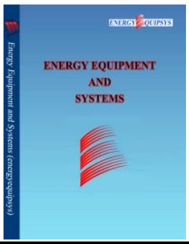
Energy Equip. Sys./ Vol. 7/No. 4/Dec. 2019/ 339-352

Energy Equipment and Systems

http://energyequipsys.ut.ac.ir
www.energyequipsys.com



Towards sustainable machining of 17-4 PH stainless steel using hybrid MQL-hot turning process

Authors

Amirhossein Moghadasi [a]
Mohammadjafar Hadad [a*]

[a] School of Mechanical Engineering, College of Engineering, University of Tehran, P.O. Box 11155/4563, Tehran, Iran

Article history:

Received : 3 August 2019
Accepted : 31 August 2019

ABSTRACT

The use of a minimum quantity of lubrication (MQL) with extremely low consumption of lubricant in machining processes has been reported as a technologically and environmentally feasible alternative to conventional flood cooling. In hot machining, the external heat source is applied during machining that will assist to increase machining performance. Many external heating techniques are available and each type has advantages/disadvantages. 17-4 PH stainless steel (AISI630) is martensitic stainless steel, which is widely used in energy equipment, aerospace and petrochemical industries. The objective of the present paper is to integrate MQL technique, for the first time, with a hot turning process for finding an optimum possible hybrid technique for a particular machining process. The effects of different machining parameters on MQL turning of 17-4 PH stainless steel have been investigated in comparison with dry and wet machining processes. Experiments were also designed for machining using MQL and dry techniques to evaluate surface roughness, tool wear, machined surface morphology, chip morphology as well as chip formation mechanism under different pre-heating temperatures. The results show that applying MQL technique with online thermally enhanced turning (MQL-hot turning) increases the efficiency of machining of 17-4 PH stainless steel. The cutting parameters and pre-heating temperature are important parameters and should be selected carefully when using hybrid MQL-hot turning. In addition, machining with MQL is beneficial to the environment and machine tool operator health as lubricant consumption during operation with MQL is 7-fold lower than in the conventional system.

Keywords: Hybrid Machining, Hot Turning, Minimum Quantity Lubricant (MQL), Surface Roughness, 17-4 PH Stainless Steel.

1. Introduction

Hybrid production/manufacturing means the combination of processes/machines in order to produce parts in a more efficient and productive way [1]. Hybrid technologies (combined several kinds of technologies) give new possibilities to machine/process materials or shapes which could not be manufactured before or at lower cost [1, 2]. Hybrid can have the meaning as a combination of different active energy sources that act at the same time in the processing zone (e.g. thermally assisted turning) [1]. In hybrid machining (removal) processes, there are generally two categories: processes in which all constituent processes are directly involved in the material removal and processes in which only one of the participating processes directly removes the material while the other only assists in removal by positively changing the

* Corresponding author: Mohammadjafar Hadad
School of Mechanical Engineering, College of Engineering, University of Tehran, P.O. Box 11155/4563, Tehran, Iran
Email: mjhadad@ut.ac.ir

conditions of machining [1-4]. The basic of hot machining operation (thermally assisted machining) is to first soften the workpiece by preheating and thereby shear strength gets reduced in the vicinity of the shear zone. Different hot machining (thermally assisted machining-TAM) processes are one of the unusual approaches in the machining of difficult-to-cut materials like heat-resistant alloys, super-alloys, hardened steels and various metal alloys. The external heat source is applied to the cutting zone during the machining process that will assist to increase machining performance [1, 2]. The achievement of hot machining is now remarkable and will extend the position in machining operations in the future [1-10]. Many external heating techniques are available and each type has advantages/disadvantages, such as [1, 2, 9-14]: Furnace heating; workpiece is machined immediately after being heated in the furnace to required temperature, Resistance heating; the entire workpiece is heated by passing current either through the workpiece itself or through resistance heaters embedded in the fixtures, Flame heating; workpiece material immediately ahead of the cutting tool is heated by welding torch moving with the tool, Arc heating; workpiece material immediately ahead of the cutting tool is heated by an electric arc drawn between the workpiece and the electrode moving with the tool, Plasma arc heating; workpiece is heated using plasma arc just above the tool tip, very high heat is produced and heating can be limited to a very small surface area. For all methods, the operators in the operation should take safety measures into account and temperature control should be quickly obtained [1, 2].

17–4 PH (AISI630) stainless steel is a martensitic precipitation age-hardening stainless steel that combines high strength and hardness with excellent corrosion resistance. It may be age-hardened by a single-step low-temperature treatment. This grade of steel is used for a variety of applications including oil field valve parts, power plant equipment, chemical process equipment, forged aircraft fittings, fasteners and pump shafts, gears, nuclear reactor parts and jet engine parts [11, 13]. Due to the required high dimensional accuracy, it is necessary to machine this steel in hard conditions. Performing the machining in a soft and solution condition and then applying an aging treatment causes the workpiece distortion and diminish the dimensional accuracy, requiring another complementary process, such as grinding. Therefore, in some cases, it is necessary to machine this material in a hard condition. Due to the high hardness of this steel and the presence of fine precipitations in the martensitic phase, the conventional machining of this steel causes severe tool wear and increases the machined surface roughness. Therefore, hot machining can potentially be used to reduce cutting forces and improve tool wear. Besides machining performances, even though the initial cost and effort involved with thermally enhanced machining are higher (equipment and safety), it can obviously offer significant sustainability benefits through shorter production cycles and the lower cost needed to machine apart as well as the enhanced productivity due to higher output

Cutting fluids are used in machining to reduce the cutting force, power consumption, thermal stresses and the need for chip removal from the machining area and to increase machining efficiency [3]. There are benefits achieved using fluid lubricants; however, numerous environmental and economic problems arise from the use of these fluids [15]. These include environmental pollution and the increased cost of the cutting fluid and its filtration and cleaning of the machine, workpiece and workshop [16]. One important drawback is that it endangers the health of the operator who works with these materials. Exposure to machining fluids can cause skin diseases such as dermatitis and folliculitis, as well as respiratory diseases such as asthma, bronchitis, allergies and, in some cases, cancer [3, 17]. Near dry machining or machining with minimum quantity lubricant (MQL) is an alternative method to conventional and dry machining. MQL machining uses the least amount of lubricant (<500 ml/h). It is mixed with compressed air (0.5-7 bar) and sprayed on the machining area. Cooling is achieved by the compressed air and evaporation of the oil droplets which reduce friction and lubricate the surface [9, 18]. Research on MQL machining has demonstrated the numerous advantages achieved using this method in turning, milling, grinding, sawing and drilling operations [3, 15-31].

The literature review [1-4, 13, 16-31] shows the lack of study on the hybrid MQL and thermally enhanced turning performance. Most studies examined specific materials and cutting tools, although the new hybrid mechanisms of lubrication and chip formation processes of different alloys have not been fully addressed [1, 2, 5-14]. Therefore, it is necessary to investigate the effects of workpiece initial temperature and different machining parameters on the hybrid MQL-hot machining performance. This paper, for the first time, deals with an investigation of the machinability of 17-4 PH (AISI 630) stainless steel using different workpiece initial temperature values under different turning and MQL parameters. The experiments, conducted under different initial temperatures of 17-4 PH stainless steel as well as different MQL machining parameters, showed the performance of the machining process based on an evaluation of workpiece surface roughness, workpiece surface quality, chip formation, chip morphology as well as cutting tool wear after machining operation.

