The work has been carried out only focussing on the project contract and the following work activities are performed as per the project contract:

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Tool wear patterns and their promoting mechanisms in hybrid cooling assisted machining of titanium Ti-3Al-2.5V/grade 9 alloy

Munish Kumar Gupta[a,*,1], P. Niesłony[a], Murat Sarikaya[b], Mehmet Erdi Korkmaz[c], Mustafa Kuntoğlu[d], G.M. Królczyk[a], Muhammad Jamil[e]

[a] Faculty of Mechanical Engineering, Opole University of Technology, 76 Proszkowska St., 45-758 Opole, Poland
[b] Department of Mechanical Engineering, Sinop University, Sinop, Turkey
[c] Department of Mechanical Engineering, Karabük University, Karabük, Turkey
[d] Selcuk University, Technology Faculty, Mechanical Engineering Department, Konya 42130, Turkey
[e] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China

ARTICLE INFO

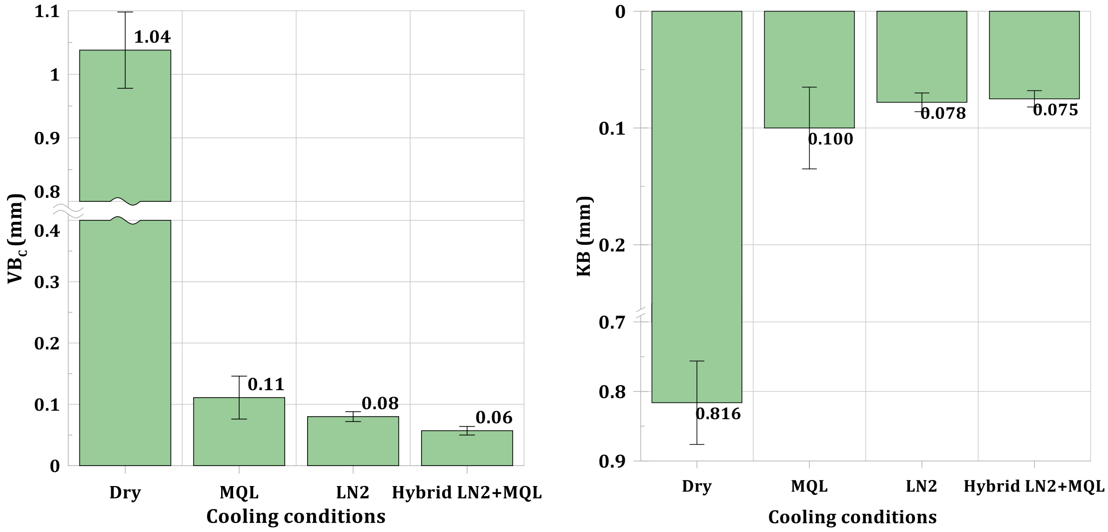
Keywords:
Lubri-cooling
Ti-3Al-2.5V/grade 9, Turning
Tribology
Wear
Titanium

ABSTRACT

Hybrid lubri-cooling is a latest technology that provides synergistic cooling and lubrication effect in the machining area especially in the cutting of titanium and its alloys. In this current study, cryogenic-LN_2, minimum quantity lubrication (MQL), and hybrid cryogenic LN_2-MQL are applied and compared against dry medium in perspective of in-depth analysis of tool flank wear, EDS mapping, and intensity of tool wear. Experimental results showed that in comparison with dry, hybrid LN_2-MQL substantially reduced the tool flank and rake wear followed by LN_2, MQL, and dry conditions, respectively. Additionally, the SEM and EDS analysis depicted relatively less severe wear and chemical elements adhesion on the tool's main cutting edge, while turning titanium alloy under a hybrid LN_2-MQL lubri-cooling environment. In addition, the dry condition has maximum value of tool wear progressions i.e., 1.04 mm and hybrid LN_2-MQL have 0.06 mm while machining titanium alloys. When tool wear is evaluated from a tribological point of view, the reduction in flank wear value compared to dry machining is 89.4 %, 92.3 % and 94.2 % owing to MQL, LN_2, MQL and hybrid LN_2-MQL cutting strategies. In terms of crater wear, the improvement was 87.7 %, 90.4 % and 90.8 % thanks to MQL, LN_2, MQL and hybrid LN_2-MQL.

