JOURNAL OF MATERIALS RESEARCH AND TECHNOLOGY 2022;21:893–904

Available online at www.sciencedirect.com

jmr&t
Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

Original Article

Determination of machinability metrics of AISI 5140 steel for gear manufacturing using different cooling/lubrication conditions

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ARTICLE INFO

Article history:
Received 10 August 2022
Accepted 15 September 2022
Available online 21 September 2022

Keywords:
AISI 5140
CNC milling
Gear manufacturing
Machinability
Dry
Minimum Quantity Lubrication (MQL)
Cryogenic-LN_2

ABSTRACT

AISI 5140 steel is mostly used in gear manufacturing for variety of industries. Those gears can be manufactured via casting, powder metallurgy or forging techniques. Nevertheless, machining (via turning and milling processes) remains the most common manufacturing method to fabricate them. Milling of gears made from 5140 steel can be challenging due to the excessive energy consumption, rapid tool wear and poor surface finish. Therefore, traditional and environmentally friendly coolants are usually applied during machining to improve the surface finish and prolong tool life. The current study aims to investigate machinability performance of 5140 steel under different cooling/lubrication conditions. Several machinability metrics were investigated and analyzed (surface roughness, cutting temperature, tool wear, chip morphology, and energy consumption). Milling tests were performed under different cutting speeds (75 and 100 m/min), different feed rates (0.15 and 0.2 mm/rev) and dry, minimum quantity lubrication (MQL), and cryogenic liquid cooling/lubrication conditions (dry, MQL and cryo-LN_2). The results showed that using Cryo-LN_2 cooling/lubrication tended to improve all the investigated machinability metrics compared to dry condition. The surface roughness was reduced by approximately 54%, while the cutting temperature was reduced by 87%. Similarity, the cutting tool flank wear was reduced by 20% thus energy consumption was minimized by 15%. The current study shows the importance of cryogenic machining in industry for difficult to cut materials.

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https://doi.org/10.1016/j.jmrt.2022.09.067

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1. Introduction

AISI 5140 steel, also called alloy steel, is a highly preferred material in the manufacturing sectors (i.e. automotive, construction and machine parts such as gears and shafts) [1]. However, the machinability of AISI 5140 steel can be challenging due to the high chromium content in its chemical structure [2]. Machinability studies can include many metrics. However, surface roughness critical wear is the most critical metric that directly affects the workpiece. Low surface roughness is an important parameter for milling operations in terms of showing machining success and product quality [3,4]. Surface roughness values change depending on factors such as cutting tool geometry, cutting temperature, vibration, and pressure during cutting. The increased wear amount, unstable cutting forces, and excessive vibrations in the cutting tool flank and rake areas affect the workpiece surface roughness. Therefore, the selection of the right lubrication/cooling conditions and cutting parameters are very important [5]. One of the machinability parameters is cutting tool wear. Cutting tool wear may vary depending on cutting conditions [6–8]. Different cutting parameters, workpiece material, cutting tool material, different C/L conditions can be given as examples of these conditions. And anomalies in these conditions can cause unpredictable changes in the cutting area, accelerating cutting tool wear [9]. Progressive tool wear affects the surface integrity, and it is of great importance to monitor the cutting tool wear to ensure the desired level of surface integrity [10].

Kahraman [11], investigated the optimization of surface roughness and cutting parameters in the machining of studs made of AISI 5140 steel using Taguchi method. It was found that the optimum cutting parameters were determined with the developed model and it could be used in metal machining industries. Elbah et al. [12], focused on surface roughness analysis of different inserts used during hard turning of AISI 4140 steel using optimization techniques. They reported that the surface quality achieved with the wiper ceramic insert was significantly improved compared to the traditional ceramic insert. Aslan [13], investigated the machinability analysis and optimization of AISI 5140 steel. Their results showed that 87% of success was achieved with RSM-based optimization and cutting forces were related to each other. Grzesik [14], investigated the effects of Al_2O_3-TiC coated cutting tools on the machinability of AISI 5140 steel to study the tool wear mechanisms, plastic flow, and BUE (Built Up Edge). Machinability processes can be difficult due to negative reasons such as high toughness, low heat conduction and low work hardening of materials [15]. These difficulties reduce productivity and worsen surface quality. A basic understanding is needed to increase productivity and tool life [16]. There are many factors to increase machinability properties. The most important of these factors is the cooling/lubrication (C/L) conditions. Adequate cooling can be achieved with the use of conventional cutting fluids [17]. But it can be quite harmful for the environment. In studies conducted by many researchers, the use of traditional cutting fluids is reduced by using environmentally friendly cooling methods (MQL, cryogenic). Thus, a sustainable manufacturing option emerges. Dry machining has many disadvantages due to negative consequences such as surface defects and maximum tool wear [18,19]. To avoid these negative situations, more efficient machining can be performed using minimum quantity lubrication (MQL) [20]. Kamata and Obikawa [21] investigated the machinability properties of nickel-based superalloys. They reported significantly improved tool life and improved surface quality with machining under MQL conditions. Ji et al. [22] used different cooling techniques for drilling Ti6Al4V alloys. They reported that by using the MQL technique, the energy consumption was reduced and they achieved a better hole quality. Khan et al. [23] investigated turning of AISI 9310, low alloy steel, under MQL conditions and found it reduces tool wear and improves surface quality compared to dry and wet machining. Another alternative to conventional cutting fluids is cryogenic cooling. In the cryogenic cooling method, a liquid cooler (such as LN_2, CO_2, etc.) is used at approximately -196 °C. The high temperature in the cutting zone can be reduced by intensely sprayed cryogenic cloud. Cryogenic machining is a sustainable choice compared to conventional cooling/lubrication conditions to produce high quality products [24]. Kara et al. [25] investigated the performance of grinding parameters of AISI 5140 steel. They reported that they obtained optimum surface roughness in cryogenically treated samples. Şap et al. [26] investigated the machinability properties of copper-based hybrid composites using different cooling techniques. They reported that with cryogenic cooling, cutting temperatures and flank wear were reduced and surface quality improved.

