Thermal Loads and Surface Quality Evaluation in Machining of Hardened Die Steel under Dry and Cryogenic Machining

Farshid Jafarian*
Faculty of Engineering, Mahallat Institute of Higher Education, Mahallat, Iran
E-mail: Fjafarian@mahallat.ac.ir
*Corresponding author

Emad Mohseni
Faculty of Engineering, Mahallat Institute of Higher Education, Mahallat, Iran
E-mail: Emad.mohseni5676@gmail.com

Received: 6 May 2019, Revised: 6 August 2019, Accepted: 13 October 2019

Abstract: AISI H13 die steel is widely used in different industries because of its especial properties. During the machining of hard materials, some of the mechanical properties of the material are changed due to the generation of intensive thermo-mechanical loads and plastic deformation into the workpiece. Controlling these intensive changes in machined surfaces is an important task and significantly affects the performance of the machined part. In addition, surface roughness is one of the aspects of surface texture and affects the fatigue life of the material. Since machining of hard materials is a difficult procedure and it is confronted with several limitations, new methods in machining processes are essential to be developed. One of these methods is using cryogenic coolant where the machining temperature may be considerably reduced by spraying liquid nitrogen on the cutting region. Based on this, at the present study, the variation of thermal loads and surface roughness at different machining parameters were evaluated under dry and cryogenic conditions. To do this, a thermal infrared camera and liquid nitrogen delivery system was used during the machining of hardened AISI H13 steel. Compared with dry condition, the effectiveness of the cryogenic coolant on surface roughness and thermal loads were analysed and discussed at different cutting speed, feed rate, and depth of cut. Finally, it was found that, applying cryogenic coolant in machining of AISI H13 die steel can be very effective to enhance performance and quality of the machined component in terms of surface roughness and thermal loads.

Keywords: AISI H13, Cryogenic Machining, Surface Roughness, Thermal Loads

Reference: Farshid Jafarian, and Emad Mohseni, "Thermal Loads and Surface Quality Evaluation in Machining of Hardened Die Steel under Dry and Cryogenic Machining", Int J of Advanced Design and Manufacturing Technology, Vol. 13/No. 1, 2020, pp. 83–90.

Biographical note: Farshid Jafarian received his PhD in Mechanical Engineering from University of Birjand. Now he is an assistant professor at Mahallat Institute of Higher Education. His research interests include numerical and experimental studies in surface integrity of machining, intelligent methods in manufacturing processes, and additive manufacturing. **Emad Mohseni** now is BSc student at Mahallat Institute of Higher Education in Mechanical Engineering. His research interests include characteristics on machined surface and enhancing performance in machining process.

1 INTRODUCTION

AISI H13 die steel includes numerous properties including high thermal strength, high resistance against high thermal shocks, reasonable toughness, and high hardness. These advantages have led to its widespread use in molding, hot forging, extrusion, and gear manufacturing industries [1-2]. Machining processes are nowadays extensively employed in manufacturing industries for production of different parts. During these processes, intense thermo-mechanical loads are generated within the material. These loads can cause microstructural changes, micro-cracks and residual stresses in the final product [3-4].

Consequently, surface integrity in difficult-to-cut materials is a significant issue. Surface integrity indications are surface texture (surface roughness and quality), metallurgical alterations (microstructural changes, white and dark layer development, and phase change), and mechanical aspects (residual stress and plastic deformation) [5]. The thermal loads produced during the process are an important factor in evaluating the surface integrity after machining. These thermal loads often lead to residual tensile stresses in the material and microstructural changes such as the formation of white and dark layers in hardened die steel [4].

Surface roughness of the machined wokpiece is a surface texture parameter that has a considerable influence on the durability and quality of the component. The thermal loads developed during the chip formation can result in an increase in surface roughness. This event leads to a reduction in fatigue life and an increase in formation and spreading of micro-cracks in the machined surface [6]. Furthermore, the changes induced by thermal loads can reduce tool life and increase production costs. Therefore, special attention should be taken into account for reduction of thermal loads and the microstructural changes in order to increase the performance and quality of the manufactured parts [7].

Recently, new strategies such as the use of high pressure coolant and cryogenic coolant have been employed for improving the machining performance. In cryogenic cooling, liquid nitrogen is sprayed onto the location of contact between the tool and the workpiece during the chip formation process which considerably reduces the temperature of the cutting zone. As a result, microstructural changes, residual tensile stress, and heat affected zone are reduced [8-10]. Dananchezian et al. [11] have shown that, using the cryogenic coolant systems can reduce the temperature at the cutting area more than 50% compared to dry conditions. In addition, using the cooling condition in machining process is effective for enhancement of tool life. Owing to these advantages, researchers extensively employ various cooling methods in order to improve the quality and efficiency of products [12]. A number of studies carried out by other researchers are mentioned in the following.

