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INVESTIGATION OF POLISHING METHODS AND SURFACE ANALYSIS AFTER MACHINING *AISI 4140* ALLOY STEEL

Qiang Qi
University of Kentucky, qqi223@g.uky.edu

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Qiang Qi, Student

Dr. Kozo Saito, Major Professor

Dr. Haluk E. Karaca, Director of Graduate Studies

INVESTIGATION OF POLISHING METHODS AND SURFACE ANALYSIS AFTER MACHINING *AISI 4140* ALLOY STEEL

THESIS

A thesis submitted in partial fulfillment of the

requirement for the degree of Master of Science in Mechanical Engineering

in the College of Engineering

at the University of Kentucky

By

Qiang Qi

Lexington, Kentucky

Director: Dr. Kozo Saito, Professor of Mechanical Engineering

Lexington, Kentucky

2017

ABSTRACT OF THESIS

INVESTIGATION OF POLISHING METHODS AND SURFACE ANALYSIS AFTER MACHINING *AISI 4140* ALLOY STEEL

AISI 4140 alloy steel has been a very common material to be investigated in automotive and aerospace industries for several decades. *AISI 4140* alloy steel is chromium, molybdenum, and manganese containing low alloy steel. It has high fatigue strength, abrasion and impact resistance, toughness, and torsional strength. The functional performance is largely determined by the surface states after machining.

The aim of the present study is to explore the polishing methods and surface analysis after machining *AISI 4140* alloy steel in different cutting speeds and cooling conditions. The surface analysis includes surface roughness, hardness and residual stresses. Compared to traditional polishing, an innovative experimental work was conducted on electro-polishing technology for removing surface layer before subsurface residual stress measurement.

The results of this work show that the electro-polishing method is a significant approach for the residual stress analysis. High cutting speed and cooling conditions can significantly improve the surface quality to achieve lower surface roughness, higher microhardness and more compressive residual stresses after machining *AISI 4140* alloy steel.

Key Words: Polishing Method, *AISI 4140* Alloy Steel, Surface Analysis, Cutting Speed, Cooling Condition, Residual Stress.

Qiang Qi

11/06/2017

INVESTIGATION OF POLISHING METHODS AND SURFACE ANALYSIS AFTER MACHINING *AISI 4140* ALLOY STEEL

By

Qiang Qi

Dr. Kozo Saito

Director of Thesis

Dr. Haluk E. Karaca

Director of Graduate Studies

11/06/2017

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Chapter 1 Introduction

1.1 Introduction

AISI 4140 alloy steel is a chromium molybdenum alloy steel specification widely used in the oil and gas industry. Typical applications include using in components such as connection rods, collets, conveyor pins, gears, pump shafts and tool holders. A large number of analytical and experimental studies have been conducted on surface quality of *AISI 4140* alloy steel in machining operations. The quality insurance of manufacturing products is very important in advanced and high precision manufacturing(Saito and Saito 2012). Few studies investigated the machined specimens under different cooling systems, but the current research provides a comprehensive research on surface analysis related to machining parameters and cooling methods, and especially introducs more detailed electro-polishing and X-ray Diffraction (XRD) technics in sub-surface residual stress measurements. Moreover, the surface quality has a great impact on the functional performance of machined materials including fatigue life and corrosion resistance of *AISI 4140* alloy steel (Schulze, Hoffmeister et al. 2011).

The conventional polishing in this study uses a mechanical grinding pad for rough polishing, and applies polishing liquid for final polishing to measure surface roughness and hardness. Due to the impact of traditional polishing method on residual stress measurement, the electro-polishing was introduced.

Additionally, the process of machining steel is complex and the surface generated is influenced by several variables: steel properties, tool material and geometry, vibration of cutting tool, cutting speed, feed, depth of cut, and lubricant, etc. (Chinchanikar and Choudhury 2015). Most research developments have been performed with the goal of optimizing the cutting conditions to obtain better surface finish. The quality of the surface produced by manufacturing processes has critical influence on the functional performance of the products. The surface layer is determined by manufacturing processes, and mainly, by finishing treatments (Schulze, Zanger et al. 2013). The influence of cutting parameters (cutting speed, feed rate and depth of cut) on surface quality, and consequently on surface, has been well studied. The importance of surface statements increases with increasing loads, temperature and frequency. This becomes critical for high strength steels, which are more sensitive to stress concentration. Recently, more and more studies on surface analysis have been reported by researchers from various countries due to its close relationship with functional performance of the manufactured products (Jawahir, Brinksmeier et al. 2011).Thus, it is necessary to know the relationship between surface quality and cutting operations. In the present study, the influence of cutting speed on the surface performance of turned specimens of *AISI 4140* alloy steel is analyzed. To analyze the results of surface finishing, four cutting speeds with one low 50m/min as a comparison speed no matter what cooling methods were applied during machining experiments.