There is a great deal of research on cryogenic machining of many materials used in industry. However, there are few studies on the processing of AISI 5140 medium carbon steel. This study focuses on improving the machinability properties of AISI 5140 steel using different processing parameters and MQL and cryo LN_2 cooling/lubrication techniques. Thus, it is aimed to increase the machinability quality of a material that is frequently used for gear manufacturing in the manufacturing sector.

2. Materials and methods

2.1. *Workpiece material and cutting tool properties*

In this study, AISI 5140 steel, with the chemical properties given in Table 1 was used in the machining tests. The effects of these elements on steel can be listed as follows;

- C: Provides strength and hardenability but reduces formability.
- Si: It is included in the steel as an oxygen remover.
- Mn: Takes place in the steel structure like carbon and shows a feature that increases the strength of the steel.
- P: Increases the yield and tensile strength of the steel and also increases the ability to be formed by machining.

Table 1 – Chemical composition of AISI 5140 steel.

Elements	C	Si	Mn	P	S	Cr
%	0.45	0.3	0.75	0.035	0.03	1

- S: It is an element that remains in the material structure in steel production. It is removed from the material due to its undesirable properties. The amount of this element can be kept high only because it increases the machined formability feature.
- Cr: Provides corrosion and oxidation resistance and increases hardenability.

A total of twelve cylindrical specimens with a diameter of Ø75 mm and a length of 25 mm were used. A HM90 APKT 1003PDR IC908 coded cutting tool was used with Al-TiN coating with ISO 13399 PVD method. A new insert was used for milling each specimen to avoid any effects of tool wear. The inserts were mounted on the APKTHM10 12-1-120 shank carding router. The cutting tool is attached to the CNC machine with a tool holder with a tool collet (MAS 403 BT 40 ER 32x70) (Fig. 1).

2.2. *Milling tests*

Milling tests were performed on a Dahlih MCV-860 CNC vertical machining center with a maximum speed of 10000 rpm and a power of 7.5 kW. Before starting the experiments, a 0.5 mm layer was removed from each specimen to eliminate the effect of slag. Fig. 2 shows the setup of the machinability experiments.

Cutting data for the experiments were used from the catalog data of the cutting tool manufacturer. Two different cutting speeds (75 and 100 m/min) and two different feed rates (0.15 and 0.2 mm/rev) were selected in the experiments. During the experiments, the cutting depth was determined as 0.5 mm for each level, and the total cutting depth was kept constant at 1.5 mm. For milling, the “Zig” toolpath is derived with the down-milling strategy using the CAM program. All processing parameters for machinability experiments are indicated in Table 2.

Fig. 1 – Cutting tool clamping system.

2.3. *Cooling/lubricating conditions*

In this study, MQL and cryo-processing medium were included along with the traditional dry working method of 5140 steel. For MQL fluid, KT-2000 cutting fluid used in spray-working systems was used for steel and its alloys, HSS-type hard steels and non-ferrous metals. Werte STN 15 was selected for the MQL spray device. With a pressure of 6 bar, the flow rate of the MQL liquid was set to 50 mL/h. The MQL nozzle, which has a liquid outlet diameter of 2 mm, the nozzle was fixed at a distance of approximately 150 mm from the cutting area and an angle of 45°. Liquid nitrogen was used as the cryogenic coolant. Heat loss was prevented by using a vacuum hose for LN_2 stored in the Taylor Wharton LD-50 nitrogen tank. The nozzle diameter of the cryo-spraying apparatus was 2 mm in diameter. The nozzle was fixed at a distance of approximately 150 mm from the cutting zone and an angle of 45°. The flow rate of LN_2 liquid with 8 bar spraying pressure was set as 20 L/h.

2.4. *Measurement processes*

During the workability tests, power measurements were made with the HIOKI PW 3198 device. While the device makes precise and simultaneous measurements for all parameters, it makes these measurements in accordance with all international standards as Class A according to IEC 61000-4-30. Active power was calculated by connecting the current clamps in the device to the main power supply cables of the CNC machine and taking the current-voltage values from three phases. Thanks to the device's software, power-energy measurement results were obtained.

During the milling tests, in the last pass (3rd pass), the cutting temperature was measured with a TESTO 885 thermal camera before the cutting tool came out of the workpiece (Fig. 3). The thermal camera measuring distance was set to approximately 500 mm. Thus, it provided a thermal image by measuring the temperature in reliable and real-time during milling environment.

Post-experiment surface roughness measurements were performed on a tracer-tipped surface roughness device (Insize ISR C100). For the accuracy and reproducibility of the results, the largest and smallest values were subtracted from the seven measurements taken at different regions in each sample. In addition, this process was applied to the shaft surface for an industrially used gear wheel. The values obtained as a result of the experiments were compared with the gear wheel shaft surface roughness. Statistical evaluations of the remaining five values were performed and their standard deviations were determined. The commonly used R_a arithmetic mean calculation method was preferred for surface roughness results [27]. Table 3 shows the information on instrument standards.

Finally, scanning electron microscope (SEM) images and energy dispersive spectroscopy (EDS) analysis was performed on the JEOL JSM 6510 SEM device to obtain information about the wear mechanisms (flank and rake wear). As a result of SEM analysis, information was obtained about the damages that occurred in the cutting tool. In addition, flank wear measurement values and chip morphology images were obtained with the Insize ISM-PM200SB measurement microscope.