2 LITERATURE REVIEW

In the study conducted by Umbrello et al. [13], the effect of the machining parameters on the surface integrity of the AISI 52100 steel was investigated. Their results show that an increase in the cutting speed leads to higher thermal loads during the machining process. Ramesh et al. [4] studied the microstructural changes (formation of white layer) during the orthogonal cutting of AISI 52100 steel. Dahlman et al. [14] have studied the effect of the tool geometry on surface integrity of the machined surface. Their results demonstrate that the negative rake angles produce higher compressive residual stresses. Zhao et al. [15] have investigated the effect of the radius of the cutting edge on the roughness of the machined surface. Their results indicate that as the cutting edge radius is increased, the roughness value initially rises, and as the radius rises further, it is reduced.

The quality of the machined surface of AISI 4340 steel was studied by Kumar et al. [16]. Their results show that the value of roughness increases with increasing feed rate and it is decreased with increasing cutting speed. In a research conducted by Aouici et al. [17], the effects of different tool geometries on the surface quality of machined AISI H11 steel was evaluated. Kumar et al. [18] have recently studied the impact of tool type and material hardness on the thermal loads generated during the machining of AISI 4340 steel. Abdelkrim et al. [19] have also found that the maximum machining temperature generally is increased at higher depth of cut and cutting speed. The research was conducted by Özel et al. [20] on AISI H13 steel and it was reported that, a smaller tool nose radius and lower material hardness lead to a higher surface roughness. Tang et al. [21] conducted research on the effect of the initial material hardness on the quality of the machined surface. They found that higher initial hardness causes the surface quality to be deteriorated. They reported that increasing the hardness value generally reduced the amount of thermal loads. Sarnobat et al. [22] have also obtained similar results in their studies on AISI D2 steel. The effect of machining parameters on the machined surface quality was investigated in by Hessainia et al. [23].

Most indications of surface integrity such as surface roughness, residual stress and microstructure state at the machined component are highly affected by the thermal loads generated during the machining process. Therefore, to improve performance and component life, it is an important task to avoid and eliminate thermal loads induced during the machining process as far as possible. Since, many advantages of liquid nitrogen make it an attractive choice as a cryogenic, it is highly recommended to conduct further studies on the consequences of its use on the machinability of final products.

As mentioned above, not only few studies have been conducted on machining of AISI H13 steel, but also no investigation can be found around evaluation of surface quality and thermal loads under dry and cryogenic machining of AISI H13 die steel. In fact, there is not any research in literature around machining of hardened die steel to compare and evaluate the surface quality and thermal loads in dry and cryogenic conditions. Hence, it seems that more investigation is essential around evaluation of new coolant delivery systems such as cryogenic system on machining performance. Based on this, at the present study, the effect of cryogenic system with liquid nitrogen was evaluated at different machining parameters. Subsequently, the impact of each process parameters was evaluated on the thermal loads and the surface roughness. To this, several experiments were conducted under dry conditions cryogenic conditions. Thermal infrared camera was used in order to assess the produced thermal loads. Then, the average roughness of the machined surface was measured using a roughness tester.

3 EXPERIMENTS

In order to evaluate the thermal loads and the surface quality in the machining process of AISI H13 alloy, the number of 10 testing experiments subject were conducted at each dry and cryogenic conditions.

Length and diameter of the samples were prepared in 100 mm and 20 mm, respectively and they were hardened up to 52 HRC. The chemical composition of the AISI H13 alloy is reported in “Table 1”.

Table 1 Chemical composition of AISI H13 steel alloy

AISI H13	Ni	Mn	C	Mo	Si	V	Cr	Fe
wt%	0.19	0.28	0.44	0.93	1.04	1.12	5.39	Rest

The cutting tool was tungsten carbide (TCMW16T304-ARNO) without a chip breaker that provided tool nose radius of 0.4 mm and cutting edge radius of 10 µm. The utilized tool holder provides rake angle and clearance angle of 7º and 0º, respectively. The experiments were carried out under dry and cryogenic cooling conditions (with liquid nitrogen) at different feed rate, depth of cut, and cutting speed and the effect of each parameter was evaluated on the thermal loads and the surface roughness. The machining parameters for each testing experiment were reported in “Table 2”. The machine tool and the liquid nitrogen source are shown in “Fig. 1”.

An infrared thermal camera with capability of measurement up to 1000º(c) was used for measuring the thermal loads produced during machining process. After machining the samples, the roughness was measured at three points using the PCE RT 2200 Roughness Tester, and the average roughness was reported.

Table 2 Machining parameters applied during machining

Test number	V_c (rpm)	a_p (mm)	a_f (mm/rev)
1	355	0.8	0.08
2	500	0.8	0.08
3	710	0.8	0.08
4	1000	0.8	0.08
5	500	0.5	0.08
6	500	1.1	0.08
7	500	1.4	0.08
8	500	0.8	0.14
9	500	0.8	0.2
10	500	0.8	0.24

Fig. 1 Machine tool and the liquid nitrogen tank.