2.Experimental setup

The current study designed and analyzed experiments to evaluate the turning process using hybrid MQL-preheating techniques and study the effect of various parameters. The settings of machining parameters in the present study are summarized in Table 1. All machining tests were conducted on a lathe (model TN50BR). The heating temperature maintained below the phase transformation temperature was aimed at softening the removable material layers. Figure 1 show the lathe, MQL and heating systems (mounted on the machine tool's carriage) used in the experiments. The equipment utilized to control the minimum quantity of lubricant (MQL) was a homemade system in which it creates the air envelope that served as the mixing chamber based on Venturi effect. The jet of MQL was delivered at the cutting zone through two nozzles, which impinge on the flank and rake faces of the cutting tool (Figure 2). The tool surfaces were covered with a thin and stable film of the lubricant, which reduced the amount of heat and friction generated in the tool-chip-workpiece interface zones. In addition, the equipment used to control the workpiece temperature was the sophisticated home-made resistance furnace heating system, which uses resistance heaters embedded in the portable furnace and allows the workpiece to be clamped on the machine's chuck and allowed to adjust the workpiece separately through the resistance heater and to move with the cutting tool in the feed direction to heat the specimen before cutting. The main parts of the resistance furnace heating system used were the temperature control unit, resistance heaters and the electricity supply system. The temperature control unit adjusts the inside temperature of the furnace with a contact thermocouple. During feeding the tool in the axial direction along the workpiece axis, the workpiece was guided to

Table 1. machining conditions

workpiece material and dimensions	hardened 17-4 PH stainless steel with 47±1 HRC (⌀ 45 mm x 250 mm)
workpiece chemical composition	(Ni-3.546%, Cr-16.179%, Cu-3.177%, Mn-0.744%, Si-0.360%, C-0.042%, P-0.028%, S-0.011%, Nb+Ta-0.356% and Fe-Balance)
cutting tool inserts	CNMG120408TC
tool holder	MCKNR2525M12
cutting tool geometry	inclination angle=-6°, rake angle=-6°, clearance angle=6°, nose radius=0.8mm, major cutting edge angle=75°
process parameters	cutting speed (V_c)= 50, 70, 90 m/min feed (f)= 0.106,0.19,0.3 mm/rev depth of cut (d): 0.5 mm
workpiece initial temperature	T= 25°C, 200°C, 350°C
Environment/coolant-lubricant	dry MQL (vegetable oil; viscosity=18 m^2/s, and ρ=850 kg/m^3): air pressure=4bar, flow rate=60ml/h (30ml/h for each nozzle) wet (1:10 Behran soluble oil): flow rate=3l/min (through external nozzle)

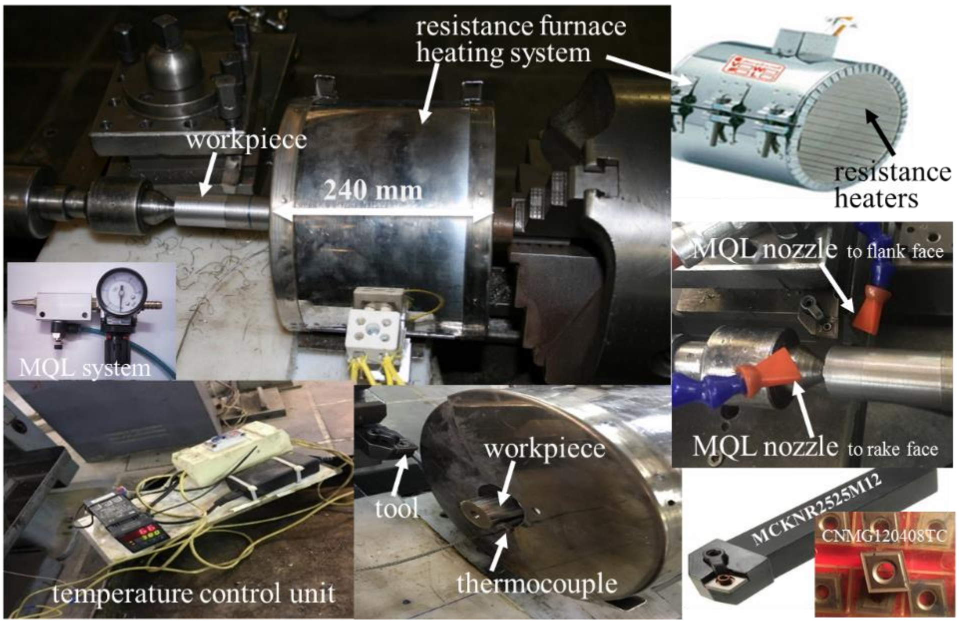


Fig.1. experimental set-up

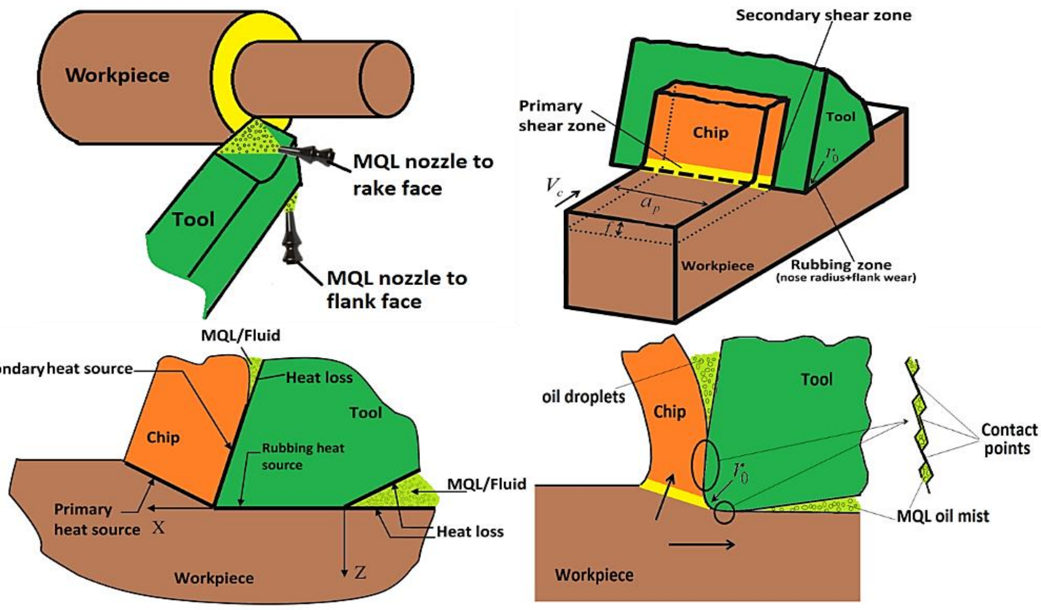


Fig.2. schematics of turning operation and the position of MQL nozzle relative to rake and flank faces

the furnace by a small gate, is heated by the resistance heaters inside the heater and then guided by the outer gate to the cutting zone.