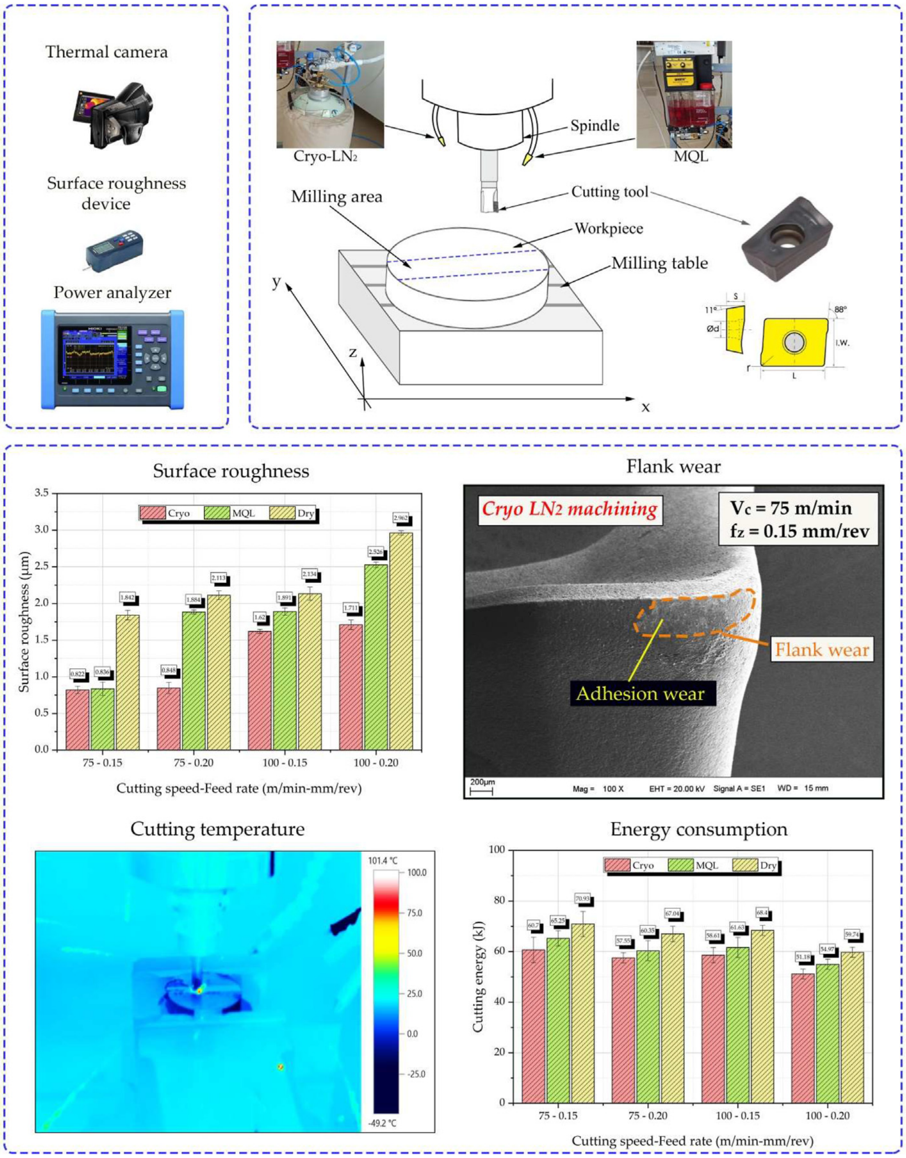


Fig. 2 – Schematic representation of machinability experiments.

Table 2 – Experiment processing parameters and levels.

Experiment number	Cutting speed (m/min)	Feed rate (mm/rev)	Cooling/ Lubricating conditions
1	75	0.15	Cryo – LN_2
2	75	0.2	Cryo – LN_2
3	100	0.15	Cryo – LN_2
4	100	0.2	Cryo – LN_2
5	75	0.15	MQL
6	75	0.2	MQL
7	100	0.15	MQL
8	100	0.2	MQL
9	75	0.15	Dry
10	75	0.2	Dry
11	100	0.15	Dry
12	100	0.2	Dry

3. Results and discussion

In this section, the results of surface roughness, cutting temperature, tool wear, chip morphology, and energy consumption analysis are reported as a result of machinability tests for 5140 steel, which shows less than 5% error rate and high repeatability.

3.1. *Surface roughness analysis*

Fig. 4 shows the effect of different cooling/lubricating conditions on surface roughness. When the mean deviation values in the test repetitions were examined, it was determined that the test results performed in cryo-LN_2 and MQL C/L conditions at low cutting speed and low feed rate were very close. However, C/L conditions did not show similar results at different cutting speeds and feed rates. It was observed that the surface

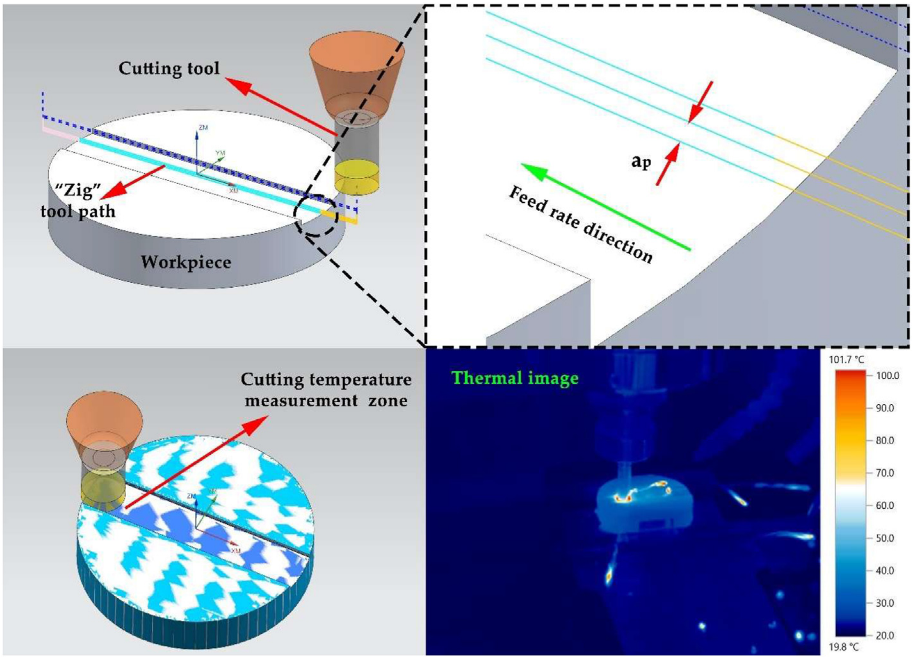


Fig. 3 – Tool path and temperature measurement procedure for milling operation.