4 RESULTS AND DISCUSSION

In this section, the experimental results on the thermal loads and the surface quality after machining are discussed. The thermal loads generated at the machined region were measured under dry and cryogenic conditions at different cutting speeds, depths of cut, and feed rates. After machining the samples, the roughness was measured at three points and the average of surface roughness was reported. Finally, the effects of the different machining conditions on maximum machining temperature produced at the cut zone and the surface roughness at machined surface were evaluated and compared.

4.1. Investigation of the Thermal Loads

The mechanical contact between the tool and the workpiece during the machining process often leads to plastic deformation and thermal gradient at the cutting region. The thermal loads produced during the machining process result in microstructural changes, residual tensile stresses, and probability of fatigue fracture in the material [24]. Based on the significance of the mentioned changes in quality of the final product, it is possible to improve the reliability, quality, and performance of the part by means of methods that decrease the temperature at the cutting region. Spraying liquid nitrogen on the machining area is an effective strategy to reduce the thermal loads generated during the process.

Therefore, at the present study, couples of experiments were conducted to compare the thermal loads produced in machining of hard material under dry and cryogenic conditions. For measuring the generated heat, a thermal infrared camera was used with the emissivity and humidity parameters taken as 0.3 and 40%, respectively. To this end, the thermal camera was located at a 1-meter distance from the machine tool, and the temperature distribution at the machining region was measured during the operation. The spray of liquid nitrogen on the machining area and arrangement of the thermal camera are shown in “Fig. 2”.

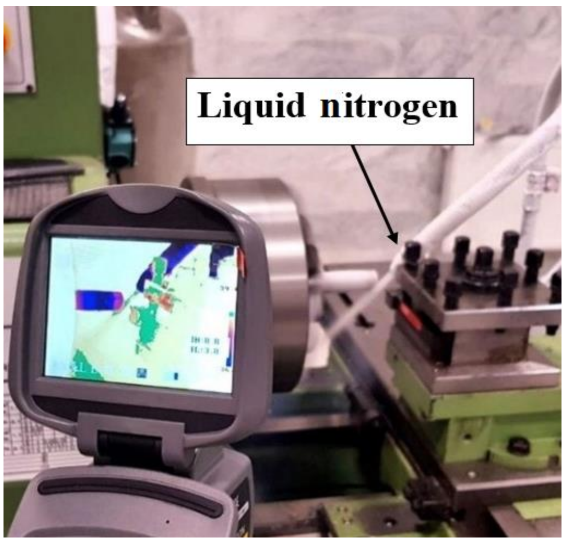

Fig. 2 The thermal camera when measuring the thermal loads generated at the machined area.

As an example, the thermal camera image for both dry and cryogenic conditions for test number of 2 can be seen in “Fig. 3”. After conducting the machining experiments, the variation of maximum machining temperature at different cutting speeds, feed rates, and depths of cut was compared and evaluated for both dry and cryogenic conditions and the results are reported in “Fig. 4”.

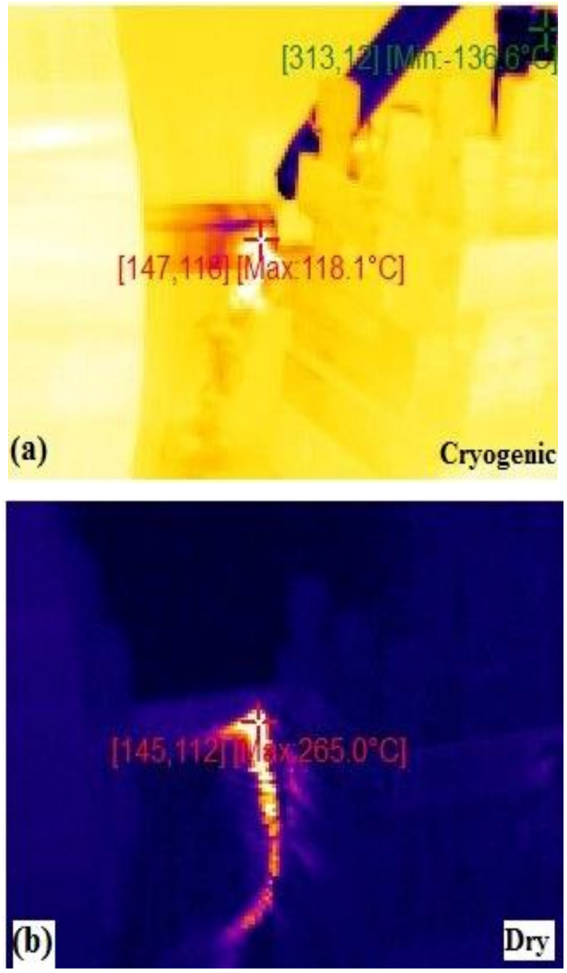

Fig. 3 A sample thermal camera image for testing number of (2): (a): cryogenic conditions and (b): dry conditions.

