YILDIZ TECHNICAL UNIVERSITY’S TECHNOPARK COMPANY OF
PROMECH TEKNOLOJİ VE BİLİŞİM SİSTEMLERI SANAYİ LTD. ŞTİ.

PROCEEDINGS BOOK OF
1th INTERNATIONAL CONFERENCE ON ENERGY AND
THERMAL ENGINEERING

SUPPORTED BY
JOURNAL OF THERMAL ENGINEERING
INTERNATIONAL JOURNAL OF ADVANCES ON AUTOMOTIVE AND
TECHNOLOGY

ICTE 2017
APRIL 25-28, 2017
ISTANBUL, TURKEY
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CUTTING TEMPERATURE IN MQL MILLING OF FERRITIC STAINLESS STEEL WHEN USING NANO MoS$_2$ REINFORCED CUTTING FLUID

*Alper Uysal
Yildiz Technical University
Besiktas, Istanbul, Turkey

Keywords: MQL; milling; nanofluid; nano MoS$_2$; cutting temperature; ferritic stainless steel

* Corresponding author: Alper Uysal, Phone: +902123832807, Fax: +902123833024
E-mail address: auysal@yildiz.edu.tr

ABSTRACT
Stainless steel materials have good mechanical properties and are preferred in many industrial areas such as automotive, aerospace, construction, manufacturing etc. But there are some difficulties in machining of these materials and studies on this issue continue. For this reason, in this experimental work, cutting temperature was investigated in milling of ferritic stainless steel under dry, MQL (Minimum Quantity Lubrication) and nanofluid MQL conditions. In MQL milling operations, two MQL flow rates were applied as 20 ml/h and 40 ml/h and all experiments were performed by using uncoated and TiN (Titanium Nitride) coated WC (Tungsten Carbide) cutting tools. Nano MoS$_2$ (Molybdenum Disulphide) particles were added to commercial vegetable cutting fluid at 0.5%wt., 1%wt., and 2%wt. to produce the nanofluids. According to the results, TiN coating and applying MQL method reduced the cutting temperatures. Additionally, the cutting temperatures decreased with increase of MQL flow rate and amount of nano MoS$_2$ particles in unadulterated cutting fluid.

INTRODUCTION
Stainless steel materials are difficult-to-cut materials due to their work hardening tendency and low thermal conductivity and these lead to poor surface quality, rapid tool wear, high cutting temperature etc. Various studies have been carried out and various methods have been applied on their machining and MQL (Minimum Quantity Lubrication) method is one of them. MQL machining has been developed as an alternative to wet machining operations. In MQL machining, very small quantities of lubricant are supplied to the machining zone as a mixture of air and oil in the form of aerosol through MQL system and so this method is environmentally friendly and cost efficient than wet machining. The role of MQL method on cutting temperature was investigated in turning of AISI 1040 steel. Based on the experimental results, MQL machining reduced the cutting temperature and showed better performance than dry cutting and conventional machining with flood cutting fluid [1,2]. Zeilmann and Weingaertner [3] presented a study on cutting temperature during drilling of Ti6Al4V titanium alloy with carbide drill tools under MQL and dry cutting conditions. The results showed that MQL method has an advantage over dry cutting especially the application of MQL with an internal nozzle. Barczak et al. [4] aimed to understand the effectiveness of MQL in plane surface grinding and the results were compared to conventional flood cooling and dry grinding. The results of grinding contact temperature measurements showed that the MQL method was less sensitive to process condition changes than wet and dry grinding. Bhowmick et al. [5] investigated the use of MQL method in drilling of lightweight AM60 magnesium alloy. The temperatures were measured by infrared thermometer and the maximum temperature in MQL drilling did not exceed that occurred in dry and wet cutting. Hosokawa et al. [6] carried out dry and MQL external turning experiments on austenitic stainless steel (AISI 304) and heat resistant nickel based alloy (Inconel 718) with actively driven rotary tool. The influences of workpiece and cutting tool revolutions on cutting point temperature were examined. In the case of MQL turning, the cutting point temperature reduced when choosing the appropriate tool revolution. Bhowmick and Alpas [7] investigated H$_2$O-MQL, dry and wet drilling behavior of AZ91 cast magnesium alloy using uncoated and non-hydrogenated diamond-like carbon coated HSS drill tools. In drilling under H$_2$O-MQL condition, increasing the temperature was restricted. Sasahara et al. [8] performed turning experiments on austenitic stainless steel with driven rotary cutting tool under dry and
MQL conditions and the cutting point temperatures were investigated. Depending on the measurement results, MQL method decreased the cutting point temperatures. According to the studies in literature, applying MQL method in machining operations provides an advantage on reducing the cutting temperature. However, some studies have been performed on using nanofluids in MQL method to improve its performance. Kalita et al. [9] investigated the impinging and lubricating mechanisms of nanolubricants in MQL surface grinding of ductile cast iron. Nano MoS\(_2\) (Molybdenum Disulphide) particles were added to paraffin oil to prepare the nanofluids. Based on the temperature measurements, a reduction in friction induced heat generation was occurred due to nanolubricants.