roughness values increased with increasing cutting speed and feed rate. It can be said that the change in cutting speed is more effective on the surface roughness values. It was observed that the dry conditions provided the worst surface roughness values compared to MQL and cryogenic tests. The lowest surface roughness occurred in specimens machined using cryo-LN_2. For example; The lowest surface roughness value (R_a = 0.822 μm) was obtained with a cryo-LN_2 cooling medium at 75 m/min cutting speed and 0.15 mm/rev feed rate. However, this case did not change at increasing cutting speeds and feed rates, and it was observed that the best surface roughness values were obtained with this cooling medium. For this case where the best surface roughness value was achieved, it was observed that the surface roughness value was improved by 53.96% compared to dry condition milling and also 1.67% compared to milling in MQL lubrication condition. High-pressure cryogenic LN_2 transferred between the cutting tool and the chip shows an endothermic reaction and evaporates by absorbing the ambient water during cutting. This case makes it wet and provide a lubrication medium on the surface and between the tool chips. Thus, it significantly reduces the surface roughness of the workpiece by providing minimum friction. In addition, high pressure contributes to the removal of old chips from the environment, preventing the deterioration of the surface quality during cutting [28]. Likewise, it was observed that the highest surface roughness value (R_a = 2.962 μm) was obtained in a dry condition at a cutting speed of 100 m/min and a feed rate of 0.2 mm/rev. Similarly, as a result of experiments with other machining parameters, it was observed that milling in dry conditions provided the worst surface roughness values. In all tests performed under MQL lubrication conditions, it was observed that it showed better surface performance than the tests performed in a dry environment due to the Rehbinder effect [29]. In addition, although the surface roughness results in samples machined at low feed rate using cryo-LN_2 at low feed rates in the experiments with MQL, it evaporates earlier in the cutting area at high feed rates [30]. Thus, the surface quality between MQL and cryo-LN_2 becomes more evident at high feed rates at the same cutting speed. In a study, it is stated that the MQL flow rate can be increased to minimize this difference [31]. The results obtained were found to agree with the literature [28,32].

Finally, the average surface roughness value obtained from the tooth surface of the gear wheel used in the industrial area was R_a = 1.857 μm Experiments with cryo-LN_2 in this study showed a high success by staying well below this value. It also succeeded in experiments with MQL at low cutting speed (V_c = 75 m/min).

3.2. *Cutting temperature*

High machining temperatures are produced during milling due to friction and plastic deformation in the cutting zone [33]. While the cutting temperature increase with tool wear, it can also affect the surface integrity of the workpiece [5,34]. The selection of different C/L conditions is important to mitigate the effects of machining temperatures. In this article, the effect of different C/L conditions on cutting temperatures was determined. Fig. 5 gives information about the cutting temperatures between the cutting tool and the cutting surface in all experiments in different C/L conditions. Since there was an apparent separation for C/L conditions in the results of repeated experiments, the mean deviation values were not at a level to affect the experimental results. The cutting temperature was found to be higher at a higher with the increase of the cutting speed. which was also observed in previous literature [35,36]. This could be attributed to the increase in

Table 3 – Surface roughness device parameters.

Parameter	Cut off	n*cut off	Standard	Range	Filter	Display R
Range	2.5 mm	1 L	ISO	±20 μm	RC	R_a

plastic deformation with cutting speed, [37]. Cryogenic LN_2 was found to significantly reduce the cutting temperature. The cooling effect of the LN_2also increases the hardness of the machined material [32] and thus better surface quality can be achieved. Fig. 4 supports this notion. In addition, this opinion is supported due to the reduction of friction with the hydrodynamic effect of the refrigerant by forming a thin tribo-film [38]. In experiments with Cryo LN_2, it was determined that the cutting temperature improved by up to 87%. With the MQL method, the cutting temperature is expected to decrease according to the dry condition [39]. In the experiments carried out in MQL conditions, it was observed that the cutting temperature improved by approximately 25% compared to dry conditions. MQL fluid entering the cutting zone reduces friction and plays an important role in dispersing the cutting temperature [40]. Finally, it was observed that the cutting temperature decreased with increasing feed rate, inversely to the cutting speed. The authors can explain this case for two reasons. Firstly, with increasing feed rate, less friction occurs, so this case results in lower cutting temperature. Another reason is that as the chip removal volume increases with the increase in the feed rate, more chip evacuation occurs from the cutting zone. Thus, increased chip volume carries more heat from the cutting zone. This result is in agreement with the result reported in the literature [41].

3.3. *Tool wear and tool wear mechanism*

Fig. 6 shows the maximum wear on the tool flank (VB_{max}) at different C/L conditions and different cutting-feed rates. It was observed that the mean deviation values between the experiments were higher at low cutting speed and lower at high cutting speed. Predictably, the maximum VB_{max} value occurred in specimens machined under dry conditions as there was no C/L condition. For example; VB_{max} was 0.537 mm at a cutting speed of 100 m/min and a feed rate of 0.15 mm/rev under dry conditions. In addition, the lowest VB_{max} values occurred in samples machined under the cryogenic condition. For example; The VB_{max} value was 0.349 mm at a cutting speed of 75 m/min and a feed rate of 0.2 mm/rev. Compared to milling in dry conditions, the MQL medium provided an improvement of about 15% for the VB_{max} value, while the cryogenic LN_2 medium provided an improvement of about 22%. There are several reasons why cryogenic cooling with LN_2 may yield the best values. Either LN_2 may have lowered the temperature effectively and reduced wear because it has a very high boiling point [42] or it may have contributed positively to the reduction of the friction coefficient [43].