The variation in temperature at different cutting speed is given in “Fig. 4(a)”. As shown, the temperature is generally decreased with increasing cutting speed under dry conditions. In contrast, this temperature undergoes little change with increasing cutting speed under cryogenic conditions. According to the results, the temperature changes from 123°C to 116.9°C with an increase in cutting speed from 355 rpm to 1000 rpm under cryogenic conditions. For dry conditions, the temperature is firstly decreased with an increase in cutting speed from 355 rpm to 500 rpm and then, it is increased from 265°C to 321.3°C. The reason of this event can be related to having no enough time for heat exchange with environment at dry machining when cutting speed is increased. It leads to a temperature increase in the cutting area [25]. According to the obtained results, with increasing cutting speed in cryogenic machining, the temperature at the machined location is reduced up to 63% relative to the corresponding values for the dry condition.

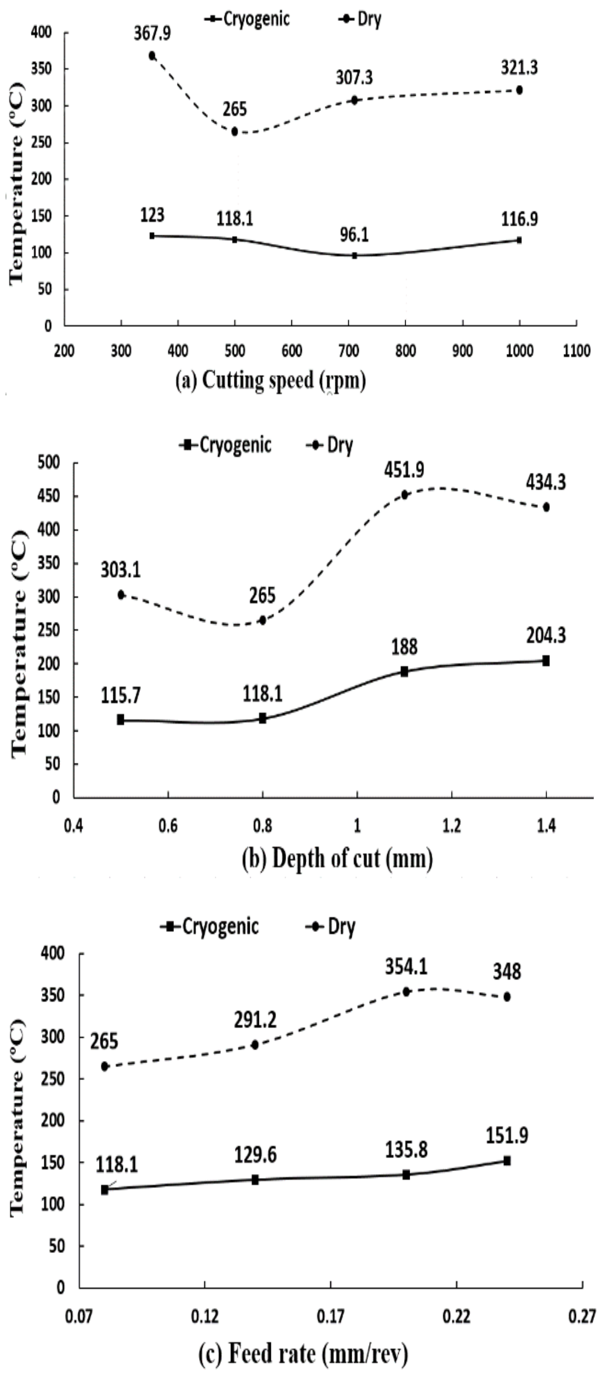

Fig. 4 Comparison temperature distribution under dry and cryogenic conditions at different: (a): cutting speed, (b): depth of cut, and (c): feed rate.

"Fig. 4(b)" displays the temperature distribution induced in machining of AISI H13 steel at different depths of cut. The results indicate that, the thermal loads are remarkably increased with increasing depth of cut for both dry and cryogenic conditions. With an increase in the depth of cut from 0.5mm to 1.4mm, the temperature increases from 265°C to 434.3°C under dry conditions and it is enhanced from 115.7°C to 204.3°C under cryogenic conditions. The reason seems to be that with an increase in the depth of cut, the tool penetrates more into the workpiece. Subsequently, the mechanical contact between the tool and the workpiece is increased, and consequently higher plastic deformation and cutting forces are induced. As the results of these events, higher thermal loads are expected to generate [26]. It was found that, the maximum machining temperature is reduced up to 56% by using cryogenic condition when the depth of cut is changed.

