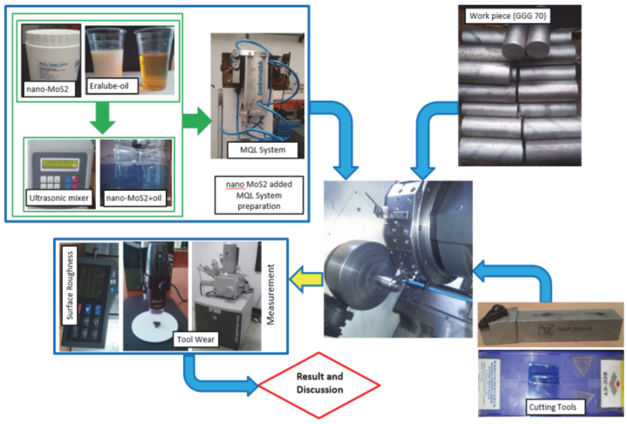


Figure 1 Experimental Procedure

Bielomatik B1-210 series MQL device was used in the experiments. With the system used, a small amount of coolant is mixed with compressed air and sprayed to cutting zone. Pressure and flow rate of the fluid were adjusted by means of valves on the device. Mineral, synthetic ester and vegetable-based cooling oils can be used in this MQL. Emulsifying oils (mixed with water) may also be used. In turning tests, 6 mm diameter flexible hose was used to reach coolant to cutting zone. It is ensured that mixture is sent to cutting zone without any nozzle attached to pipe end. Correct positioning of the pipe is important to ensure adequate spraying in cutting zone. In the literature, it is seen that MQL spraying is directed to tool surface and/or side surface during turning operations. It is recommended that spraying focuses between tool-chip. Adjusting distance of spray tip to cutting zone to closest distance (approximately 30 mm) permitted by turning process is effective in cooling and lubrication [2, 9, 26]. Spray positioning conditions used in the study were determined as in Fig. 2.

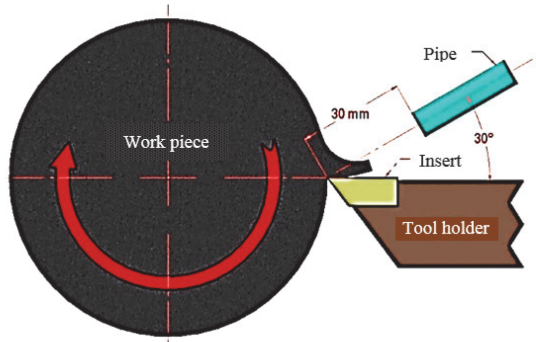


Figure 2 Spraying position of MQL

Cutting fluid, which is an important variable of the study, was preferred to emulsified oils. Emulsified oils are widely used in manufacturing sector. ERALUBE$_{TM}$ BIO CF 350 oil, which can be mixed with water in certain proportions, was chosen. This oil is a high performance, semi-synthetic cutting fluid developed for medium and heavy machining operations of all alloyed and non-alloyed metals. Recommended mixing ratio is between 5% and 6% [27]. MoS_2's solid lubricant feature enables incorporation of greases used in pressure, high temperatures and loads. Nano MoS_2 powders used were 90 nm in diameter, 99.9% purity and spherical. Firstly, it was mixed with water and $ERALUBE_{TM}$ BIO CF 350 according to mixing ratio of 5% (1:20). The mixture was divided into 5 equal portions. Three of these fractions were mixed with different proportions of MoS_2. One of them was used for pure MQL and the other one for conventional cooling. Within the framework of test parameters, nano MoS_2 powders were weighed at 0.5-1% and 1.5% by weight on a precision balance and mixed into coolant with an ultrasonic mixer. It is suggested that the most suitable method of mixing such nanoparticles with ideal homogeneity in the fluid is ultrasonic mixing [28]. Sonics Vibracell VCX-750 ultrasonic mixing device was used for mixing MoS_2 into coolant. For optimal dispersion, an ultrasonic stirring process time of 40 minutes was applied. MoS_2 powders, which were initially in the form of pellets, were dispersed homogeneously into liquid after mixing.