It was observed that VB_{max} increased in parallel with the increase in cutting speed. In addition, it was observed that the cutting speed was effective in flank wear. This result was found to agree with the literature [39]. It was observed that the cutting temperature increased with the increasing cutting speed, as mentioned in Fig. 6. The high temperature in the cutting zone causes an increase in tool wear [44]. For VB_{max}, it was reported that the feed rate did not have as much effect as the cutting speed [45]. It was determined that the VB_{max} value decreased by approximately 3% when the cutting speed was increased to 75 m/min, and by approximately 16% when the feed rate was increased to 100 m/min. It can be said that this decrease is due to the decrease in friction between the cutting tool and the workpiece with the increase in the feed rate. This case is supported by a study conducted [46].

Figs. 7 and 8 present SEM micrograph under different C/L conditions. In addition to SEM analysis, the presence of BUE is detected with EDS analysis. The same cutting parameters were used for each SEM micrograph so that a clear comparison could be made. It is important to be able to understand the

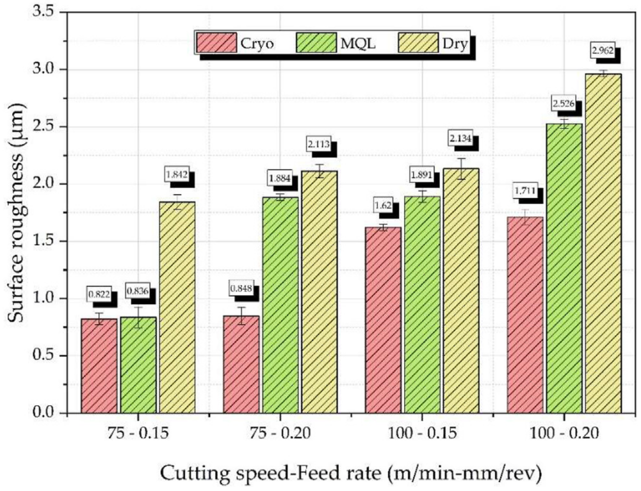


Fig. 4 – Effect of machinability test parameters on surface roughness.

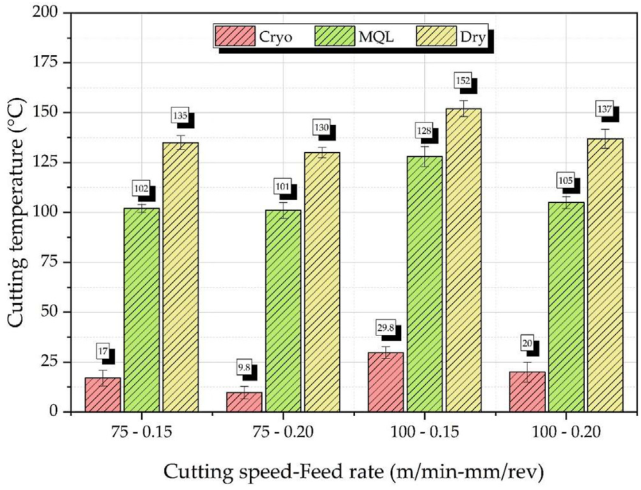


Fig. 5 – Effect of machinability test parameters on cutting temperature.

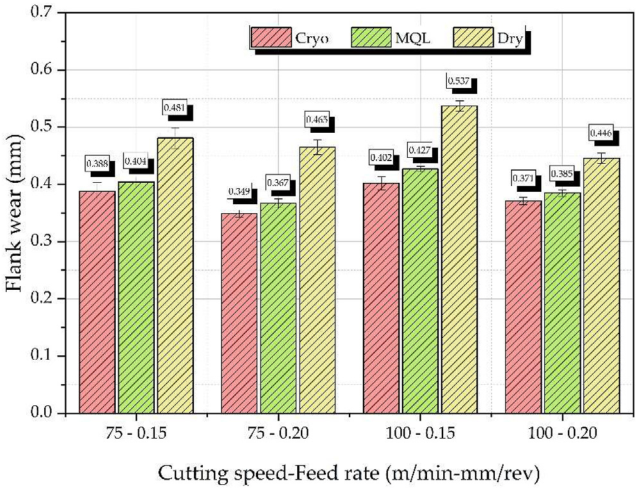


Fig. 6 – Effect of machinability test parameters on flank wear.

wear progression and application, and to know the wear mechanisms for the cutting tool. Examples of these wear mechanisms are adhesive, abrasive, diffusion and oxidation. Knowing these wear mechanisms is important for improving machinability [9]. It is critical to know the cutting tool wear mechanisms in order to reduce the manufacturing cost, especially since the use of this type of material is very high in the industry. The most common wear mechanisms encountered after the experiments were adhesive and abrasive. Flank wear and crater wear can be seen in Figs. 7 and 8. In experiments with the cryo LN_2 cutting medium, it was observed that the flank wear and crater wear regions were relatively smaller. In addition, it was observed that the crater wear area was smaller in the experiments performed at low cutting speeds compared to the experiments performed at high cutting speeds. It causes diffusion with chemical affinity due to high cutting temperatures between the cutting tool and the workpiece during the milling process [47]. This case often occurs behind the rake face and thus can lead to crater wear. BUE formation was not observed in milling under MQL and cryo-LN_2 conditions. MQL and cryo LN_2 conditions have a lower cutting temperature than the dry cutting conditions and also MQL and cryo LN_2 conditions form a thin film on the cutting tool-chip friction surface. Therefore, the BUE phenomenon does not occur as the friction and cutting temperature is not sufficient to cause melting of the material [37]. Plastic deformation that occurs at high temperatures during cutting makes the material unstable in the chip flow region. Thus causing adhesion wear mechanism [48]. BUE formations were found on the cutting tool under dry conditions. It was determined that BUE formations decreased in experiments with lower cutting speeds. Fig. 9 provides insight into understanding the type of wear occurring, along with the EDS analysis. It was observed that this case caused an increase in the surface roughness values. Although BUE is unstable, it reduces the cutting ability of the cutting tool and is known to increase surface roughness values [37]. In this study, the high surface roughness values that occurred in a dry environment can be attributed to BUE formation.