1. The machining analysis in terms of detailed tool wear is performed and the results are published in Tribology International Journal with the entitled of "Tool wear patterns and their promoting mechanisms in hybrid cooling assisted machining of titanium Ti-3Al-2.5V/grade 9 alloy". The short summary is given below:

This experimental study put forward a comparison of tool wear mechanism under dry, cryogenic-LN_2, MQL, and hybrid LN_2-MQL cooling conditions in the turning of titanium alloy. Consequently, comparison of tool flank wear under different cooling environments underscored minimum tool wear VB=0.06mm under hybrid LN_2-MQL, while maximum tool wear VB=1.04mm under dry conditions. Similarly, the minimum rake wear KB=0.075mm was measured under hybrid LN_2-MQL and a maximum of KB=0.816mm under dry conditions. In other words, the reduction in flank wear value compared to dry machining is 89.4%, 92.3% and 94.2% owing to MQL, LN_2, MQL and hybrid LN_2-MQL cutting strategies. In terms of crater wear, the improvement was 87.7%, 90.4% and 90.8% thanks to MQL, LN_2, MQL and hybrid LN_2-MQL. SEM of tool flank face showed predominant wear mechanisms were adhesion, diffusion, and wear, each of which is affected differently under cooling environments. Progressive wear was observed under hybrid LN_2-MQL, while accelerated tool wears under dry conditions. EDS analysis showed that adhesion of chemical elements such as aluminum (Al), nitrogen (N), titanium (Ti), and tungsten carbide (WC) are dominant on worn flank edge under all environments, however deposition concentration under hybrid LN_2-MQL was far less than dry conditions. A comparison of tool life under cryogenic LN_2, MQL, and hybrid LN_2-MQL in terms of cutting length showed maximum tool life (1000mm) under hybrid LN_2-MQL and minimum tool life (600mm) under dry conditions. Figure 1 illustrates the size changes (wear amount in terms of VBc and KB) of the tools on both the flank and rake faces. Accordingly, as seen in Figure 5(a) excessive flank wear observed in dry turning indicates the end of the tool's life according to the ISO standard mentioned above. Excessive heat is created because to high tool-chip-workpiece friction in a dry cutting environment where adequate heat evacuation is not possible, resulting in an increase in tool temperature. The tool material softens as the tool temperature rises, resulting in severe workpiece adhesion and increased wear. There was a tremendous reduction in flank wear with the penetration of cooling/lubricating means into the cutting medium. Even thanks to these lubrication/cooling tools, the flank wear value of the cutting tool remained within the favorable tool life limits i.e. VB<0.3 mm. The atomized cutting oil and compressed air delivered with the MQL penetrate the cutting zone interfaces as an aerosol promoting both the boundary lubrication and cooling action. In this way, friction, temperature and contact length can be reduced. On the other hand, LN2 reduces the temperature tremendously, reducing adhesion and contact length. Also, the minimum wear achieved in hybrid cooling is attributed to the longer time the oil droplets stay in the environment without evaporation, with the effect of cryogenic cooling. A similar trend to flank wear results was also observed in crater wear as provided in Figure 1(b). High-temperature formation in the secondary cutting zone (chip surface) can induce fast crater wear by diffusion when machining titanium alloys at medium/elevated cutting speeds using carbide cutting insert. The advanced and hybrid refrigerating and oiling methods utilized in this study have gradually contributed to the limiting of this type of wear. In hybrid cooling/lubrication experiments, cryogenic cooling of the cutting tool and a stable lubrication service to the contact surfaces are considered to significantly reduce crater dissolution-diffusion wear. When tool wear is evaluated from a tribological point of view, the reduction in flank wear value compared to dry machining is 89.4%, 92.3% and 94.2% owing to MQL, LN2, MQL and hybrid LN2-MQL cutting strategies. In terms of crater wear, the improvement was 87.7%, 90.4% and 90.8% thanks to MQL, LN2, MQL and hybrid LN2-MQL. The results claim prove that the good lubrication as well as cooling effects promotes the tool life during machining of titanium alloys. As a future scope, the more detailed studies on other cooling conditions with different materials could be performed.



(a) (b)

Figure 1. Geometrical wear aspects of cutting tools

2. The effect of cooling/lubrication was also studied and the experiments on tribological tests were performed under different cooling conditions. Two papers entitled "A novel use of hybrid Cryo-MQL system in improving the tribological characteristics of additively manufactured 316 stainless steel against 100Cr6 alloy" and "Understanding the lubrication regime phenomenon and its influence on tribological characteristics of additively manufactured 316 Steel under novel lubrication environment" were published in Tribology international. The brief summary is given below:

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A novel use of hybrid Cryo-MQL system in improving the tribological characteristics of additively manufactured 316 stainless steel against 100 Cr6 alloy

Recep Demirsöz [a], Mehmet Erdi Korkmaz [a], Munish Kumar Gupta [b,*,1]

[a] Department of Mechanical Engineering, Karabük University, Karabük, Turkey
[b] Faculty of Mechanical Engineering, Opole University of Technology, 76 Proszkowska St., 45-758 Opole, Poland

ARTICLE INFO

Keywords:
Friction force
Lubrication
MQL
Tribology
Wear, Cryo-MQL

ABSTRACT

Reflecting the broad interest in additive manufacturing (AM), this study focuses on the tribological behavior of 316 L stainless steel against 100 Cr6 alloy under various cooling environments. Tribological experiments were conducted on additively manufactured 316 stainless steel using a ball-on-flat tribometer under dry, minimum quantity lubrication (MQL), cryogenic, and hybrid cryo+MQL conditions. Subsequently, the most critical tribological variables such as friction forces, volume loss, wear depth, and micrographs were investigated. The results revealed that the combination of cryo and MQL cooling conditions are helpful in improving the tribological performance while minimizing material volume loss and wear rates. Cryo+MQL condition shows better performance based on volume loss as 2.33, 11.2 and 14.8 times than MQL, cryo and dry conditions, respectively.