A precise temperature control unit was designed for this system which controls an adjustable inside temperature of the furnace to continuously control the workpiece temperature. In the present study, turning operations have been carried out at 200°C, 350°C, and ambient temperature. To carry out hot turning at 200°C and 350°C, the workpiece has been first incubated in an online furnace (mounted on the machine tool carriage) at around 230°C and 380°C for 10 minutes, respectively. A thermal model program based on equations of transient heat transfer was used to calculate the time-dependent temperatures on the surface and at depths within the workpiece due to the pre-heating by resistance heater. The model was used to determine the effect the ambient air has on the temperature of the workpiece at the cutting point. Also, the variation of the surface temperature of the rotary workpiece in the ambient air has been measured using an infrared thermometer (Fig.3).

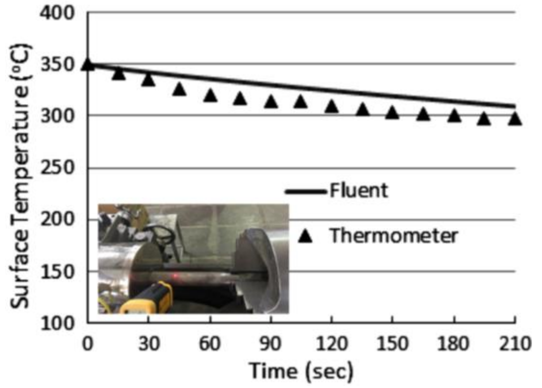


Fig.3. workpiece surface temperature versus time

It was observed that after three minutes, a maximum of 50°C, the temperature drop occurred at the surface of the workpiece. The reason for the low-temperature drop is the low conductivity of this steel. The thermal conductivity of AISI630 is 17W/m°C, while the conductivity of low carbon steels is 48W/m°C. Because of short machining time, it could be estimated from the results of Figure 3 that the hot turning experiments should be performed at the temperatures about 30 °C higher than the desired temperatures. All machining experiments have been conducted on bars 45 mm in diameter and 250 mm in length made of hardened AISI630 stainless steel (17-4PH with a hardness of 47±1 HRC in the solution condition) mounted on the lathe machine between the chuck and center. After one-hour aging treatment at 482°C (900°F) in the furnace the specimens' hardness has been increased to 47±1 HRC and its structure changed to H900 (according to ASTM A564 standard). The phase transformation temperature of the17-4 PH is about 750°C. During cutting operation, MQL and heating systems move continuously close to the cutting tool in the feeding direction of the machine tool. A surface roughness measuring instrument (model T8000; Hommel Werke profilometer) was used to measure the surface roughness of the workpieces after machining (according to DIN EN ISO 3274:1998). To ensure the accuracy of the results, the surface roughness of each workpiece was measured three times at three different angles and the average was reported. The surface morphology of the workpieces and chips as well as the tool wear were observed using a digital microscope (DigiMicro manufactured by DNT Company), which possesses a maximum magnification of 200 times. In addition, surface morphology and subsurface investigation of some machined parts were performed on a Philips model XL Series (XL30).

3. Results and Discussion

The results of the turning experiments on 17-4PH hardened stainless steel using different conditions (conventional dry and wet and MQL as well as dry and MQL hot machining processes with different workpiece initial temperatures) are described in this section. All experiments were performed at a depth of cut of 0.5 mm. For MQL machining, the air pressure was 4 bar and the oil flow rate was 30 ml/h for each nozzle. The MQL nozzle spray was directed at two surfaces simultaneously (rake and flank surfaces).

3.1. Analysis of surface roughness

Figure 4 shows the surface roughness variation using different cutting conditions.

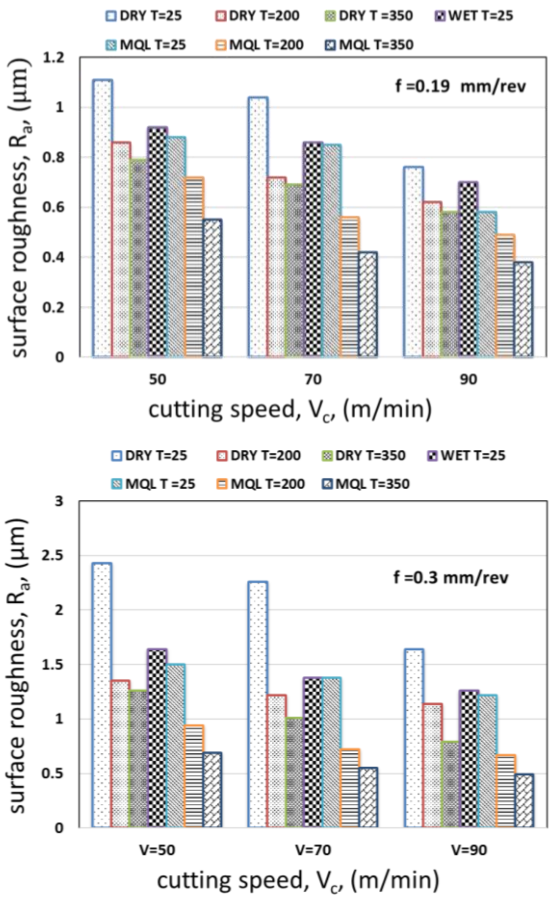


Fig.4. surface roughness versus different machining parameters and conditions

Figure 4 shows that as cutting speed increases, surface roughness decreases. It was observed that cutting speed had a greater influence than feed rate on surface roughness. It can also be seen that increasing the feed rate increased surface roughness by increasing the physical contact between the tool and the workpiece, resulting in an increase in the friction and machining force. Figure 4 shows that the hybrid MQL-hot machining technique strongly reduced the roughness of the machined surfaces over that of the conventional dry, MQL and continuous fluid machining conditions. It can be seen that lubrication during machining generally reduces the surface roughness because it decreases the friction and plowing forces. However, for all workpiece initial temperatures, the MQL system performed better than the wet and dry conditions because the high-pressure air containing oil droplets caused the lubricant to more thoroughly coat the contact surface between the tool and workpiece and facilitated the cutting. In addition, the heat generated in the workpiece in the resistance furnace heating system causes the "thermal softening" of the metal and reduces its strength before coming to the cutting zone. Therefore, it reduces the shear strength of the workpiece material and reduces the friction at the tool rake face-chip interface and consequently the shear plane angle increases. If all other factors remain the same, a higher shear plane angle results in a smaller shear plane area. Since the shear strength is applied across this area, the sheer force required to form the chip will decrease when the shear plane area is reduced. A greater shear plane angle results in lower cutting energy, lower surface roughness requirements, lower cutting temperature and better chip formation. On the other hand, increasing lubrication (decreasing tool-chip-workpiece interface friction) increased the shear plane angle and decreased chip thickness (increased chip thickness ratio). Reducing the chip thickness decreased the shear plane area and initial deformation zone and reduced the energy required for material removal and the cutting force [32, 33]. Increasing the feed rate increased the machining tangential force which increased the power consumption of the machine. Furthermore, increasing the feed rate increased the friction coefficient between the tool and workpiece, which increased the cutting force. It can be concluded that hybrid MQL with thermally enhanced machining is a better choice in terms of reducing surface roughness and better surface quality. The results indicated that machining with MQL is promising because the consumption of lubricants in the MQL method is 7-fold less than with continuous lubrication. This decreases the risk of disease for the machine operator and environment pollution.