GGG-70 spherical graphite cast iron was used in turning experiments. Its mechanical properties are close to steels and has good castability. Therefore, they are widely used in parts where high strength and abrasion resistance are expected [29]. GGG-70 has satisfactory machinability and surface quality. It also has sound and vibration damping. They are preferred for high-strength gears, automotive and machine gears and wheels of roof cranes [30]. Test samples were cast at Ø60 × 160 mm. Before turning tests, casting surfaces were turned to 56 mm diameter. In turning tests, working length was taken as 90 mm. Chemical and mechanical properties of GGG-70 are given in Tab. 1.

Table 1 Mechanical and chemical properties of GGG-70

Chemical Analysis / %	C	Si	Mn	S	Mg	P	Balance
	3.842	2.301	0.141	0.016	0.050	0.022	--
Mechanical Properties	Tensile Strength				661.40 N/mm^2		
	Yield Strength				416.27 N/mm^2		
	Hardness				271 HB		
	Density				7		
	Percentage Elongation				1.94		
	Matrix Structure				Perlitic		

Experiments were carried out on a HYUNDAI WIA L300A CNC lathe with 18.5 kW engine power and 3600 rpm. As with machining other materials, correct selection of inserts is important for machining of spheroidal graphite cast irons. Characteristics of cutter suitable for GGG-70 are similar to those of cast irons. High red hardness, chemical stability, toughness, resistance to thermal impact and strength are the required properties [31]. In turning experiments, multi-layer coated carbide inserts with PVD method coded TNMG 160408 produced by ZCC.CT were used. These inserts are moderately capable of good chemical and thermal stability, wear resistance and toughness, while being first choice for stainless steels and second choice for steel and cast irons. It is recommended to select tip radius as large as possible under conditions where stiffness and chip formation are favorable in terms of insert geometry. Considering general tendency to use, insert radius was specified as 0.8 mm for this study [28]. SMOXH brand 93° approach angle MTJNR-2525 M16 coded tool holder was selected for these mechanically held interchangeable inserts.

Surface roughness after each turning test was measured to determine turning quality and factors affecting it. Ra measurements were made from three different regions of machined surface at 120° intervals and their averages were evaluated. Roughness measurements were made with TIME TR200 tracer end type roughness tester. Sampling length was 0.25 mm and evaluation length was 1.25 mm. After experiments, photos of inserts were taken using INSIZE electronic microscope in order to interpret effects of MQL with and without MoS_2 on inserts in terms of tool wear. Following evaluation of these photographs, scanning electron microscopy (SEM) photographs of inserts that need to be examined in depth were taken with SEM device in KDPU-ILTEM. Formed W wear types and mechanisms were evaluated with the help of these photographs.

Firstly, cutting parameters and details to be used in turning, given in the literature review [32], were determined by evaluating recommendation information of insert. In this context, after experimental tests were performed, appropriate cutting parameter alternatives were determined. These cutting parameters were kept constant in experiments. One cutting edge was used in each experiment. Turning tests were carried out at 4 mm cutting depth. After taking averages of measured roughness values, graphs were prepared to determine relationship of results with parameters. Electronic microscope, SEM and EDX results were investigated to determine tool wear type and mechanisms. Experimental parameters are given in Tab. 2.

Table 2 Experimental Parameters

Changeable Parameters				
Parameters	Levels			
	1	2	3	4
Dry	✔	----	----	----
Cooling	✔	----	----	----
MQL methods	MQL	MQL + 0.5% MoS_2	MQL + 1% MoS_2	MQL + 1.5% MoS_2
Pressure / bar	3	5	7	----
Flow rate / ml/h	160	310	----	----
Constant Parameters				
Cutting speed	350 m/min			
Feed	0.2 mm/rev			
Depth of cut	4 mm			