The variation in temperature versus feed rate is reported in "Fig. 4(c)". Based on the results, the machining temperature is continuously increased with increasing feed rate for both dry and cryogenic conditions. With an increase in the feed rate from 0.08 mm/rev to 0.24 mm/rev, the temperature is enhanced from 265°C to 348°C and from 118.1°C to 151.9°C for dry and cryogenic conditions, respectively. It seems that with an increase in the feed rate, higher chip formation rate and higher work hardening lead to a higher temperature at the machined region. By increasing the feed rate, it is possible to increase the machined area temperature under cryogenic conditions compared to the corresponding values under dry conditions.

A comparison was made among the obtained results, and it was found that the depth of cut is the most effective cutting parameters for enhancement of temperature. According to the results, utilizing a cryogenic coolant plays an important role in reducing the machining thermal loads. Furthermore, it can decrease the temperature of the machined region up to 50% relative to the corresponding values under dry machining. Since thermal loads significantly affect surface roughness, studying these loads is beneficial for studying the surface roughness. The following will investigate the experimental value of the surface roughness.

4.2. Investigation of Surface Quality

Surface roughness is considered a key parameter of surface texture [27]. It has a great impact on the fatigue life of the part, and its high values make the assembly of parts problematic. Therefore, the investigation of this parameter seems imperative. To this end, a number of tests under dry and cryogenic conditions were carried out at different cutting parameters. Subsequently, surface roughness of the machined surface was measured using the PCE RT 2200 Roughness Tester at three points, and the average of surface roughness was reported. Finally, the effect of each cutting conditions on the post-machining surface roughness was reported and evaluated.

The changes in the surface roughness versus the cutting speed for both dry and cryogenic conditions can be observed in "Fig. 5(a)". Based on the results, the surface roughness values were initially increased and then they were decreased at higher cutting speeds under dry conditions. In contrast, the surface roughness value almost remains constant under cryogenic conditions. With an increase in cutting speed from 355 rpm to 710 rpm under dry conditions, the surface roughness rises from 0.72 µm to 1.46 µm, whereas it almost remains fixed at higher cutting speeds. Under cryogenic conditions, an increase in cutting speed from 355 rpm to 1000 rpm results in a negligible variation in surface roughness. It seems that the Built-Up Edge (BUE) formation in dry machining at low cutting speeds leads to an increase in surface roughness.

The variation in surface roughness versus depth of cut is reported in “Fig. 5(b)”. According to the results, the surface roughness was initially deteriorated and then, it was improved with increasing depth of cut under dry conditions. In more detail, with increase in the depth of cut from 0.5 mm to 1.1 mm, the surface roughness changes from 1.28 µm to 0.84 µm. In addition, an increase in the depth of cut from 1.1 mm to 1.4 mm leads to a rise in roughness from 0.84 µm to 1 µm. It seems, BUE formation at low depths of cut temporarily changes cutting edge geometry so that, this event can lead to the improvement of surface quality. On the other hand, when the cryogenic condition is applied, the surface roughness continuously is enhanced from 0.61 to 0.95 µm with increasing depth of cut. It shows that under cryogenic conditions, BUE is not generated during the process and the surface quality is deteriorated at higher depth of cut due to the higher tool vibration. Comparing the results of surface roughness for both dry and cryogenic conditions indicate that, the effectiveness of the cryogenic coolant for improvement of surface quality is more dominant at lower depths of cut.

The effect of feed rate on surface quality is indicated in “Fig. 5(c)”. The results indicate that the surface roughness is increased considerably at higher feed rates for both dry and cryogenic conditions. With an increase in the feed rate from 0.08 mm/rev to 0.24 mm/rev, the surface roughness rises from 1.231 µm to 15.71 µm under dry conditions and it is changed from 0.61 µm to 6.12 µm under cryogenic conditions. It is probable that the tool wear rate is increased with rising feed rate, leading to a remarkable enhancement of surface roughness [26]. Employing cryogenics has a positive impact on reducing the surface roughness when high feed rate is applied so that, the surface roughness is changed from 15.71 µm at dry conditions to 6.12 µm under cryogenic coolant conditions.

Finally, the effects of different machining conditions on the surface quality were evaluated by comparing the results. It was found that machining at dry conditions and increasing the feed rate play significant roles in increasing the surface roughness. In contrast, cryogenic machining can reduce the surface roughness by more than 50%. It shows, cryogenic machining with liquid nitrogen is really influential for improving the post-machining surface quality.