3.2. Analysis of surface morphology

The obvious differences in the morphology of surfaces machined with different initial temperatures and coolant-lubricant types suggest a considerable influence of the MQL and preheating techniques on the chip-formation mechanisms (Figs. 5 and 6). Analysis of the results of applying dry, wet and MQL the indicated that in general under different workpiece initial temperatures, the application of cutting fluid with MQL to the turning process resulted in a performance superior to that of the conventional methods, possibly by providing greater lubricant penetration efficiency into the machining zone. From the results of surface roughness (Fig.4), surface morphology (Figs. 5 and 6) and analysis of the chips (Fig. 7), it is considered that the oil mist supplied to the cutting zone lowers the total natural contact length due to the cooling/lubricating effect of air that results in chip up-curling that decreases the contact length. The oil droplets decrease the friction at a sliding region which is observed as thinner clad material at sliding region on the tool for MQL. The wider chips are the result of side flow that can make the surface finish worse for dry cutting in comparison to MQL turning. A change from dry to MQL can result in benefits due to shorter contact length but a change from emulsion to MQL should be evaluated in terms of other parameters such as surface finish, forces, temperature and so on [3]. Furthermore, with regard to the surfaces of the machined specimens (Figs. 5 and 6), it can be observed that there are hardly any side flows and defects on surfaces machined with applying a hybrid MQL-hot cutting technique. However, surfaces generated under dry and fluid conditions in ambient temperature as well as dry with pre-heated conditions are characterized by side flow and more surface damages. It can be seen that in these conditions, lower thermal damages and material side flow can be observed when using MQL technique.

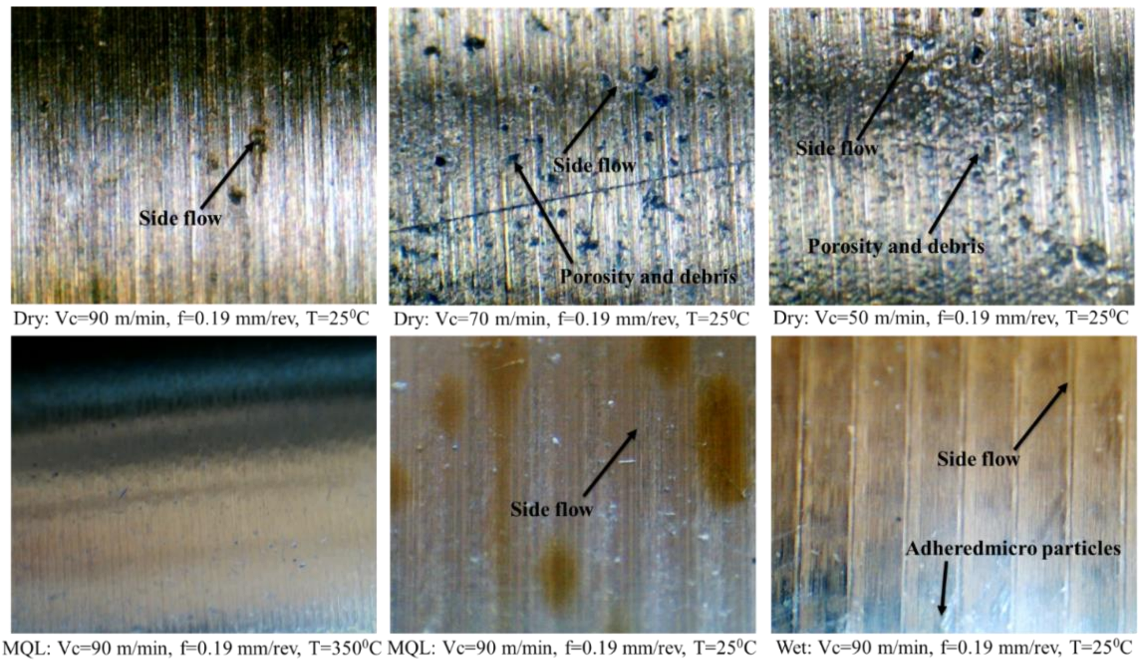


Fig.5. surface morphology of machined specimens under different machining parameters and conditions

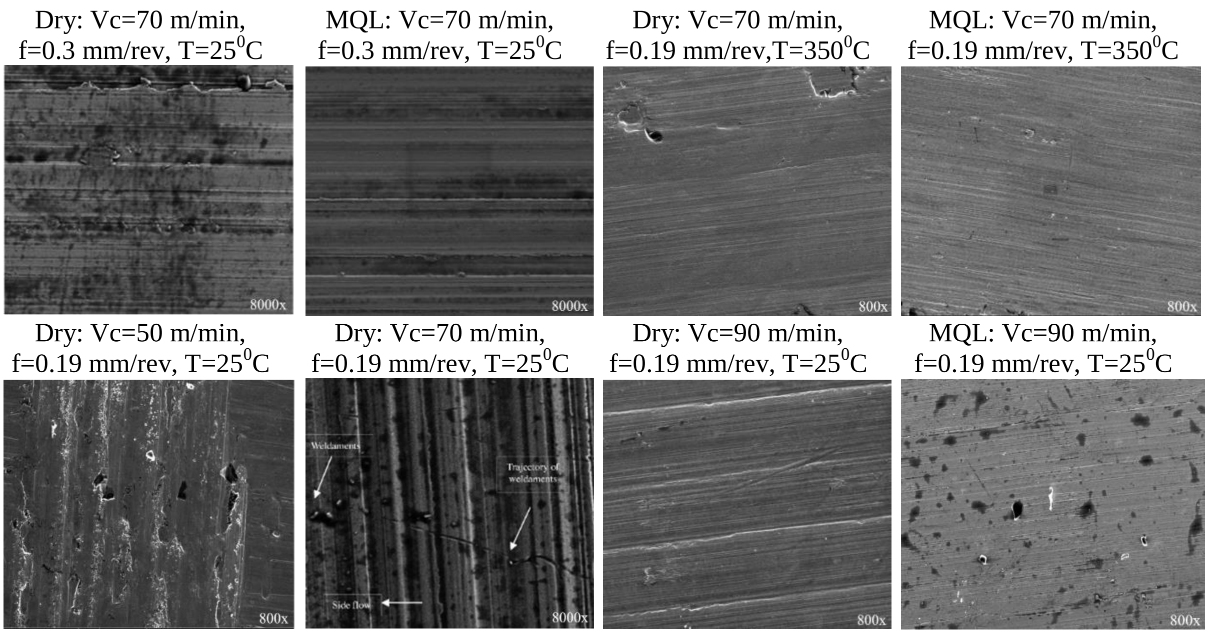


Fig.6. SEM micrographs of machined specimens under different machining parameters and conditions