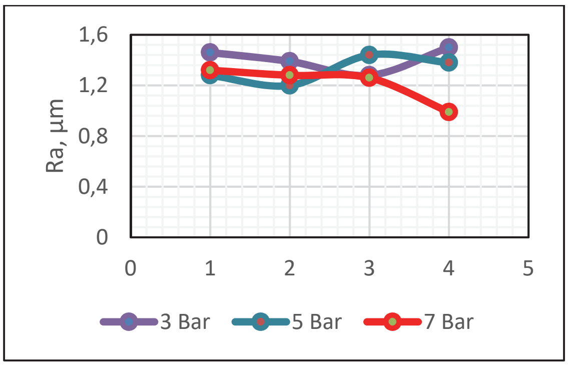
3 RESULTS AND DISCUSSIONS
3.1 Surface Roughness

Results obtained after turning tests were evaluated by graphical and statistical methods. After each turning, roughness (*Ra*) of turned surfaces was measured. Measured values after experiments were given in detail in Tab. 3. The lowest *Ra* value was measured as 0.99 µm at 7 bar pressure, 160 ml/h fluid flow rate and nano-MoS_2 spray parameters of MQL + 1.5%. Maximum *Ra* values were measured as 1.58 µm in dry turning. Here, a 37% reduction in *Ra* was obtained with respect to dry processing conditions. It can be said that these results are quite good in terms of surface roughness. It was also showed to be similar to the studies in the literature [22]. With increased flow rate, *Ra* roughness slightly decreased [33].

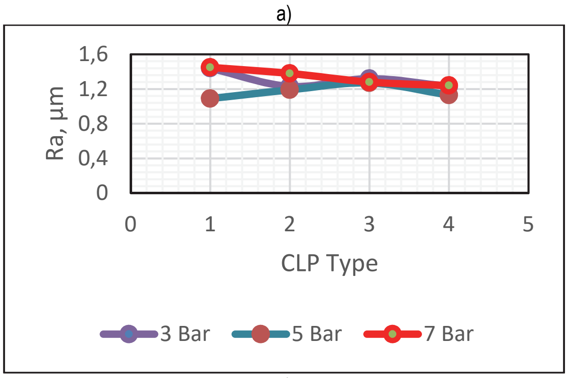
Table 3 Experimental results

Exp. Number	Cooling	% MoS_2	Pressure / bar	Flow rate / ml/h	*Ra*
1	Dry	…….	…….	…….	1.58
2	Conventiona	…….	…….	…….	1.36
3	MQL	0	3	160	1.46
4	MQL	0	3	310	1.44
5	MQL	0	5	160	1.28
6	MQL	0	5	310	1.09
7	MQL	0	7	160	1.44
8	MQL	0	7	310	1.45
9	MQL	0.5	3	160	1.39
10	MQL	0.5	3	310	1.23
11	MQL	0.5	5	160	1.20
12	MQL	0.5	5	310	1.19
13	MQL	0.5	7	160	1.28
14	MQL	0.5	7	310	1.38
15	MQL	1	3	160	1.28
16	MQL	1	3	310	1.32
17	MQL	1	5	160	1.44
18	MQL	1	5	310	1.27
19	MQL	1	7	160	1.26
20	MQL	1	7	310	1.28
21	MQL	1.5	3	160	1.50
22	MQL	1.5	3	310	1.23
23	MQL	1.5	5	160	1.38
24	MQL	1.5	5	310	1.13
25	MQL	1.5	7	160	0.99
26	MQL	1.5	7	310	1.24

Graphs showing the relationship between surface roughness values and turning parameters are given in Fig. 3.



a)



b)

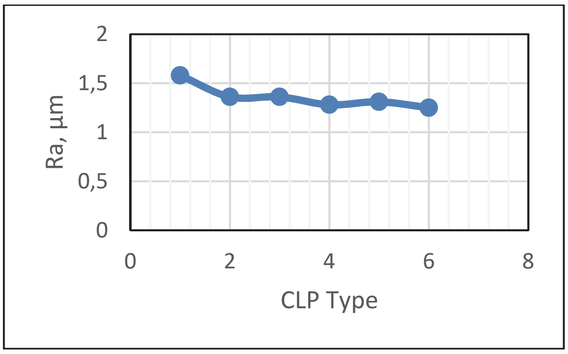
CLP	Code
MMY	1
MMY + 0.5% MoS_2	2
MMY + 1% MoS_2	3
MMY + 1.5% MoS_2	4