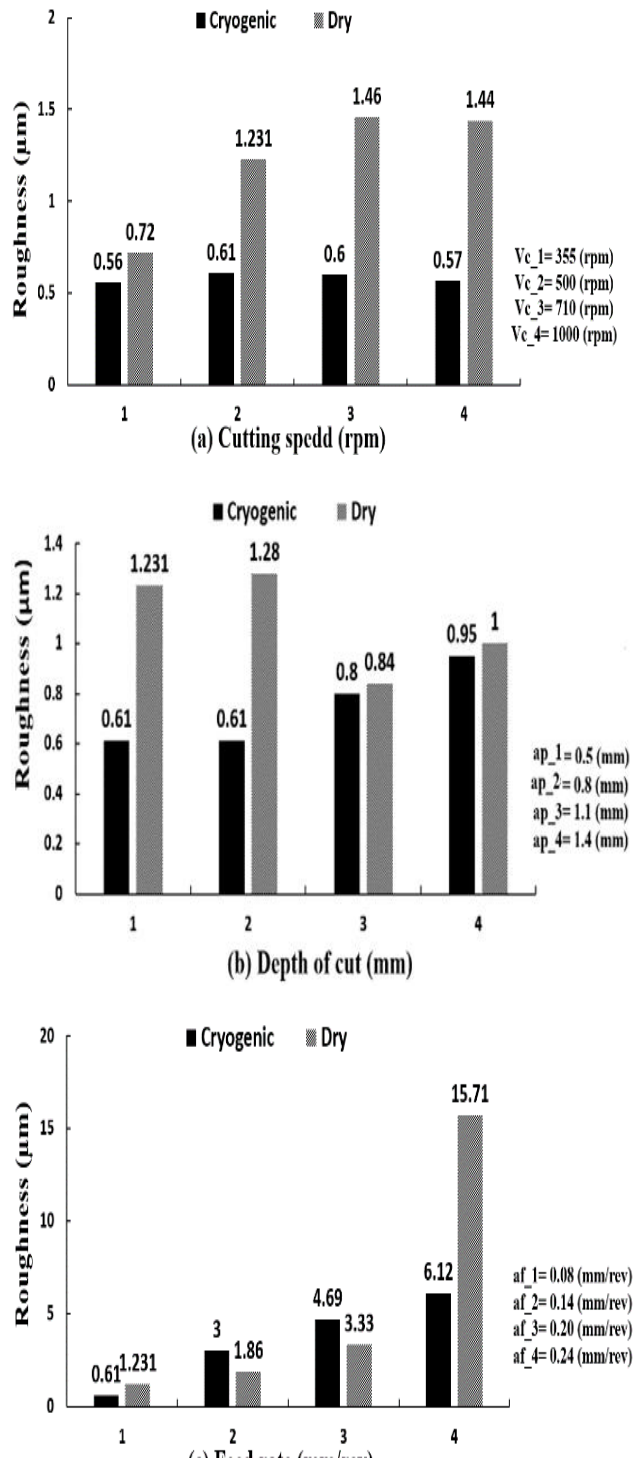

Fig. 5 Comparison of changes in the surface roughness of the machined surface due to changes in: (a): cutting speed, (b): depth of cut, and (c): feed rate, under dry and cryogenic conditions.

5 CONCLUSION

At the present study, cryogenic machining with liquid nitrogen was introduced as the new coolant system for machining process of hardened AISI H13 steel and its performance on thermal loads and surface quality were compared with dry conditions at different cutting conditions. Some of the results can be listed as follows:

- After comparing the results, it was found that depth of cut has the most dominant influence on temperature enhancement in machining process. By increasing the depth of cut, maximum machining temperature was 451.9°C and 204.3°C for dry and cryogenic conditions, respectively. In addition, at the lower depths of cut, cryogenic coolant was more effective for reduction of machining temperature than higher depths.
- Compared with feed rate, when cutting speed is increased, the difference between the maximum machining temperature under dry and cryogenic conditions becomes more. Based on this, with an increase in the feed rate from 0.08 mm/rev to 0.24 mm/rev, the temperature was changed from 265°C to 348°C and from 118.1°C to 151.9°C for dry and cryogenic conditions, respectively.
- The results indicate that, the feed rate is the most effective parameter on surface roughness for both under both dry and cryogenic conditions. By increasing the feed rate from 0.08 to 0.24 mm/rev, the surface roughness is increased from 1.231 to 15.71 µm and from 0.61 to 6.12 µm for dry and cryogenic conditions, respectively. It was also shown that, at highest feed rate, the surface quality is satisfactorily better when cryogenic coolant is employed.
- Compared with dry conditions, the effect of cryogenic coolant is more visible for improvement of surface quality at lower depths of cuts (less than 1mm) and at higher cutting speeds (more than 500rpm). For cutting depth of 0.5 mm, while the resurface roughness was 0.61 µm at dry conditions, it was 1.231 µm under dry conditions.