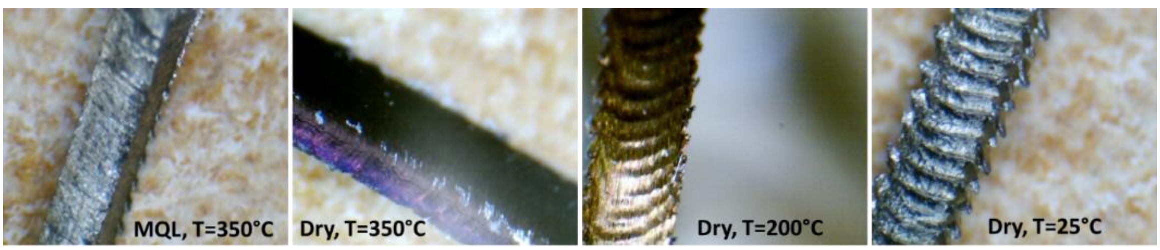


Fig.7. chip morphology obtained from machined specimens under different conditions and Vc=70mm/min and f=0.19mm/rev

3.3. Analysis of chip formation

Under different machining conditions, different chip forms are formed (Figs. 8 and 9). It is obvious that long chips, like ribbon chips, snarled chips and flat helical chips, are disadvantageous and can endanger persons, tools, workpieces and the machine tool [3, 4, 32, 33]. Short chips, like discontinuous chips and spiral chip segments, can cause problems in the transport from the material separation zone or if the operator is not adequately protected. Spiral chips and helical chip segments are most favorable [3, 32, 33]. The formation of the different chip forms depends greatly on the friction conditions in the contact area between the chip and the rake face, the workpiece initial temperature, the cutting parameters, and the material properties. The feed influences the chip compression ratio, i.e., the chip thickness, and thus the chip deformability. Therefore, the chip forms highly depend on the feed. The cutting speed has an essential influence on the temperatures in the chip formation zone due to heat conduction and convection. Higher cutting speeds lead to higher chip formation temperatures. It is indicated from Figs. 8 and 9 that 17-4 PH is more deformable at higher temperatures so that it is less damaged in the chip formation process. In other words, chip forms in high initial workpiece temperatures are regular, non-snarled and non-convoluted, and this can lead to significant lamellae as well as a fine segmentation to continue chip types. As shown in Fig.10, 17-4 PH stainless steel is known to produce serrated (saw-tooth) chips during machining process (due to a repeated thermo-plastic instability occurring within the primary shear zone), which is associated with decreased tool life, degradation of the workpiece surface finish and less accuracy in the machined part. Generally, thermal softening is one of the main reasons for the formation of shear bands in the primary shear zone and consequently the formation of saw-tooth chips. It is indicated in Fig. 10 that by increasing cutting speed the chip formation changes from continues to saw-tooth chips. By increasing cutting speed, the temperature increases in the primary shear zone (shear plane), and therefore thermal softening will provide the conditions for the formation of shear bands and saw-tooth forms. The geometry of the chips produced

Fig.8. chips obtained from machined specimens under dry condition and different machining parameters

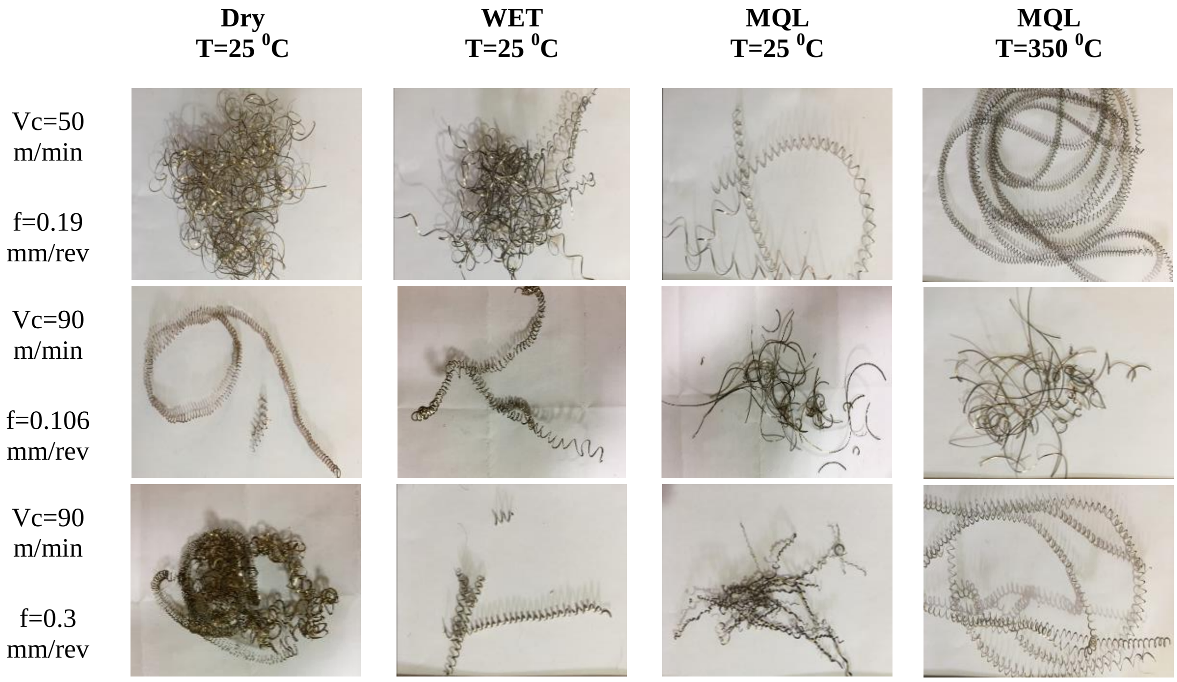


Fig.9. Chips obtained from machined specimens under different machining parameters and conditions

by different machining conditions is evidence that MQL and preheating techniques are causing the material to deform differently (Figs. 7-9). A scanning electron microscope (SEM) was used to observe the chips produced by both conventional and hot turning processes (Fig.11). In both cases, the chips are saw-toothed. It can be seen from these pictures that the chip segments are separated from each other at the outer surface side of the workpiece, while connected with each other at the tool rake face side. However, Fig.11 shows that the chips from dry and wet conditions when cutting 17-4 PH stainless steel at the ambient temperature seems to have sheared a lot cleaner than the MQL as well as hot machining chips. By increasing workpiece temperature, and therefore thermal softening of the workpiece material before cutting, it is obvious that the softer and more ductile a material is, the lower its yield stress will be and hence it will shear more often as is seen in Fig.11. Applying MQL to the turning process provides greater lubricant penetration efficiency into the machining zone, results in lower energy required at the shear plane and tool-chip friction zones, greater shear plane angle and consequently better chip formation (Fig. 12).