Figure 3 Change of *Ra* according to CLP at a) 160 ml/h; b) 310 ml/h flow rate

Graphs were prepared according to flow rate and pressure. Graphs were prepared according to cooling-lubrication process type (CLP). Numbering according to cooling types is as in Fig. 3. In each numbering value, average of measured values is reflected in graphs. In Fig. 3a, change of *Ra* according to CLP for 160 ml/h is given. It is seen that *Ra* value decreases MoS_2 additive when pressure is 7 bar. A similar trend is observed under 3 bar pressure conditions. Roughness value tends to increase since addition of 0.5% MoS_2 at pressure of 5 bar. The highest *Ra* value was obtained at 3 bar pressure and the lowest at 7 bar pressure at MQL + 1.5% MoS_2 parameters. In addition, a uniform change in pressure value of 3 bar was not observed. A steady decrease was observed at 7 bar pressure. However, the lowest value was obtained at pressure of 5 bar.

In order to evaluate results more broadly, graphs in Fig. 4 were created. Each point on the graph shows average of experiments performed in that parameter. Referring to Fig. 4, *Ra* has the highest value in dry turning. Roughness tends to decrease in normal, MQL and nano MoS_2 added MQL environments.

The lowest *Ra* value of experimental study was obtained under MQL + 1.5% MoS_2 conditions. It is clearly seen here that nano MoS_2 additive improves surface roughness. This is due to the fact that lubricating property of nano MoS_2 particles reduces coefficient of friction [12]. This was emphasized in different studies [12, 34]. It was found that MoS_2's preferred solid lubricant characteristics in industry reinforce positive effect on MQL turning.



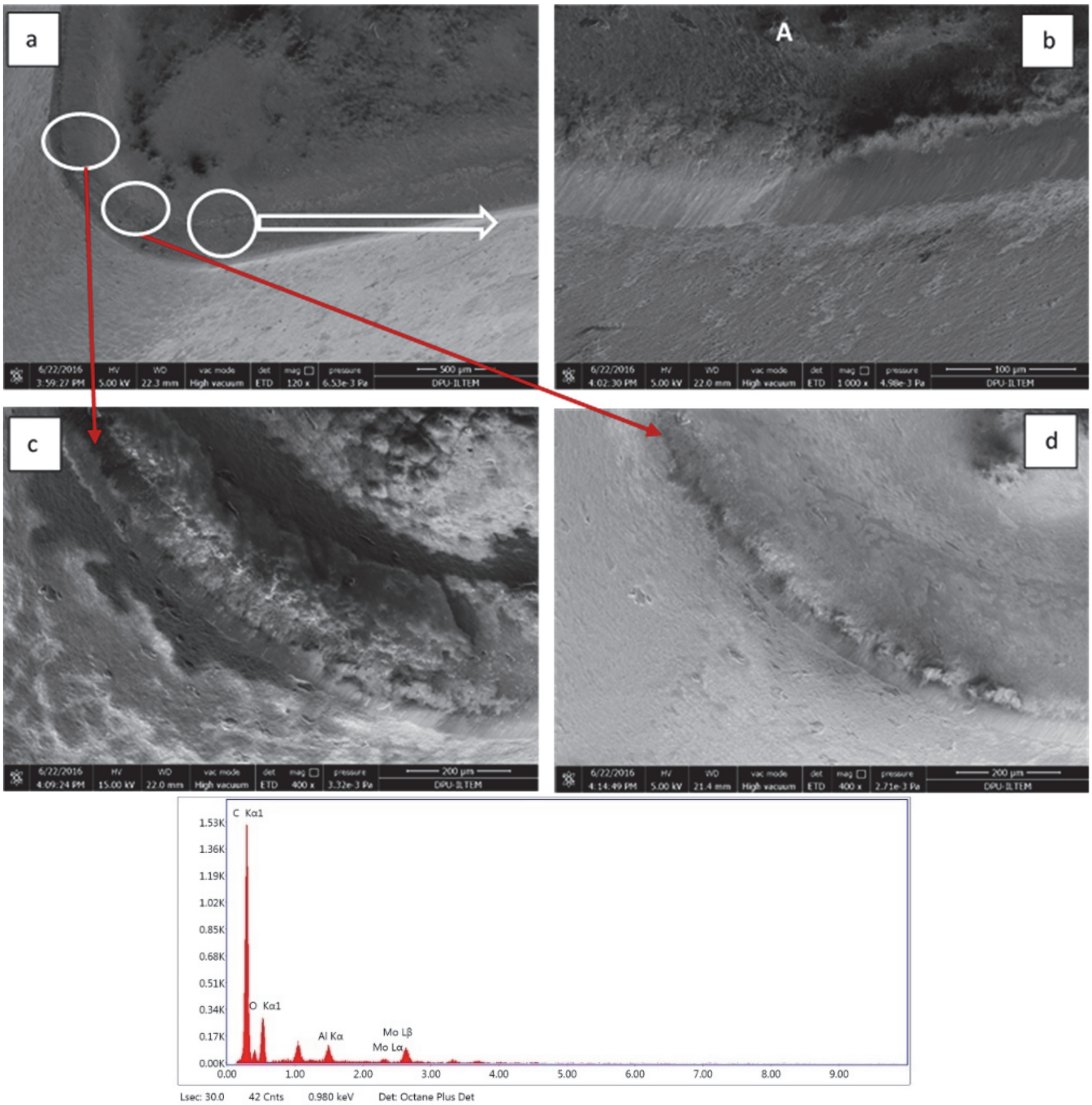
CLP	Code
Dry	1
Normal	2
MMY	3
MMY + 0.5% MoS_2	4
MMY + 1% MoS_2	5
MMY + 1.5% MoS_2	6