REFERENCES

[1] Boy, M., yaşar, N., and Çiftçi, I., Experimental Investigation and Modelling of Surface Roughness and Resultant Cutting Force in Hard Turning of Aisi H13 Steel, Materials Science and Engineering, Vol. 161, 2016, pp. 012039, DOI: https://doi.org/10.1088/1757-899X/161/1/012039.

[2] Cui, X., Zhao, J., and Tian, X., Tool Wear in High-Speed Face Milling of Aisi H13 Steel, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Tribology, Vol. 226, No. 10, 2012, pp. 1693-1684, DOI: https://doi.org/10.1177/0954405412455378.

[3] Shi, L., Investigation of Tool Wear and Surface Roughness When Turning Titanium Alloy (Ti6Al4V) Under Different Cooling and Lubrication Conditions, Ferroelectrics, Vol. 526, No. 1, 2018, pp. 199-205, DOI: https://doi.org/10.1080/00150193.2017.1391003.

[4] Jafarian, F., 3D Modeling of Recrystallized Layer Depth and Residual Stress in Dry Machining of Nickel-Based Alloy, Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol. 41, No. 4, 2019, pp. 198, DOI: https://doi.org/10.1007/s40430-019-1707-x.

[5] Masoudi, S., Vafadar, A., Hadad, M., and Jafarian, F., Experimental Investigation into The Effects of Nozzle Position, Workpiece Hardness, And Tool Type in Mql Turning of Aisi 1045 Steel, Materials and Manufacturing Processes, Vol. 33, No. 9, 2018, pp. 1011-1019, DOI: https://doi.org/10.1080/10426914.2017.1401716.

[6] Dhar, N. R., Paul, S., and Chattopadhyay, A. B., Machining of AISI 4140 Steel Under Cryogenic Cooling - Tool Wear, Surface Roughness and Dimensional Deviation, Journal of Materials Processing Technology, Vol. 123, No. 3, 2002, pp. 483-489, DOI: https://doi.org/10.1016/S0924-0136(02)00134-6.

[7] Jafarian, F., Masoudi, S., Soleimani, H., and Umbrello, D., Experimental and Numerical Investigation of Thermal Loads in Inocnel 718 Machining, Materials and Manufacturing Processes, Vol. 33, No. 9, 2018, pp. 1020-1029, DOI: https://doi.org/10.1080/10426914.2018.1424907.

[8] Masoudi, S., Esfahani, M. J., Jafarian, F., and Mirsoleimani, S. A., Comparison the Effect of MQL, Wet and Dry Turning on Surface Topography, Cylindricity Tolerance and Sustainability, International Journal of Precision Engineering and Manufacturing-Green Technology, Vol. 6, No. 2, 2019, pp.100-113, DOI: https://doi.org/10.1007/s40684-019-00042-3.

[9] Sun, S., Brandt, M., and Dargusch, M. S., Thermally Enhanced Machining of Hard-To-Machine Materials—A Review, International Journal of Machine Tools and Manufacture, Vol. 50, No. 8, 2010, pp. 663-668, DOI: https://doi.org/10.1016/j.ijmachtools.2010.04.008.

[10] Karmakar, D. P., Gopinath, M., and KumarNath, A., Effect of Tempering on Laser Remelted Aisi H13 Tool Steel, Surface and Coatings Technology, Vol. 36, 2019, pp. 136-149, DOI: https://doi.org/10.1016/j.surfcoat.2019.01.022.

[11] Dhananchezian, M., Kumar, M. P., and Sornakumar, T., Cryogenic Turning of AISI 304 Stainless Steel with Modified Tungsten Carbide Tool Inserts, Materials and Manufacturing Processes, Vol. 26, No. 5, 2011, pp. 781-785, DOI: https://doi.org/10.1080/10426911003720821.

[12] Evans, C., Bryan. J. B., Cryogenic Diamond Turning of Stainless Steel, CIRP Annals-Manufacturing Technology, Vol. 40, No. 1, 1994, pp. 571-575, DOI: https://doi.org/10.1016/S0007-8506(07)62056-3.

[13] Umbrello, D., Influence of Material Microstructure Changes On Surface Integrity in Hard Machining of Aisi 52100 Steel, International Journal of Advance Manufacturing Technology, Vol. 54, 2011, pp. 887-898, DOI: https://doi.org/10.1007/s00170-010-3003-x.

[14] Dahlman, P., Gunnberg, F., and Jacobson, M., The Influence of Rake Angle, Cutting Feed and Cutting Depth On Residual Stresses in Hard Turning, Journal of Materials Processing Technology, Vol. 147, No. 2, 2004, pp. 181-184, DOI: https://doi.org/10.1016/j.jmatprotec.2003.12.014.

[15] Zhao, T., Zhou, J. M., Bushlya, V., and Ståhl, J. E., Effect of Cutting Edge Radius On Surface Roughness and Tool Wear in Hard Turning of Aisi 52100 Steel, International Journal of Advanced Manufacturing Technology, Vol. 91, 2017, pp. 3611-3618, DOI: https://doi.org/10.1007/s00170-017-0065-z.