In the first paper, the tribological aspects of additively manufactured 316L stainless steel versus 100Cr6 alloy has been investigated. The cooling conditions used were dry, MQL, cryogenic cooling, and hybrid cryo-MQL and the wear results were investigated. It is seen that the minimum material loss is 0.1040 mm3 with a 20 N load. Where, the highest volume loss was observed in the test conditions carried out in dry environments, as shown in Figure 2.

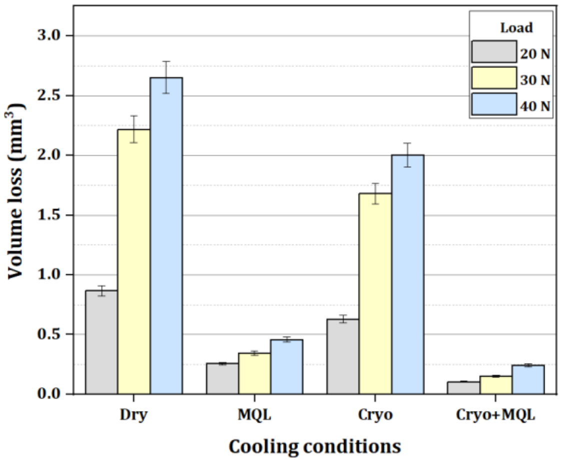


Figure 2. Volume loss values at different cooling conditions and loads.

The maximum wear depth value was obtained as 180 μm concerning the dry experiment with a load value of 40 N. The smallest wear depth value for MQL lubrication conditions was measured as 37 μm under the 20 N load value condition. The smallest wear depth value for Cryo environment conditions was measured as 66 μm under the 20 N load value condition. The lowest wear depth value was 20 μm for Cry-MQL lubrication test conditions, and it was measured from the wear track obtained from the experiments carried out at a load value of 20 N. The best condition was found as Cryo-MQL based on wear depth in the wear tests as. The lowest friction force value was obtained at 20 N load under Cryo-MQL lubrication conditions, and this value is 0.37 N. The friction force values obtained at 20 N, 30 N, and 40 N normal force under MQL lubrication conditions are 0.43, 0.76, and 1.14, respectively. In a dry test condition, the friction forces are highest among other wear environments attributed to the unnecessary heat generation and friction. The more cracks that are visible in dry conditions are due to the greater amount of material that has been removed from the surface. Cracks and deposited materials are minimized as a result of changing lubricant conditions. The hybrid Cryo-MQL term showed better tribological behavior of additively manufactured 316L stainless steel against the 100Cr6 alloy when compared to other cutting conditions, as shown in Figure 3. This is due to the combined effect of cooling and lubrication under cryo + MQL conditions.