The cooling condition often cannot control the high cutting temperature in high production machining (Umbrello, Micari et al. 2012). Compared with dry machining of *AISI 4140* alloy steel, many researchers studied lubricated conditions such as minimum quantity lubrication (MQL), straight oil, and small quantity lubrication with fluid during machining process. Most of lubrication conditions has been proved to lead a large beneficial effect on cutting tools and surface states. During machining process, the surface layer is subjected to plastic deformation and heating, which result in structural changes, strain hardening and residual stresses change, and creating surface roughness. Increasing in cutting velocity machining with high productivity is generally restricted by the elevated cutting temperature, which causes rapid tool failure. However, Cryo-cooling is an environment friendly clean technology for desirable control of cutting temperature. The present study of machining *AISI 4140* alloy steel is not only to focus on the implementation of polishing method on surface analysis, but also to explore the effect of machining process in surface changes.

1.2 Overview of Thesis

The purpose of present work is to investigate the role of cooling condition by applying liquid nitrogen jet on chip–tool interface in surface analysis after turning *AISI 4140* alloy steel. This thesis is organized as follows:

Chapter 2 is a literature review which presented many previous research has been done in conventional polishing approach in surface analysis, also introduced the studies in machining *AISI 4140* alloy steel.

In Chapter 3, it presented experimental setup for machining, and turning experiments with four cutting speeds was conducted under different cooling condition including dry, flood and Cryo-cooling. This chapter show the approach of surface characteristics measurement including surface roughness, microhardness and residual stress, especially introduced conventional polishing method, X-Ray Diffraction technology and electropolishing removal technics.

In the following of Chapter 4, experimental results on surface analysis, resulting from different cutting speeds and cooling conditions are presented. The detailed surface factors are investigated.

In Chapter 5, the findings and results of the current work are summarized with final remarks and conclusions. The directions and recommendations of the future work are discussed briefly based on the results and observations presented in this thesis.

Chapter 2 Literature Review

The polishing method is identified for sample preparation work at the beginning of research. Mechanical polishing preparation as conventional approach has been applied for alloy steel materials for many years. The electropolishing has been developed for aluminum and steel recently using for surface analysis. These two methods will illustrated in this chapter for research background. The studies in machining of *AISI 4140* alloy steel provided a lot of profound knowledge for current study. Machining *AISI 4140* alloy steel is a competitive alternative industry process for producing a wide range of mechanical components, such as gears, cams, shafts, axles and others. Many researchers have investigated the effect of machining parameters on surface significantly. Therefore, this chapter begins with an overview of recent studies in polishing method and machining *AISI 4140* alloy steel. Then, the surface is reviewed this chapter by previous research findings in different machined materials and *AISI 4140* alloy steel. It show that functional performance of some materials has been improved due to different machining parameters influenced several surface analysis.

2.1 Polishing Method Application

2.1.1 Mechanical Polishing Preparation

Mechanical preparation is the most common method of preparing material graphic specimens for microscopic examination. The particular type of analysis determines the specific requirement of the prepared surface. Specimens can be prepared when the surface is acceptable for a specific examination.

Grinding is the first step of mechanical material removal. Proper grinding removes damaged or deformed surface material, while limiting the amount of additional surface deformation(Aida, Takeda et al. 2014). Grinding removes material using fixed abrasive particles that produce chips of the specimen material. The process of making chips with a sharp abrasive grain produces the lowest amount of deformation in the specimen, while providing the highest removal rate. The grinding process started with plane grinding. Plane grinding ensures that the surfaces of all specimens are similar, despite their initial condition and their previous treatment. In addition, when processing several specimens in a holder to make sure they are all at the same level, or "plane," before progressing to the next step, fine grinding. To obtain a high, consistent material removal rate, short grinding times and maximum flatness, totally fixed grains with a relatively large grain size are preferred for plane grinding. Suitable plane grinding surfaces will provide perfectly plane specimens, thus reducing the preparation time on the following fine grinding step.