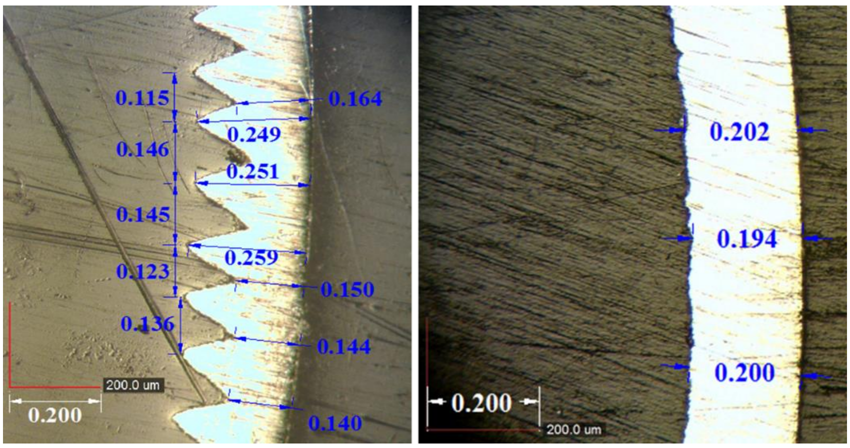


Fig.10. experimental chips at: Vc=123 m/min and f=0.175 mm/rev (left) and at Vc=28 m/min and f=0.175 mm/rev (right)

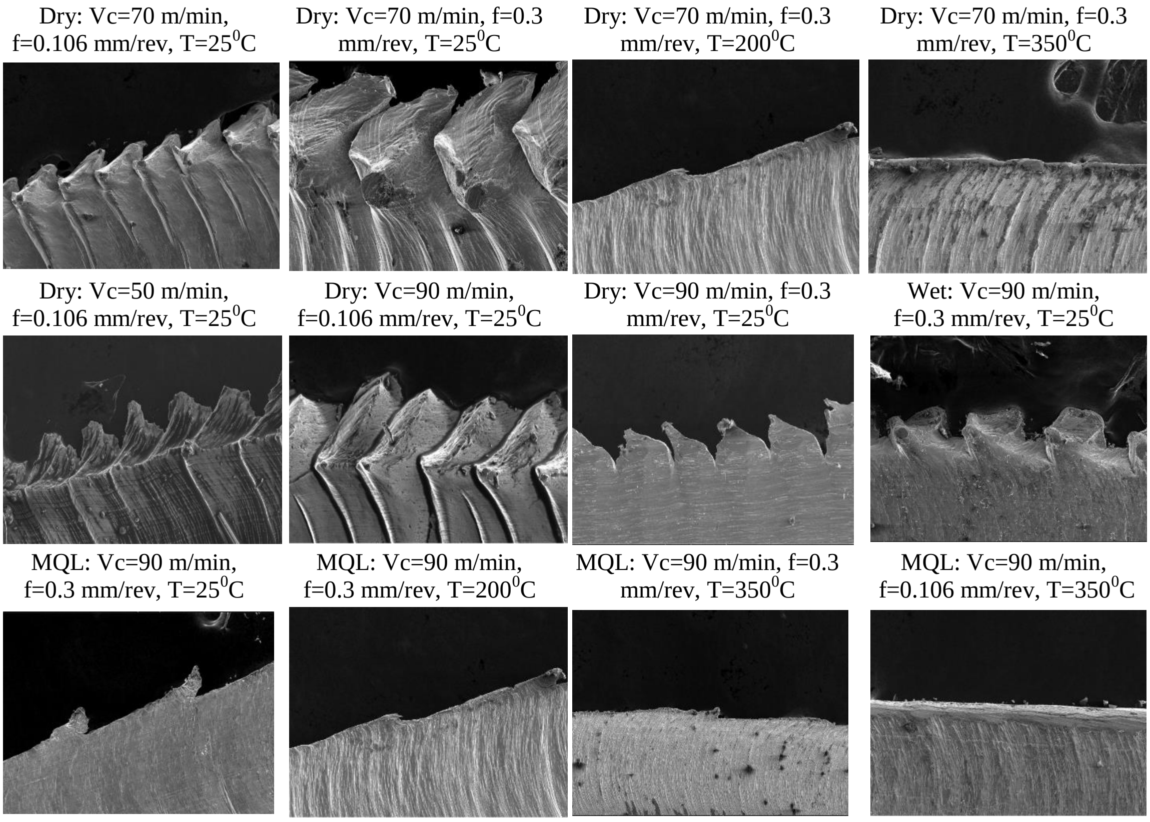


Fig.11. SEM micrographs of chips obtained from machined specimens under different machining parameters and conditions (magnification: 300x)

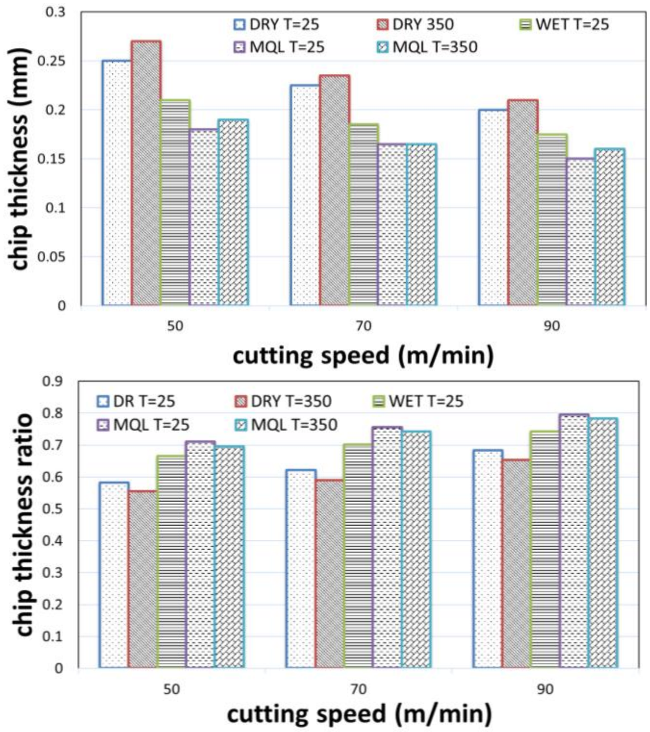


Fig.12. measured chip thickness and chip thickness ratio versus different machining parameters

3.4. Analysis of cutting tool wear

Figure 13 shows the tool wear micrograph at the flank side of used tools under different cutting conditions for 5min machining time. As shown in Fig.13, MQL, as well as hot machining techniques, caused lower damage at the flank face of the cutting tool in comparison with the dry and wet machining operations. In all machining conditions build-up edge and abrasive wear on the cutting edge and flank face can be easily seen, however in wet and dry as well as cutting in ambient temperature the levels of these defects were higher in comparison to MQL and hot machining processes. Another reason behind these results could be temperature reduction in the MQL cutting. In fact, in the MQL machining due to the lower temperature in the tool-chip-workpiece interface and improving cutting conditions, the thermomechanical forces on the tool's edge significantly reduced and consequently lower tool wear and better surface roughness were achieved. Under dry machining at V_c=90m/min, the cutting edge has been broken which demonstrate the effect of the cutting lubricants on the reduction of pressure, contact temperatures and friction on the tool edge. In wet machining moderate and in MQL technique as well as hot machining negligible wear were observed (Figs. 13 and 14). Indeed, in the cutting process absorbed lubricants films on tool surface significantly reduces friction and adhesion and prevent forming of micro cracks. The micro-cracks in tool surface act as a stress concentrator and increase the potential risk of cutting edge fracture [9]. MQL-hot cutting condition provides a long steady state wear which means thermal softening and oil droplets penetration at tool-workpiece-chip interface reduced the risk of high tool wear rate. It can be concluded that the high rate of tool wear may be a reason for high cutting and friction temperatures and forces and consequently higher surface