Figure 4 Relationship between cooling process type and *Ra*

3.2 Tool Wear

After turning experiments, scanning electron microscopy (SEM) images of cutters were taken in order to determine tool wear types and mechanisms occurring on inserts. EDX image was taken from required areas and cutting tool wear was determined. SEM images of insert used in dry turning are given in Fig. 5. When turning parameters are taken into consideration and looking at the images, there is no significant tool wear on cutting edge. There are traces of chip flow on cutting edge chip surface and free surface due to abrasive wear mechanism. Also, it is seen that there is a small amount of material adhesion on cutting edge and chip surface and they are stable. Adhesive wear mechanism is mostly seen in steel, aluminum and cast iron type materials [31]. Very limited amount of adhesion can be attributed to the fact that overcoat is Al_2O_3 because Al_2O_3 does not react with almost any workpiece material as coating material [31]. Referring to the picture (d) in Fig. 5, crater region, which is formed by effect of diffusion and abrasive wear mechanisms, is striking. In dry conditions, it is possible that heat generated by turning at a cutting depth of 4 mm at a cutting speed of 350 m/min triggers diffusion wear mechanism [35]. No particle breaks from tool surface were observed in area exposed to diffusion. If region marked with "A" is examined, a low-thickness layer adhesion is observed. In order to fully analyze this region, EDX image of point "A" given in Fig. 5 was taken. It is seen that this region mainly contains C (76.93%) and O (19.25%) elements which show that it belongs to cutting tool.

Fig. 6 shows SEM photographs of insert used in MQL + 1.5% MoS_2 parameter. Breakage of small particles or plastic deformation on cutter was not observed. Traces of abrasive wear mechanism are not intense.



Element	C	O	Mo	Al	C
Weight / %	76.93	19.25	1.25	2.58	76.93
Atomic / %	83.00	15.59	0.17	1.24	83.00

Figure 5 SEM images of cutting tool and EDX results belong to A point in dry turning

This may be related to the positive effect of nano MoS_2 added MQL cooling. Abrasive wear marks and cavities on chip surface and free surface are indistinctly observed. In addition, if their temperature is low, adhered chip formation can be seen. Increased cutting zone temperature, on the other hand, resulted in chip formation [31]. From this point of view, cooling and lubrication conditions included in experimental design may prevent heat build-up and create an environment suitable for adhesion. It can be said that the formation here is material adhesion. First of all, this adhesion can occur due to adhesion wear mechanism and high pressure at tool-chip interface in addition to effect of cooling conditions.