Mao et al. [10] used nanofluid MQL method in grinding of hardened AISI 52100 steel with Al\(_2\)O\(_3\) (Alumina) grinding wheel. Nanofluids were prepared by adding different sized nano Al\(_2\)O\(_3\) particles to base fluid (deionized water). The results indicated that the peak grinding temperature was not affected from diameter of nano particles. Sayuti et al. [11] carried out nanofluid MQL milling experiments on aerospace AL6061-T6 aluminum alloy and nano SiO\(_2\) (Silicon Dioxide) particles were used at 0.0, 0.2, 0.5, and 1.0 wt% in preparing nanofluids. According to the experimental results, much less friction and thermal deformation between tool and workpiece contact surfaces occurred in nanofluid MQL milling using huge amount of nano SiO\(_2\) particles. Padmini et al. [12,13] performed MQL turning experiments on AISI 1040 steel by using nano MoS\(_2\) particles reinforced vegetable cutting fluids. The cutting temperature was effectively reduced by applying nanofluid MQL method when compared to dry machining. As is seen in previous studies, the use of nanofluids in MQL method is beneficial and nano MoS\(_2\) particles help reducing the cutting temperatures due to being well lubricant. Therefore, in this work, the cutting temperatures were examined in milling of AISI 430 ferritic stainless steel workpiece with uncoated and coated carbide tools in dry, MQL and nanofluid MQL environments. Nano MoS\(_2\) particles were used in nanofluid preparations at three weight ratios and the influences of nano MoS\(_2\) amount, coating and MQL flow rate on the cutting temperature were specified.

### MATERIALS, EQUIPMENTS AND NANOFLUID PREPARATION

In experimental studies, AISI 430 ferritic stainless steel workpieces in dimensions of 400x250x6 mm were machined by utilizing a vertical CNC machining center. The chemical composition of the workpiece material can be seen in Table 1. In the experiments, uncoated and TiN (Titanium Nitride) coated WC (Tungsten Carbide) cutting tool inserts were used and mounted on an end mill tool holder in diameter of 32 mm.

![Table 1. Chemical composition of ferritic stainless steel](image)

<table>
<thead>
<tr>
<th>C%</th>
<th>Mn%</th>
<th>S%</th>
<th>P%</th>
<th>Si%</th>
<th>Ni%</th>
<th>Cr%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.052</td>
<td>0.69</td>
<td>0.002</td>
<td>0.029</td>
<td>0.67</td>
<td>0.26</td>
<td>16.54</td>
</tr>
</tbody>
</table>

In milling operations, the cutting temperatures were measured by Optris® CTlaser 3MH1 two-wire infrared thermometer. This device has measurement range of 150°C - 1000°C and response time of 1 ms. During measurements, the laser beam was focused on the cutting tool and the measurements were performed as seen in Figure 1. The arithmetic means of the cutting temperature measurements were determined.

![Figure 1. Cutting temperature measurement during milling operation](image)

Before the milling experiments, nanofluids were prepared by adding nano MoS\(_2\) (Molybdenum Disulphide) particles to the commercial vegetable cutting fluid at 0.5%wt., 1%wt. and 2%wt. Firstly, the nano MoS\(_2\) particles (10-20 nm) seen in Figure 2 were dried in a drying oven at 120°C for 2 hours. Then, the mixture consisting of dried nano MoS\(_2\) particles, commercial vegetable cutting fluid and sodium dodecyl sulfate was stirred by using Daihan WiseTis HG-15D digital homogenizer at 5000 rpm for 2 hours. Sodium dodecyl sulfate was added to the mixture to enhance the homogeneity.
The milling experiments were carried out under dry, MQL (Minimum Quantity Lubrication) and nanofluid MQL cutting conditions by using process parameters given in Table 2. In MQL milling operations, Werte DKN 25 micro lubrication system was utilized at MQL pressure of 5 bar, nozzle distance to cutting tool of 50 mm and nozzle angle in parallel to workpiece surface of 10°.