3.4. *Chip morphology*

Chip morphology is also of great importance in order to obtain a quality surface in machinability tests. It is also critical to know and evaluate chip morphologies for cutting tool life [49]. Cutting parameters, C/L conditions, cutting tool and workpiece material are variables that affect chip morphology [50].

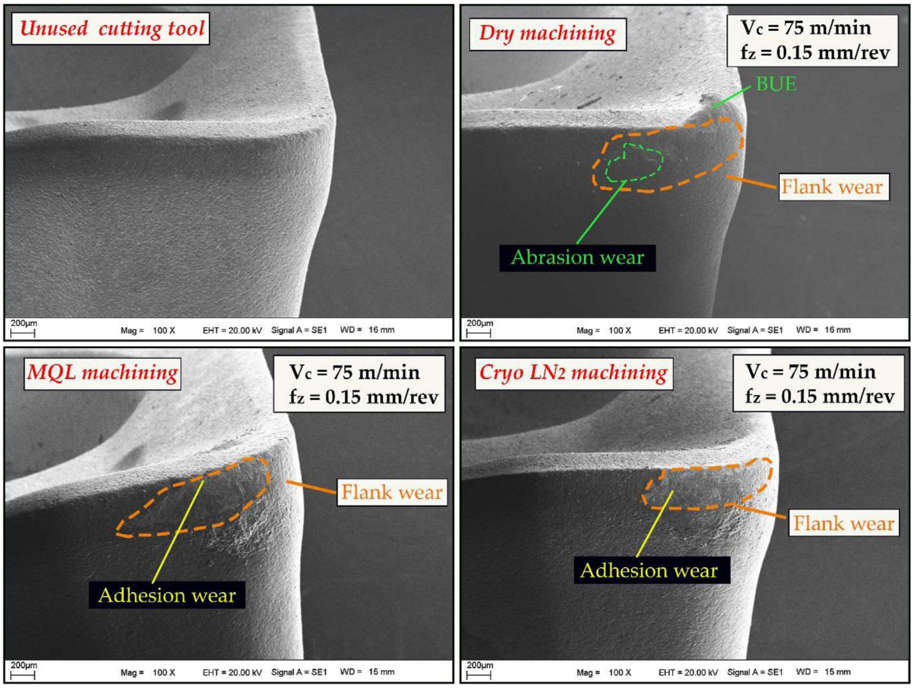


Fig. 7 – Imaging of wear mechanisms on the flank face of different C/L conditions by SEM analysis.

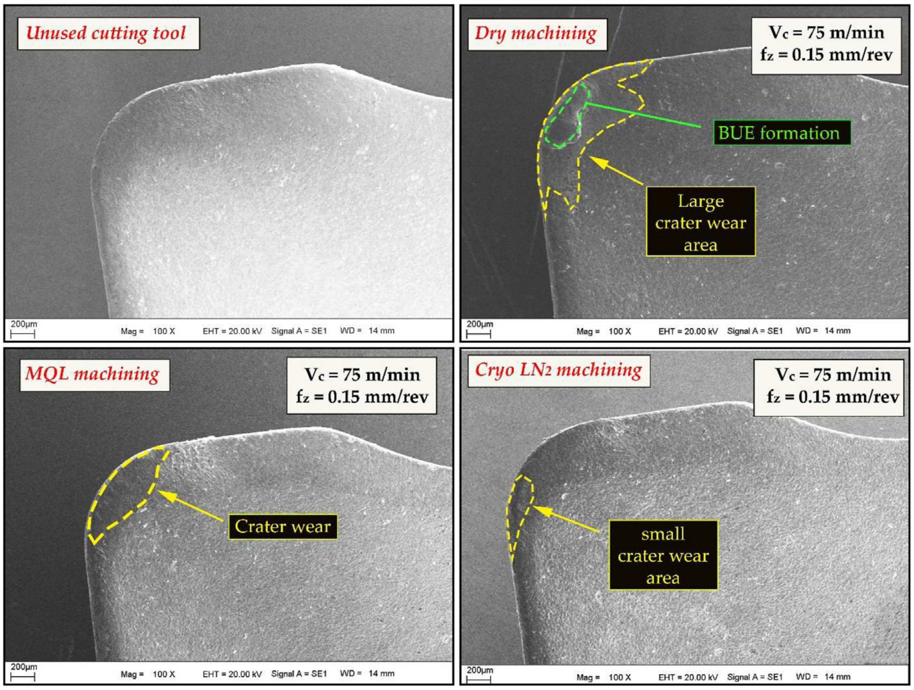
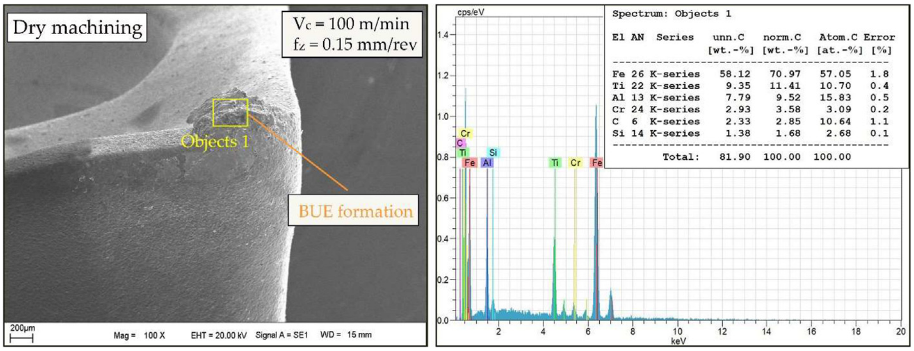


Fig. 8 – Imaging of wear mechanisms on the rake face of different C/L conditions by SEM analysis.