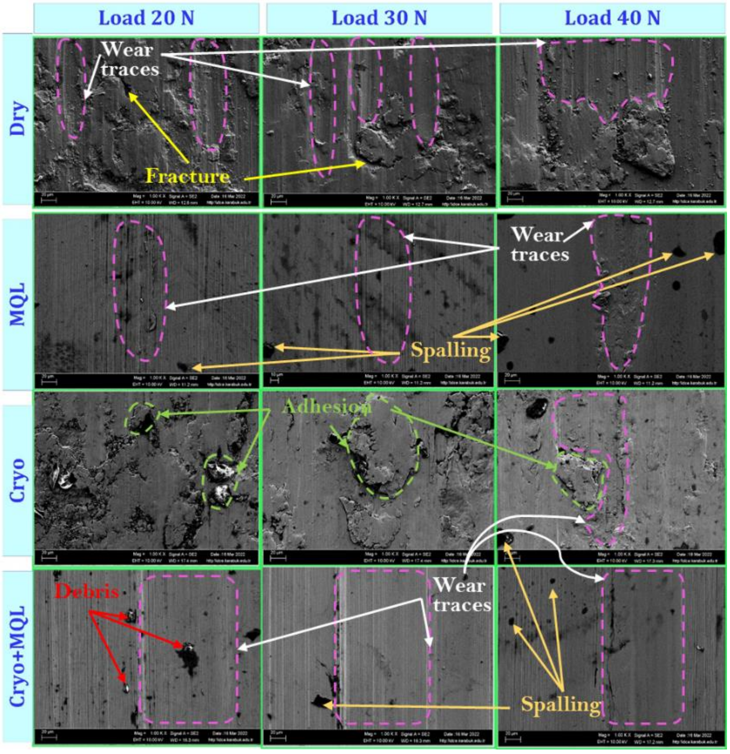
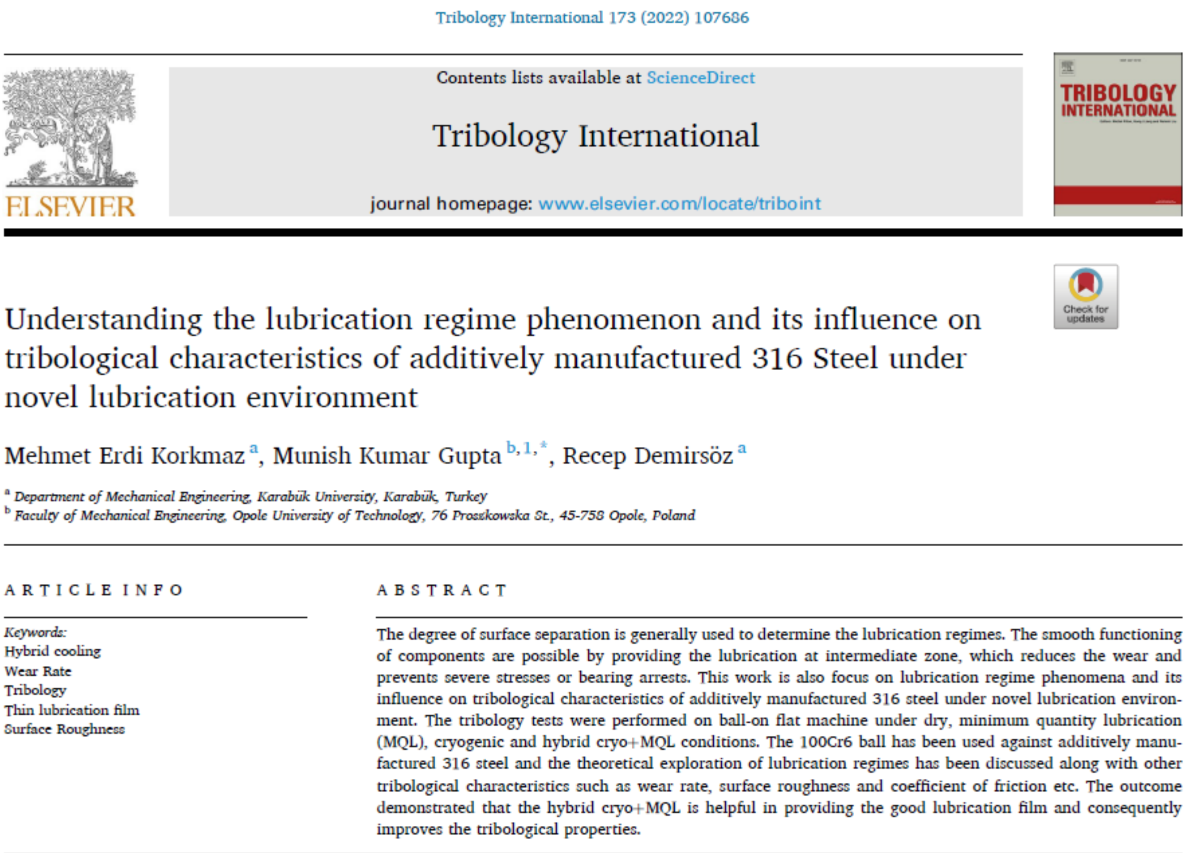


Figure 3. SEM of specimen surface with respect to load and cooling conditions.



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Understanding the lubrication regime phenomenon and its influence on tribological characteristics of additively manufactured 316 Steel under novel lubrication environment

Mehmet Erdi Korkmaz [a], Munish Kumar Gupta [b,1,*], Recep Demirsöz [a]

[a] Department of Mechanical Engineering, Karabük University, Karabük, Turkey
[b] Faculty of Mechanical Engineering, Opole University of Technology, 76 Prószkowska St., 45-758 Opole, Poland

ARTICLE INFO

Keywords:
Hybrid cooling
Wear Rate
Tribology
Thin lubrication film
Surface Roughness

ABSTRACT

The degree of surface separation is generally used to determine the lubrication regimes. The smooth functioning of components are possible by providing the lubrication at intermediate zone, which reduces the wear and prevents severe stresses or bearing arrests. This work is also focus on lubrication regime phenomena and its influence on tribological characteristics of additively manufactured 316 steel under novel lubrication environment. The tribology tests were performed on ball-on flat machine under dry, minimum quantity lubrication (MQL), cryogenic and hybrid cryo+MQL conditions. The 100Cr6 ball has been used against additively manufactured 316 steel and the theoretical exploration of lubrication regimes has been discussed along with other tribological characteristics such as wear rate, surface roughness and coefficient of friction etc. The outcome demonstrated that the hybrid cryo+MQL is helpful in providing the good lubrication film and consequently improves the tribological properties.