Table 2. Process parameters

<table>
<thead>
<tr>
<th>Milling conditions</th>
<th>Dry, MQL, nanofluid MQL (0.5%wt., 1%wt., 2%wt. nano MoS₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MQL flow rate</td>
<td>20 ml/h and 40 ml/h</td>
</tr>
<tr>
<td>Cutting tool</td>
<td>uncoated WC and TiN coated WC</td>
</tr>
<tr>
<td>Cutting speed</td>
<td>100 m/min</td>
</tr>
<tr>
<td>Feed rate</td>
<td>180 mm/min</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>0.5 mm</td>
</tr>
</tbody>
</table>

EXPERIMENTAL RESULTS

In MQL milling, cutting fluid is pulverized through MQL system and applied to the cutting zone form nozzles. Thus, the cutting fluid can reach the inner zones between cutting tool and workpiece and penetrate the cutting zone completely. Therefore, in this experimental study, MQL method had advantages on dry cutting as seen in Figure 3 and Figure 4. For instance, the cutting temperature was measured as 373.9°C in dry cutting with uncoated WC cutting tool whereas this value was 353°C and 334.8°C when used MQL system at MQL flow rate of 20 ml/h and 40 ml/h, respectively. Additionally, nano MoS₂ particles enhanced the lubrication properties of the commercial cutting fluid due to being well lubricant and so the cutting temperatures decreased. Increasing the amount of nano MoS₂ particles in unadulterated cutting fluid reduced the cutting temperatures. For example, in MQL milling with TiN coated WC cutting tool at MQL flow rate of 20 ml/h, the cutting temperatures were measured as 337.5°C, 319.8°C, 299.1°C and 286.24°C for unadulterated, nanofluid reinforced 0.5%wt. MoS₂, nanofluid reinforced 1%wt. MoS₂ and nanofluid reinforced 2%wt. MoS₂ cutting fluids, respectively. When compared to the uncoated and TiN coated cutting tools, the coated tools caused reducing the cutting temperatures due to high hardness and wear resistance of TiN coating.

CONCLUSION

In this work, ferritic stainless steel parts were cut under dry, MQL and nanofluid MQL conditions with uncoated and TiN coated WC cutting tools by a CNC machining center. Nano MoS₂ particles reinforced commercial vegetable cutting fluids were produced for nanofluid MQL cutting operations and the cutting temperatures were measured. Depending on the experimental results, TiN coating reduced the cutting temperature by about 6.09% as compared with uncoated WC cutting tool. Besides, the cutting temperatures decreased by about 7.74% when used the MQL method as referenced to the dry cutting and were reduced by about 5.17% when increased the MQL flow rate from 20 ml/h to 40 ml/h. The minimum cutting temperature values were measured in nanofluid MQL milling and increasing the amount of nano MoS₂ particles in unadulterated cutting fluid had advantage on decreasing the values. In nanofluid MQL milling, the cutting temperatures decreased by about 10.66%, 16.48% and 19.75% as used nanofluid produced by adding 0.5%wt., 1%wt. and 2%wt. nanofluid reinforced 0.5%wt. MoS₂, nanofluid reinforced 1%wt. MoS₂ and nanofluid reinforced 2%wt. MoS₂ cutting fluids, respectively when compared with the dry cutting.
Figure 4. Cutting temperature in milling at MQL flow rate 40 ml/h with a) uncoated WC, b) TiN coated WC cutting tool

ACKNOWLEDGMENTS

In this study, the experiments and measurements were carried out by using MQL system, infrared thermometer and digital homogenizer which were acquired in the project of The Scientific and Technological Research Council of Turkey (TÜBİTAK, Project Number: 114M098).

NOMENCLATURE

Al₂O₃  Alumina
HSS  High Speed Steel
MoS₂  Molybdenum Disulphide
MQL  Minimum Quantity Lubrication
SiO₂  Silicon Dioxide
TiN  Titanium Nitride
WC  Tungsten Carbide

REFERENCES