The chip morphology obtained after the experiments is also important for this study. Fig. 10 shows the chip formed under different cooling conditions. It can be seen that different chip lengths were obtained under different cooling conditions. The chip forms obtained were of the "C" type, with intermediate length. The longest chip types were obtained under dry condition, while the shortest chip were formed under cryogenic condition. Short chips are easy to remove from the cutting zone which reduces the damage caused from the chips on the machined surface [49]. Regular and small serrations were observed in milling operations performed in the cryo-LN_2 condition, while this order was maintained for milling operations performed in other conditions, but growth and enlargement of serrations were observed. This result, like other results, once again emphasizes the importance of cryo-LN_2 on machinability. Especially in the milling process in dry condition, the presence of large and wide serrations caused by intense friction can be supported by other results obtained in the study, which negatively affects the cutting tool wear and the workpiece surface. In the experiments carried out under MQL C/L condition, it was determined that the chips helped to obtain a higher quality surface. With these results, it was seen that the superior cooling and lubrication conditions of cryogenic cooling and MQL provide significant advantages to chip formation and, accordingly, other machinability metrics affected by chips.

3.5. *Energy consumption*

Minimizing energy consumption in a manufacturing process is critical [51]. Improvements in energy costs can have a major impact on machining (milling, turning, and drilling, etc.) economics [52]. In this study, the effect of different C/L conditions was investigated to ensure minimum cutting energy consumption of 5140 steel. Fig. 11 systematically presents the effects of different cutting parameters and different cooling conditions on cutting energy consumption. Between repeated experiments, the mean deviation values were low at low



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Spectrum: Objects 1

El AN  Series    unn.C    norm.C   Atom.C Error
               [wt.-%]  [wt.-%]  [at.-%]  [%]
-----------------------------------------------
Fe 26 K-series   58.12    70.97    57.05   1.8
Ti 22 K-series    9.35    11.41    10.70   0.4
Al 13 K-series    7.79     9.52    15.83   0.5
Cr 24 K-series    2.93     3.58     3.09   0.2
C   6 K-series    2.33     2.85    10.64   1.1
Si 14 K-series    1.38     1.68     2.68   0.1
-----------------------------------------------
        Total:   81.90   100.00   100.00
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Fig. 9 – Analysis of BUE formation with EDS.

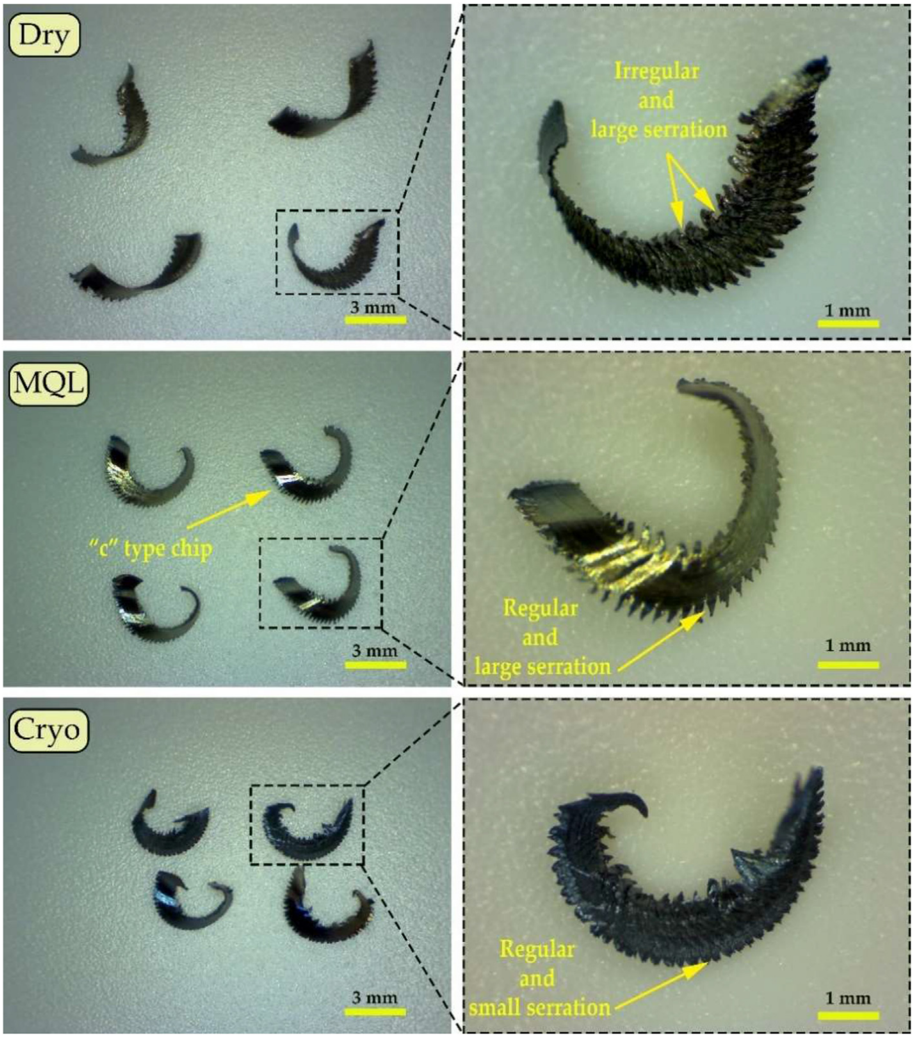

Fig. 10 – **Effect of different C/L conditions on chip formation ($V_c = 75$ m/min and $f_z = 0.2$ mm/rev).**