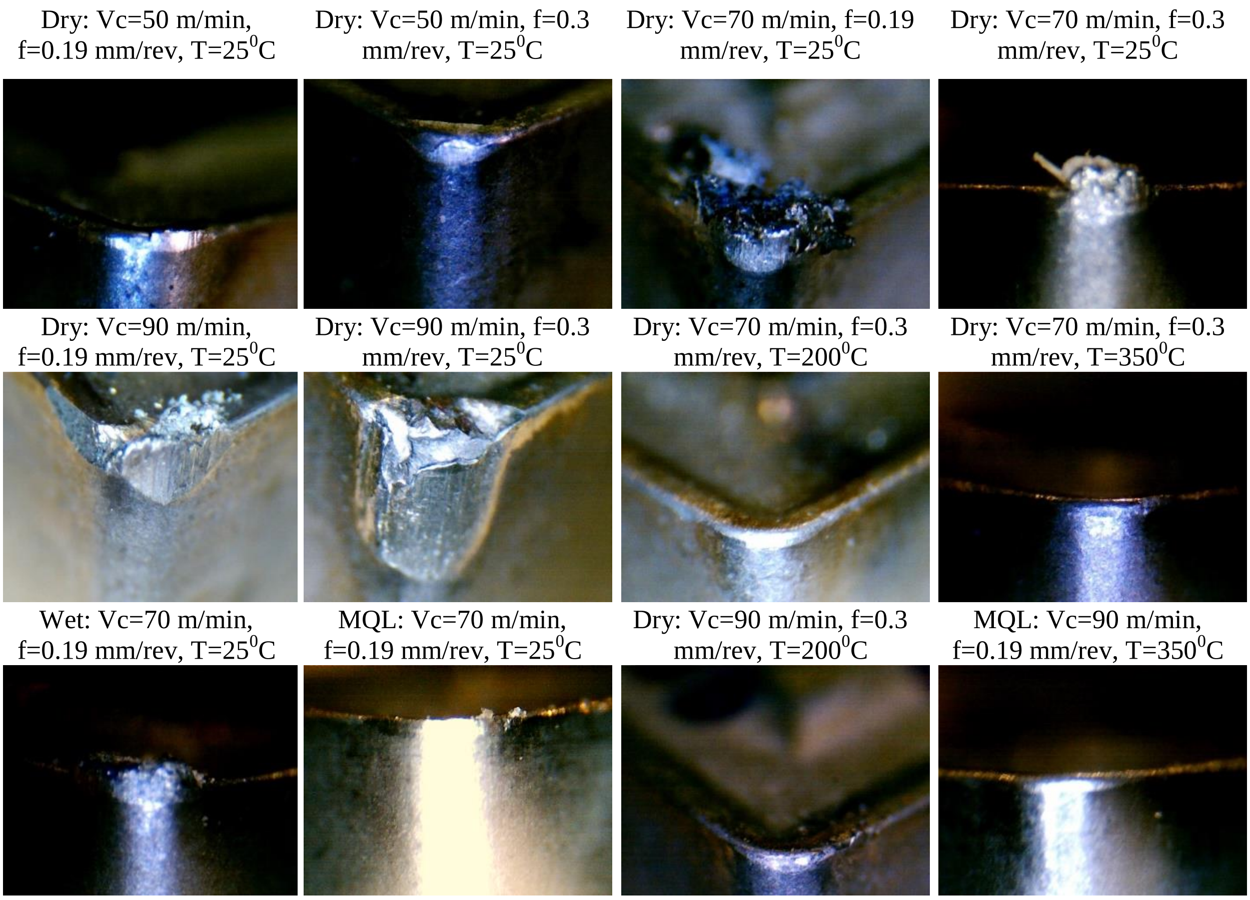


Fig.13. Tool wear micrographs at flank side of cutting tools under different machining conditions

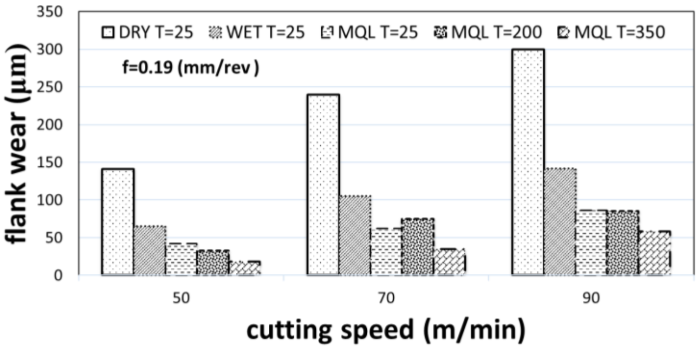


Fig. 14. measured flank wear values versus different machining parameters and conditions

roughness in the wet, dry and machining in the ambient temperature. In the machining processes, reducing the forces and temperatures at the cutting zones is one of the most important factors to achieve optimized outputs [9]. A remarkable point in the hot turning is that due to thermal softening of AISI630 steel the tool temperature does not increase much compared to the conventional turning. In hot turning, the uncut chip strength is less than that of a conventional turning. Therefore, mechanical work due to the plastic deformation and accordingly the heat generation at the primary and secondary shear zones should be less than conventional turning (lower shear bands in Figs. 10 and 11), and consequently the chip temperature rise in hot turning operation is lower than that in conventional turning.

4. Conclusion

The current study, for the first time, designed and analyzed experiments to investigate hybrid MQL-hot machining of AISI630 stainless steel (17-4PH) and the effect of various parameters. The main results of this research are:

1. MQL-hot machining technique strongly improved the surface quality and chip formation in comparison with the conventional turning processes. Reduction of friction and better chip curling are other reasons for the improvement of the cutting efficiency in hybrid MQL-hot machining.
2. MQL-hot turning reduces the tool to wear compared to conventional turning. In this case, the dominant factor in tool wear is to reduce the cutting and friction forces, so that the effect of reducing the cutting force will overcome the slight increase in the tooltip temperature and generally reduce the tool wear.
3. Hot turning increases the temperature at the primary shear zone. Therefore, the hardness and strength of the uncut chip are reduced and consequently cutting force decreases. As a result, cutting operation will be easier to do. Therefore, the surface roughness of the workpiece is reduced.
4. The consumption of lubricants in the MQL system is much less than that of continuous fluid/wet machining. This decreases machining costs and the risks to the operator health and the environment. Moreover, the hybrid MQL-hot machining significantly improved the surface quality, tool wear and chip formation in the turning of 17-4 PH stainless steel.
5. According to the obtained results in this study, hybrid MQL-hot machining improves the technical and economic aspects of machining difficult to cut materials, and it also reduces the problems associated with the environment and operator health.