Similarly, in the second article, An additively manufactured 316L stainless steel was tested in a ball-on-flat tribometer under various wear conditions (dry, cryogenic cooling, MQL, cryo-

MQL) to see how the lubrication regime is related with the tribological properties. Additionally, the curvature radius of wear traces (as indicated by the contact length) and characteristics were studied. Finally, the effect of the curvature radius and the lubrication regime (λ parameter) was evaluated. As a result, the lowest wear rate value for Cryo-MQL lubrication test conditions is 0.0010 mm3/m while the wear rates are 0.0087 mm3/m, 0.0063 mm3/m, and 0.0026 mm3/m for Cryo, MQL and dry conditions, respectively. The lowest surface roughness value is obtained by Cryo-MQL lubrication test conditions as 0.11x10-3 µm, while MQL, Cryo and dry conditions have the surface roughness values of 0.16x10-3, 1.29x10-3 and 1.90x10-3 µm, respectively. If the pressure on the surface roughness of the surfaces in contact is high enough to cause local plastic deformation, very high-pressure acts on the small roughness peaks. When the stress at these points exceeds the yielding limit of the roughness, plastic deformation, scratching of the roughness and plastering and welding starts. During the sliding movement, these points break off and cause wear and tear. This type of material loss creates adhesive wear. It is recommended to harden the contact surfaces with surface hardening methods against adhesive wear and to use lubricants. The lowest coefficient of friction value for Cry-MQL lubrication test conditions is 0.019, while it is 0.022, 0.121 and 0.138 for MQL, Cryo and dry conditions, respectively. Due to the higher curvature radius, friction coefficients decrease. The drop in contact pressure generated by an increase in contact area, which in turn reduces frictional interaction severity, may account for the reduced severity of frictional interactions. When using Cryo-MQL lubricant/cooling system, the viscosity is increased since the lubricant temperature is reduced by cryogenic cooling. Because this method of lubrication/cooling changed the lubrication regime from boundary to mixed and elasto-hydrodynamic by increasing the λ parameter due to the increasing viscosity of the lubricant when the temperature and surface roughness were decreased, as shown in Figure 4.

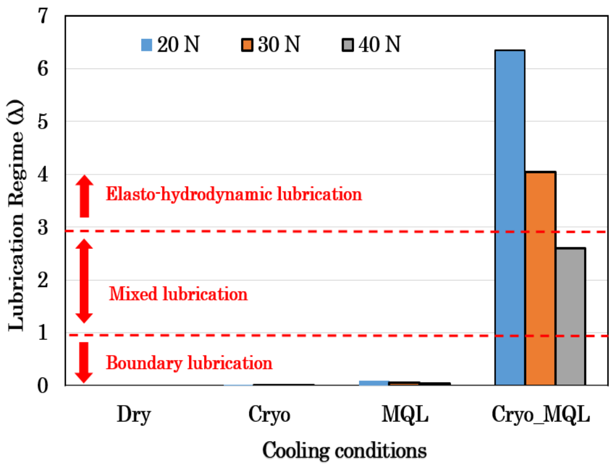

Figure 4. The variation of lubrication regime based on different wear environments

Figure 5 shows that the lowest thin film thickness for MQL lubrication conditions was 3.92x10-6 mm under the 20N load value. Thickness results for 30N and 40N load values were 4.14x10-6 mm, respectively, for thin film thickness measurements. The thin film thickness rises by 5.61% when the load is increased from 20N to 30N. This 7.65% and 1.93% rise occurs when the load goes from 20N to 40N, and from 30N to 40N. Cry-MQL lubrication test settings yielded the lowest thin film thickness of 85.96x10-6 mm at a load value of 20N. For loads of 30N and 40N, the thin film thickness was found to be 102.08x10-6 mm and 117.51x10-6 mm, respectively.