cutting speeds and different feed rates. In contrast, the mean deviation values were relatively lower at high cutting speeds and feed rates. After the machinability tests, it can be said that the best option for the minimum cutting energy (51.18 kJ) occurs when using cryogenic cooling followed by MQL and then dry condition. When it provides minimum cutting energy ($V_c = 100$ m/min and $f_z = 0.2$ mm/rev) with cryogenic cooling, it offers an improvement of about 15% compared to dry milling. As explained in the previous sections, the superior cooling/lubrication effect of cryogenic cooling leads to an improvement in the tribological performance between the cutting tool-chip-workpiece, keeping the energy requirement at a minimum compared to other C/L conditions. These results were found to agree with the knowledge in the literature [32,46]. It can be said that the friction will be more in the milling operations carried out in dry conditions, therefore it consumes more energy with the deformation occurring in the cutting tool. Energy consumption is also related to cutting parameters. It was determined that as the cutting speed increased, the energy consumption decreased by approximately 3–5 kJ. The main reason for this decrease can be related to the fact that the increase in cutting speed provides

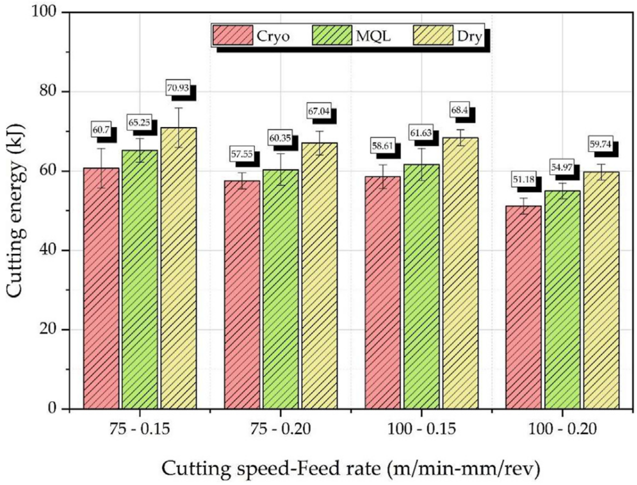

Fig. 11 – **Effect of workability test parameters on energy consumption.**

easier deformation in the workpiece and the milling process requires less energy. A study by Salur [32], supports this opinion. Another reason is that with the increase in cutting speed, the table feed (V_f) will increase and the total milling time will decrease, so the energy consumption may have decreased somewhat. It is also seen as an increase in feed rate with another cutting parameter that causes the total machining time to decrease. It was observed that the increase in the forward speed decreased the energy requirement.

4. Conclusion

5140 steel is a very important material for the gear manufacturing industry. Therefore, it is very important to improve the machinability metrics of this material. This study, it was aimed to develop machinability metrics of 5140 steel according to dry environment using cryo-LN_2 and MQL C/L conditions. The results obtained in this context are summarized as follows:

- ✓ In the study, the best surface quality (R_a = 0.822 μm) for different environments (C/L conditions) was obtained for the cryo-LN_2 C/L condition at the smallest cutting speed (Vc = 75 m/min) and the smallest feed rate. While this value was 0.836 μm for MQL, it was determined as 1.842 μm for dry milling. In addition, it was determined that the surface roughness values increased with increasing cutting speed and increasing feed rate.
- ✓ In experiments performed under cryo-LN_2 C/L conditions, it was observed that the cutting temperature improved dramatically. The lowest cutting temperature (9.8 °C) was obtained at a cutting speed of 75 m/min and a feed rate of 0.2 mm/rev. In the same experiment with MQL C/L condition, this value was 101 °C, while the experiment in dry condition reached 145 °C.
- ✓ Tool wear values were determined by measuring flank wear. The best value (0.349 mm) was determined for the cryo-LN_2 C/L condition at a cutting speed of 75 m/min and a feed rate of 0.2 mm/rev in parallel with the cutting temperature. This value was followed by MQL with 0.367 mm, and dry condition with 0.465 mm, respectively.
- ✓ Considering the chip morphologies, the chip types obtained in all experiments were mostly determined as “c” types. Undesirable spiral and complex chip types were not encountered. When the results were compared in terms of C/L conditions, it was seen that the best chip shape was provided by cryo-LN_2. Serrations for chip shapes for this condition were as desired.
- ✓ Compared to other C/L conditions, cryo-LN_2 has a good friction coefficient reduction feature, so less energy consumption occurred in experiments with this media. It has been determined that it provides 15% energy savings compared to the dry processing environment.
- ✓ The experiment's results determined a parallel relationship between surface roughness, flank wear, and cutting temperature. For example, for an experiment with cryo-LN_2 (V_c: 75 m/min and f_n: 0.15 mm/rev), the lower cutting temperature resulted in less cutting tool wear and, therefore, a higher surface quality. Only the energy consumption was different. The reason for this was that the increase in the feed rate decreased the experiment time. The energy consumed decreased depending on the duration of the experiment.
- ✓ When the results given above are analyzed collectively, the cryo-LN_2 in milling process for 5140 steel presented a success for all machinability metrics. Offers an alternative C/L condition for the gear manufacturing industry.

5. Future work

In this study, three different C/L conditions (cryo-LN_2, MQL, and dry) were presented for 5140 steel, which is frequently used in gear manufacturing.

- In future studies, machinability properties with different C/L conditions can be investigated. In particular, the effect of nanofluid and cryo-MQL hybrid C/L environments, which are known to have significant effects recently, on machinability metrics can be examined.
- The machinability tests of 5140 steel can be enriched by determining the effect of different C/L environments on cutting forces. Thus, more detailed information can be obtained for the cutting tool wear phenomena.
- By examining sustainable metrics such as cutting cost and energy analysis, studies can be conducted on the sustainable manufacturing of 5140 steel.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This study was produced from the doctoral thesis titled “Development of a New Type External Gear Pump Using Circular Evolvent Gears and Analysis of Performance Characteristics”. Also, this work was supported by the Research Fund of the Inonu University. (Project Number: FDK-2021-2658).

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