References

[1] Lauwers B, Klocke F, Klink A, Tekkaya AE, Neugebauer R, Mcintosh D (2014) Hybrid processes in manufacturing, CIRP Annals-Manufacturing Technology 63:561–583.

[2] Gupta K, Jain NK, Laubscher RF (2016) Hybrid Machining Processes; Perspectives on Machining and Finishing, Springer International Publishing AG Switzerland.

[3] Davim JP (2008) Machining: fundamentals and recent advances. Springer-Verlag, London, UK.

[4] Shaw MC (1996) Metal Cutting Principles. Oxford University Press, New York, USA.

[5] Ganta V, Chakradhar D (2014) Multi objective optimization of hot machining of 15-5PH stainless steel using grey relation analysis. Procedia Materials Science 5:1810-1818.

[6] Lajis MA, Nurul Amin A, Karim ANM, Radzi H, Ginta TL (2009) Hot Machining of Hardened Steels with Coated Carbide Inserts. American J. of Engineering and Applied Sciences 2:421-442.

[7] Wang ZY, Rajurkar KP, Fan J, Lei S, Shin YC, Petrescu G (2003) Hybrid machining of Inconel 718. International Journal of Machine Tools & Manufacture 43:1391–1396.

[8] Bermingham MJ, Palanisamy S, Dargusch MS (2012) Understanding the tool wear mechanism during thermally assisted machining Ti-6Al-4V. International Journal of Machine Tools & Manufacture 62(1):76-87.

[9] Masoudi S, Vafadar A, Hadad MJ, Jafarian F (2018) Experimental investigation into the effects of nozzle position, workpiece hardness, and tool type in MQL turning of AISI 1045 steel. Materials and Manufacturing Processes 33(9):1011–1019.

[10] Germain G, DalSanto P, Lebrun JL (2011) Comprehension of chip formation in laser assisted machining. International Journal of Machine Tools & Manufacture 51:230–238.

[11] Chien WT, Tsai CS (2003) The investigation on the prediction of tool wear and the determination of optimum cutting conditions in machining 17-4PH stainless steel. Journal of Materials Processing Technology 140:340–345.

[12] Rabiei F, Rahimi AR, Hadad MJ, Saberi A (2017) Experimental evaluation of coolant-lubricant properties of nanofluids in ultrasonic assistant MQL grinding. Int J Adv Manuf Technol 93:3935–3953.

[13] Khani S, Farahnakian M, Razfar MR (2015) Experimental study on Hybrid Cryogenic and Plasma-Enhaced Turning of 17-4PH Stainless Steel. Materials and Manufacturing Processes 30:868–874.

[14] Bermingham MJ, Kent D, Dargusch MS (2015) A new understanding of the wear processes during laser assisted milling 17-4 precipitation hardened stainless steel. Wear 328-329:518-530.

[15] Tawakoli T, Hadad MJ, Sadeghi MH (2010) Investigation on minimum quantity lubricant-MQL grinding of 100Cr6 hardened steel using different abrasive and coolant-lubricant types. International Journal of Machine Tools & Manufacture 50:698-708.

[16] Tawakoli T, Hadad MJ, Sadeghi MH, Daneshi A, Sadeghi B (2011) Minimum quantity lubrication in grinding: effects of abrasive and coolant-lubricant types. Journal of Cleaner Production 19:2088-2099.

[17] Sadeghi MH, Hadad MJ, Tawakoli T, Vesali A, Emami M (2010) An investigation on surface grinding of AISI 4140 hardened steel using minimum quantity lubrication-MQL technique. International Journal of Material Forming 3:241-251.

[18] Tawakoli T, Hadad MJ, Daneshi A, Sadeghi MH, Sadeghi B (2011) Study on the effects of abrasive and coolant-lubricant types on minimum quantity lubrication-MQL grinding. Advanced Materials Research 325:231-237.

[19] Hadad MJ, Tawakoli T, Sadeghi MJ, Sadeghi B (2012) Temperature and energy partition in minimum quantity lubrication-MQL grinding process. International Journal of Machine Tools & Manufacture 54-55:10-17.

[20] Rabiei F, Rahimi AR, Hadad MJ, Ashrafijou M (2015) Performance improvement of minimum quantity lubrication (MQL) technique in surface grinding by modeling and optimization. Journal of Cleaner Production 86:447-460.

[21] Hadad MJ, Sharbati A (2017) Analysis of the effects of dressing and wheel topography on grinding process under different coolant-lubricant conditions. Int J Adv Manuf Technol 90:3727-3738.

[22] Rabiei F, Rahimi AR, Hadad MJ (2017) Performance improvement of eco-friendly MQL technique by using hybrid nanofluid and ultrasonic-assisted grinding. Int J Adv Manuf Technol 93:1001-1015.

[23] Tawakoli T, Hadad MJ, Sadeghi MH (2010) Influence of oil mist parameters on minimum quantity lubrication-MQL

grinding process. International Journal of Machine Tools & Manufacture 50:521-531.

[24] Hadad MJ (2015) An experimental investigation of the effects of machining parameters on environmentally friendly grinding process. Journal of Cleaner Production 108:217-231.

[25] Hadad MJ, Sadeghi B (2013) Minimum quantity lubrication-MQL turning of AISI 4140 steel alloy. Journal of Cleaner Production 54:332-343.

[26] Tawakoli T, Hadad MJ, Sadeghi MH, Daneshi A, Stöckert S, Rasifard A (2009) An experimental investigation of the effects of workpiece and grinding parameters on minimum quantity lubrication-MQL grinding. International Journal of Machine Tools & Manufacture 49:924-932.

[27] Hadad MJ (2010) Minimum Quantity Lubrication-MQL grinding process & investigation of surface quality. Ph.D. Thesis, Manufacturing Engineering Division, School of Engineering, Tarbiat Modares University, Tehran, Iran.

[28] Hadad MJ, Tawakoli T, Sadeghi MH, Sadeghi B (2012) Temperature and energy partition in minimum quantity lubrication-MQL grinding process. International Journal of Machine Tools & Manufacture 54:10-17.

[29] Hadad MJ, Sadeghi B (2012) Thermal analysis of minimum quantity lubrication-MQL grinding process. International Journal of Machine Tools & Manufacture 63:1–15.

[30] Sadeghi MH, Haddad MJ, Tawakoli T, Emami M (2009) Minimal quantity lubrication-MQL in grinding of Ti-6Al-4V titanium alloy. International Journal of Advanced Manufacturing Technology 44:487-500.

[31] Sivaiah P, Chakradhar D (2017) Experimental investigation on feasibility of cryogenic, MQL, wet and dry machining environments in turning of 17-4 PH stainless steel. Materials and Manufacturing Processes 32(15): 1775-1788.

[32] Toenshoff HK, Denkena B (2013) Basics of Cutting and Abrasive Processes. Springer-Verlag, London, UK.

[33] Klocke F (2011) Manufacturing Processes 1; Cutting. Springer-Verlag, London, UK.