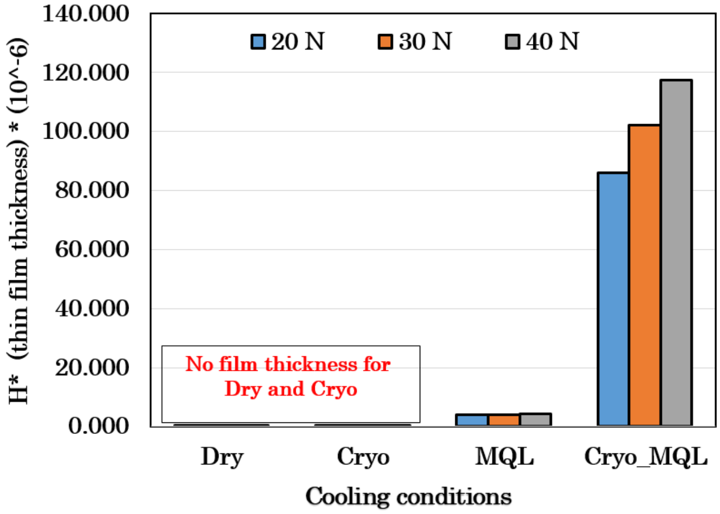

Figure 5. The variation of thin film thickness based on different wear environments

3. The effect of cooling conditions were also studied in the machining of different materials and two papers entitled “On tribological characteristics of TiC rollers machined under hybrid lubrication/cooling conditions” and “Role of sustainable cooling/lubrication conditions in improving the tribological and machining characteristics of Monel-400 alloy” were published in Tribology International Journals. The summary is given below:

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On tribological characteristics of TiC rollers machined under hybrid lubrication/cooling conditions

Mehmet Erdi Korkmaz [a], Munish Kumar Gupta [b,1,*], Recep Demirsöz [a], Mehmet Boy [c], Nafiz Yaşar [d], Mustafa Günay [a], Nimel Sworna Ross [e,2]

[a] Department of Mechanical Engineering, Karabük University, Karabük, Turkey
[b] Faculty of Mechanical Engineering, Opole University of Technology, 76 Proszkowska St., 45-758 Opole, Poland
[c] TOBB Vocational High School, Karabük University, Karabük, Turkey
[d] Yenice Vocational High School, Karabük University, Karabük, Turkey
[e] Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai 602105, Tamil Nadu, India

ARTICLE INFO

Keywords:
Hard turning
Cryo+MQL
Lubrication/cooling
Tool wear
Surface integrity

ABSTRACT

The titanium carbide is considered as a hard to cut material and it is very helpful in critical applications especially in guide roller applications. This study investigated the machining based tribological characteristics of TiC rollers during hard turning under sustainable cooling/lubrication conditions. Surface quality, power consumption, tool wear, microstructural changes, microhardness after machining, and SEM-EDX analysis were evaluated under dry, minimum quantity lubrication (MQL), cryogenic and hybrid cryo+MQL environments. Although the surface quality did not meet the expectations in dry cutting, MQL improved slightly than cryo methods. However, the best surface quality, the smallest tool wear and power consumption was obtained in the hybrid cryo+MQL lubrication/cooling method.

In the first article, the titanium carbide is considered as a hard to cut material and it is very helpful in critical applications especially in guide roller applications. This study investigated the machining based tribological characteristics of TiC rollers during hard turning under sustainable cooling/lubrication conditions. Surface quality, power consumption, tool wear, microstructural changes, microhardness after machining, and SEM-EDX analysis were evaluated under dry, minimum quantity lubrication (MQL), cryogenic and hybrid cryo+MQL environments. Although the surface quality did not meet the expectations in dry cutting, MQL improved slightly than cryo methods. However, the best surface quality, the smallest tool wear and power consumption was obtained in the hybrid cryo+MQL lubrication/cooling method. The initial study of tool wear claim that the tool wear is a prominent aspect that is produced with the applications of mechanical, thermal, fatigue and chemical loads during the machining operations. The distinct types of mechanism such as abrasion, built up edge, adhesion, diffusion etc. were observed while machining difficult-to-cut materials. When tool wear values were examined as shown in Figure 6, it was determined that the highest cutting speed under dry test produced a maximum flank wear of 334 µm. For low and medium cutting speeds, the flank wear values are 265 µm and 305 µm. Cutting speed improved from 40 to 60m/min, yet tool wear increased by 15.09% within this time period. Under Cryo+MQL lubrication conditions, the experiment at low cutting speed yielded 98 µm. This is the least flank wear in this study. Flank wear was determined to be 109 µm at medium and 121 µm at high cutting speeds. From 40 to 60m/min, the cutting speed increased the tool wear by 11.22%. Raising the cutting speed from 40 to 80m/min resulted in a 23.47% rise and increasing it from 60 to 80m/min resulted in an 11.01% increase. Flank wear of 252 µm was achieved using MQL lubrication at modest cutting speeds. The study found that medium and high cutting speeds result in 285 and 311 µm flank wear. When speed of cutting is raised from 40 to 60m/min, tool wear increases 13.10%. These values increase by 23.41% and 9.12%, respectively, when the cutting speed is raised from 40 to 60m/min and 60 to 80m/min. At a modest cutting speed, 123 µm tool wear was the lowest ever recorded in a cryo environment. Flank wear measurements were 142 µm and 168 µm for low and high cutting speeds, respectively. The flank wear value increases by 15.45% as the cutting speed rises from 40 to 60m/min. Cutting speed increases by 36.59% and 18.31% when the speed is adjusted from 40 to 60m/min or 60 to 80m/min, respectively. When the dry conditions were substituted with the Cryo+MQL lubrication test conditions, the results were significantly improved. , it decreased by 270% for the low cutting speed value. These reduction values are 280% and 276% for medium and high cutting speeds, respectively.