[16] Kumar, S., Singh, D., and Singh Kalsi, N., Surface Quality Evaluation of Aisi 4340 Steel Having Varying Hardness During Machining with Tin-Coated Cbn Inserts, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Vol. 231, No. 7, 2016, pp. 925-933, DOI: https://doi.org/10.1177/1350650116684243.

[17] Aouici, H., Fnides, B., Elbah, M., Benlahmidi, S., Bensouilah, H., and Yallese, M. A., Surface Roughness Evaluation of Various Cutting Materials in Hard Turning of Aisi H11, International Journal of Industrial Engineering Computations, Vol. 7, 2016, pp. 339-352, DOI: https://doi.org/10.5267/j.ijiec.2015.9.002.

[18] kumar, S., Dilbag, S., and Singh Kalsi, N., Study on the Effect of Workpiece Hardness and Toolnose on Cutting Force and Chip-Tool Interface Temperature During Dry Hard Turning of Aisi 4340 Steel, I-Manager's Journal on Mechanical Engineering, Vol. 8, No. 1, 2018, pp. 8-19, DOI: https://doi.org/10.26634/jme.8.1.13821.

[19] Abdelkrim, M., Brabie, G., Belloufi, A., Catalin, T., and Chirita, B., Experimental Investigations to Evaluate the Effects of Cutting Parameters on Cutting Temperature and Residual Stresses During Milling Process of the AISI 1045, IOP Conference Series: Materials Science and Engineering, Vol. 227, 2017, pp. 012001, DOI: https://doi.org/10.1088/1757-899X/227/1/012001.

[20] Özel, T., Hsu, T. K., and Zeren, E., Effects of Cutting Edge Geometry, Workpiece Hardness, Feed Rate and Cutting Speed on Surface Roughness and Forces in Finish Turning of Hardened Aisi H13 Steel, The International Journal of Advanced Manufacturing Technology, Vol. 25, 2005, pp. 262-269, DOI: https://doi.org/10.1007/s00170-003-1878-5.

[21] Tang, L., Gao, C., Huang, J., Shen, H., and Lin, X., Experimental Investigation of Surface Integrity in Finish Dry Hard Turning of Hardened Tool Steel at Different Hardness Levels, International Journal of Advance Manufacturing Technology, Vol. 77, 2015, pp. 1655-1669, DOI: https://doi.org/10.1007/s00170-014-6484-1.

[22] Sarnobat, S. S., Raval, H. K., Experimental Investigation and Analysis of the Influence of Tool Edge Geometry and Work Piece Hardness on Surface Residual Stresses, Surface Roughness and Work-Hardening in Hard Turning of Aisi D2 Steel, Measurement, Vol. 131, 2019, pp. 235-260, DOI: https://doi.org/10.1016/j.measurement.2018.08.048.

[23] Hessainia, Z., Yallese, M. A., Chaoui, K., Mabrouki, T., and Rigal, J. F., On the Prediction of Surface Roughness in The Hard Turning Based on Cutting Parameters and Tool Vibrations, Measurement, Vol. 46, No. 5, 2013, pp. 1671 – 1681, DOI: https://doi.org/10.1016/j.measurement.2012.12.016.

[24] Rotella, G., Dillon., O. W., Umbrello, D., Settineri, L., and Jawahir, I. S., The Effect of Cooling Condition on Surface Integrity in Machining of Ti6Al4V, International Journal of Advance Manufacturing Technology, Vol. 71, No. 14, 2014, pp. 47-55, DOI: https://doi.org/10.1007/s00170-013-5477-9.

[25] Garcı´a Navas, V., Gonzalo, O., and Bengoetxea, I., Effect of Cutting Parameters in the Surface Residual Stresses Generated by Turning in Aisi 4340 Steel, International Journal of Machine Tools & Manufacture, Vol. 61, 2012, pp. 48-57, DOI: https://doi.org/10.1016/j.ijmachtools.2012.05.008.

[26] Akhtar, W., Sun, J., and Chen, W., Effect of Machining Parameters on Surface Integrity in High Speed Milling of Super Alloy GH4169/Inconel 718, Materials and Manufacturing Processes, Vol. 31, No. 5, 2014, pp. 620-627, DOI: https://doi.org/10.1080/10426914.2014.994769.

[27] Kaynak, Y., Lu, T., and Jawahir, I. S., Cryogenic Machining-Induced Surface Integrity: A Review and Comparison with Dry, MQL, and Flood-Cooled Machining, International Journal of Machining Science and Technology, Vol. 18, No. 2, 2014, pp. 149-198, DOI: https://doi.org/10.1080/10910344.2014.897836.