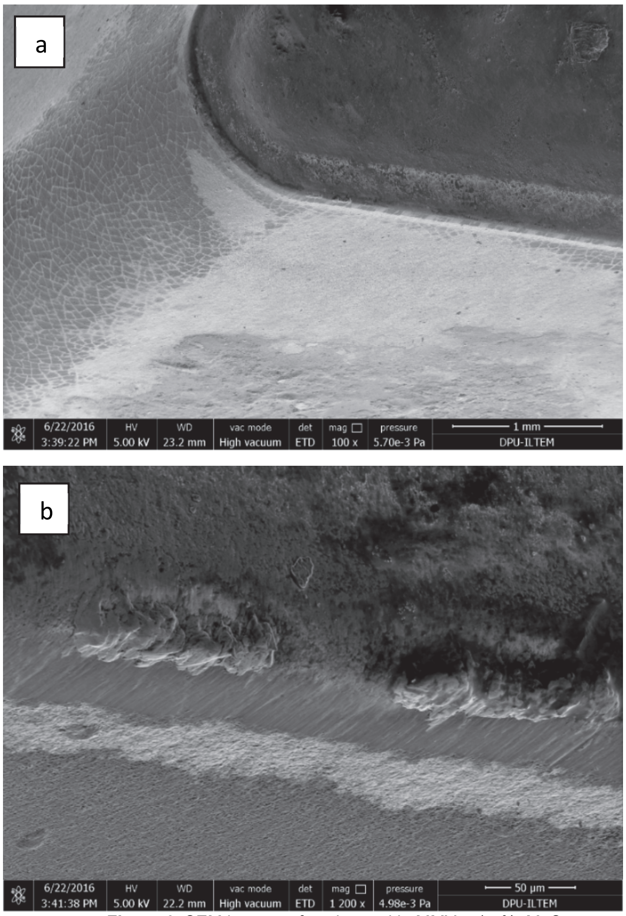


Figure 6. SEM images of cutting tool in MMY + 1,5% MoS_2

4 CONCLUSIONS

The results obtained after the evaluation of all the findings obtained from the study are given below:

- The lowest *Ra* at 7 bar pressure, 160 ml/h flow rate and MQL + 1.5% nano-MoS_2 spray were measured as 0.99 µm according to the test results. It is evident here that addition of nano MoS_2 improves roughness. The highest *Ra* in dry machining was measured as 1.58 µm.
- A 37% reduction in *Ra* was obtained with respect to dry machining conditions. It can be said that these results are quite good in terms of surface roughness. The meaning of this result will be strengthened with cost analysis that will be performed.
- There was no linear interaction between *Ra* and pressure. Increased flow rate resulted in slightly decreased *Ra* roughness.
- Nano-MoS_2 contributed positively to reducing tool wear in cutting edge area of cutter. In SEM/EDX images, abrasive, adhesive and diffusion wear mechanisms were observed. In cutting tools used in normal spraying and nano MoS_2 turning, newly started flank wear and adhesion/galling were determined.

Positive results were obtained from the nano-MoS_2 added coolant used in MQL system to improve lubrication and cooling properties. Considering increasing tendency of academic and industrial interest in nanoparticle contribution in this subject, this study successfully fulfilled its presented hypothesis.

Acknowledgements

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Contact information:

Şafak SERTSÖZ, MSc
CESAN Crane 1st Organized Industrial Zone,
11030, Bilecik, Turkey
E-mail: safaksertsoz@hotmail.com

Alaattin KAÇAL, Associate Professor, Dr.
(Corresponding author)
Mechanical Engineering Department,
Simav Technology Faculty, Kutahya Dumlupinar University,
43500, Simav, Kütahya, Turkey
E-mail: alaattin.kacal@dpu.edu.tr