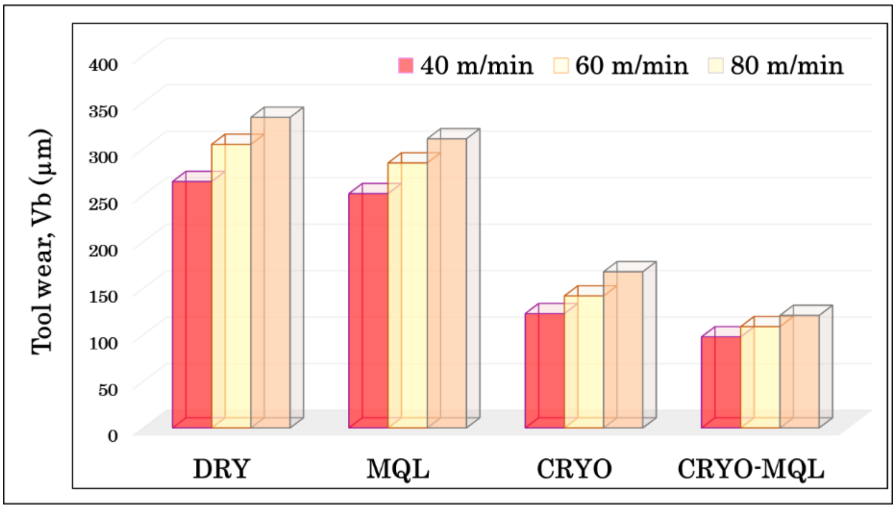
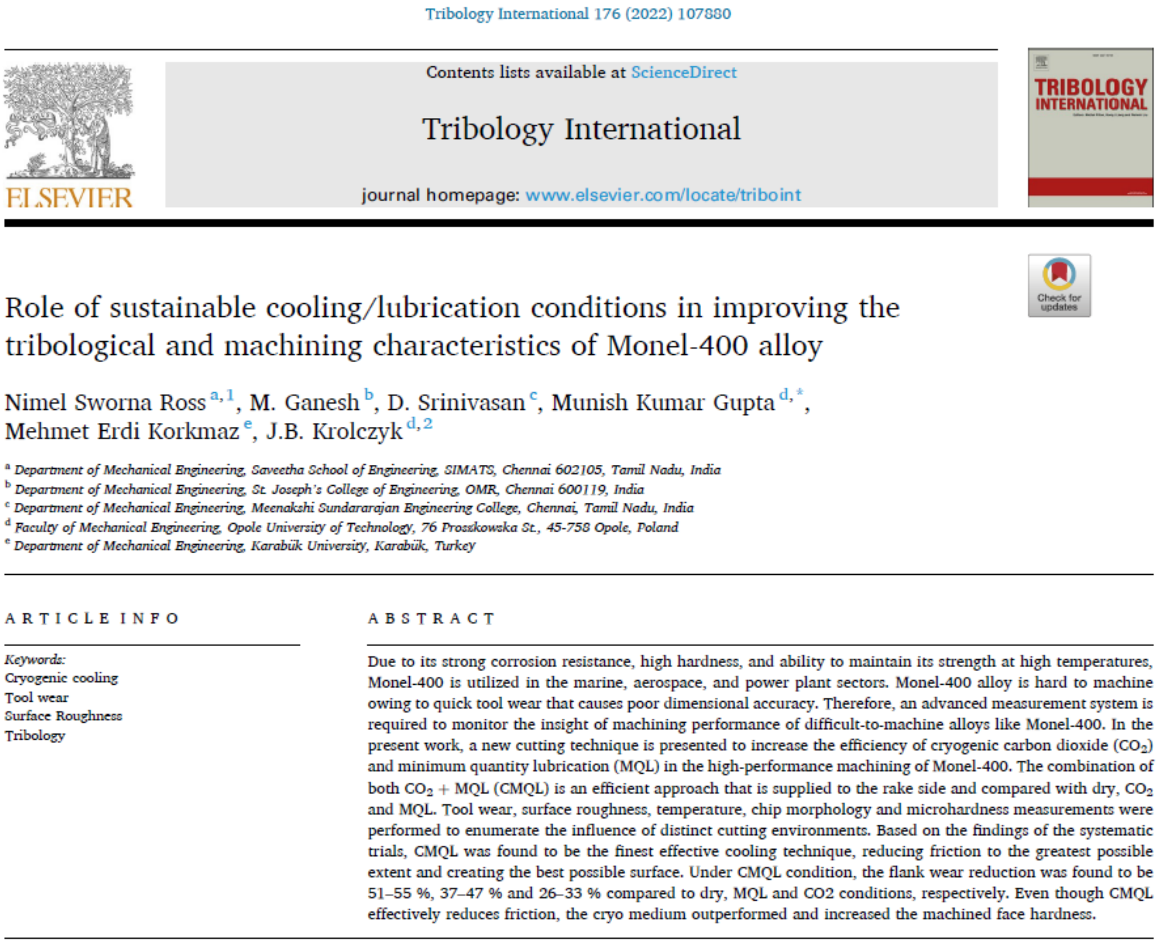


Figure 6. Flank wear evaluation under different Lubri/cooling environments

Heat is generated during all metal removal processes. As a reason of plastic deformation at the cutting tool tip and friction between the chip and tool-chip contact during cutters movement. Utilizing cutting fluid, removes heat from the interface amid tool and workpiece. [18]. This cooling outcome diminishes the yield strength of the tools and delays the wear from exceeding the critical temperature. Another important task of coolant is to lubricate the tool, workpiece and chip. One of the utmost noteworthy roles of cutting fluids is to remove the chip from the cutting area while also cooling it and preventing minute particles such as dust from mixing into the air and remaining in the liquid. The cutting area must be regularly cleaned of chips created during machining to prevent deterioration of the finished surface, which delays tool wear. Since coolant application also affects chip formation, coolant played a chip breaker role in high pressure systems. In the Cryo+MQL method, spraying from the back of the chip not only cooled the chip, it provides both lubrication and cooling, and also ensured that the chip was divided into small pieces. Thus, scratches in the tool and additional heat generation due to friction amid tool and the workpiece are reduced.



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Role of sustainable cooling/lubrication conditions in improving the tribological and machining characteristics of Monel-400 alloy

Nimel Sworna Ross [a,1], M. Ganesh [b], D. Srinivasan [c], Munish Kumar Gupta [d,*], Mehmet Erdi Korkmaz [e], J.B. Krolczyk [d,2]

[a] Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai 602105, Tamil Nadu, India
[b] Department of Mechanical Engineering, St. Joseph's College of Engineering, OMR, Chennai 600119, India
[c] Department of Mechanical Engineering, Meenakshi Sundararajan Engineering College, Chennai, Tamil Nadu, India
[d] Faculty of Mechanical Engineering, Opole University of Technology, 76 Prószkowska St., 45-758 Opole, Poland
[e] Department of Mechanical Engineering, Karabük University, Karabük, Turkey

ARTICLE INFO

Keywords:
Cryogenic cooling
Tool wear
Surface Roughness
Tribology

ABSTRACT

Due to its strong corrosion resistance, high hardness, and ability to maintain its strength at high temperatures, Monel-400 is utilized in the marine, aerospace, and power plant sectors. Monel-400 alloy is hard to machine owing to quick tool wear that causes poor dimensional accuracy. Therefore, an advanced measurement system is required to monitor the insight of machining performance of difficult-to-machine alloys like Monel-400. In the present work, a new cutting technique is presented to increase the efficiency of cryogenic carbon dioxide (CO_2) and minimum quantity lubrication (MQL) in the high-performance machining of Monel-400. The combination of both CO_2 + MQL (CMQL) is an efficient approach that is supplied to the rake side and compared with dry, CO_2 and MQL. Tool wear, surface roughness, temperature, chip morphology and microhardness measurements were performed to enumerate the influence of distinct cutting environments. Based on the findings of the systematic trials, CMQL was found to be the finest effective cooling technique, reducing friction to the greatest possible extent and creating the best possible surface. Under CMQL condition, the flank wear reduction was found to be 51–55 %, 37–47 % and 26–33 % compared to dry, MQL and CO2 conditions, respectively. Even though CMQL effectively reduces friction, the cryo medium outperformed and increased the machined face hardness.

Similarly, in next article, an advanced measurement system is required to monitor the insight of machining performance of difficult-to-machine alloys like Monel-400. In the present work, a new cutting technique is presented to increase the efficiency of cryogenic carbon dioxide (CO2) and minimum quantity lubrication (MQL) in the high-performance machining of Monel-

400. The combination of both CO_2 + MQL (CMQL) is an efficient approach that is supplied to the rake side and compared with dry, CO_2 and MQL. Tool wear, surface roughness, temperature, chip morphology and microhardness measurements were performed to enumerate the influence of distinct cutting environments. Based on the findings of the systematic trials, CMQL was found to be the finest effective cooling technique, reducing friction to the greatest possible extent and creating the best possible surface. Under CMQL condition, the flank wear reduction was found to be 51–55 %, 37–47 % and 26–33 % compared to dry, MQL and CO_2 conditions, respectively. Even though CMQL effectively reduces friction, the cryo medium outperformed and increased the machined face hardness.