Fine grinding produced a surface with little deformation that can easily be removed during polishing. Because of the drawbacks with grinding papers, alternative fine grinding composite surfaces are available, in order to improve and facilitate fine grinding. The use of a diamond abrasive on the fine grinding disks guarantees a uniform removal of material from hard, as well as soft, phases. There is no smearing of soft phases or chipping of brittle phases and the specimens will maintain a perfect planeness. Thus, the diamond grains are allowed to embed the surface and provide a fine grinding action. With this step, a very plane specimen surface could be obtained. A high material removal rate is obtained by using grain sizes of 15, 9.0 and 6.0 µm. This is investigated on hard composite disks with a surface of a special composite material(Ardashev 2016). Subsequent polishing steps can be carried out in a very short time with excellent final grinding.

Polishing is used to remove the damage remaining from the previous steps. This is achieved with steps of successively finer abrasive particles. Polishing is catalyzed into two different processes: Diamond Polishing and Oxide Polishing. Diamonds polishing are used as an abrasive to accomplish the fastest material removal and the best possible planeness. No other available abrasive can produce similar results. Because of its hardness, diamonds cut extremely well through all materials and phases. During polishing, a smaller chip size is desirable to ultimately achieve a specimen surface without scratches and deformation. Oxide Polishing, Certain materials, especially those that are soft and ductile, require a final polish, using oxide polishing to obtain the best quality. Colloidal silica, with a grain size of approximately 0.04 µm and a pH of about 9.8, has shown remarkable results. The combination of chemical activity and fine, gentle abrasion produces scratch-free and deformation-free specimens. Polishing is performed using abrasive film and cloths in the case of diamond polishing along with a lubricant. The choice of cloth, diamond grain size, and lubricant depends on the material to be polished.

The grinding and polishing process also have to be considered the factors for Lubricant, Rotation Peed, Force and Time. Lubricant option is depended on the type of material and the preparation stage, different lubricants combine levels of lubricating and cooling levels and liquid characteristics. This may include thin lubricants with high cooling and low lubrication effect, special lubricants for polishing of soft and ductile materials, alcohol-based or water-based, etc. Depending on the type of material and the grinding and polishing disk used for preparation, the amounts of lubrication and cooling have to be leveraged. Generally, it can conclude that soft materials require high amounts of lubricant to avoid damage, but only small amounts of abrasive, as there is very little wear on the abrasive. Hard materials require less lubricant but higher amounts of abrasive, due to faster wear. The amount of lubricant has to be adjusted correctly to get the best result of surface requirement. Excess lubricant will flush the abrasive from the disk and remain as a thick layer between the specimen and disk, thus reducing material removal to a minimum. Rotational Speed for Proper grinding, a high disk speed is used to get a fast material removal. When working with loose abrasives, high speeds would throw the suspension from the disk, thus requiring higher amounts of both abrasive and lubricant. The force depended on samples' size and set up. The specimens are mounted, and the specimen area should be approximately 50% of the mount. If the specimens are smaller, or there are fewer specimens in a holder, the force has to be reduced to avoid damage, such as deformations. For larger specimens, the force only needs to be slightly increased. Instead, the preparation time shall be extended. Higher forces increase the temperature because of higher friction, so thermal damage may occur. Preparation time is the time during which the specimen holder is rotating and pressed against the grinding/polishing disk. It should be kept as short as possible to avoid artifacts such as relief or edge rounding. Depending on the specimen size, the time may have to be adjusted. For larger specimens, the time shall be extended. With specimens smaller than the standard, the time is kept constant and the force reduced.

2.1.2 Electropolishing

Electropolishing is an electrochemical process that removes material from a metallic specimen. It is used to polish, passivate, and deburr metal parts. Electropolishing has many applications in the metal finishing industry because of its simplicity and its ability to be used on irregularly-shaped objects, such as electropolished stainless steel drums of washing machines, stainless steel surgical devices, and copper semiconductors(Abbott, Capper et al. 2005). Electropolishing is also commonly used to prepare thin metal samples for transmission electron microscopy because the process does not cause the mechanical deformation of surface layers observed with mechanical polishing. Ultra high vacuum components are typically electropolished in order to have a smoother surface for improved vacuum pressures, out-gassing rates, and pumping speed. Typically, the work-piece is immersed in a temperature-controlled bath of electrolyte and serves as the anode; it is connected to the positive terminal of a DC power supply, the negative terminal being attached to the cathode. A current passes from the anode, where metal on the surface is oxidised and dissolved in the electrolyte, to the cathode. At the cathode, a reduction reaction occurs, which normally produces hydrogen. Electrolytes used for electropolishing are most often concentrated acid solutions having a high viscosity, such as mixtures of sulphuric acid and phosphoric acid. Other electropolishing electrolytes reported in the literature include mixtures of perchlorates with acetic anhydride and methanolic solutions of sulphuric acid(Uzoh 2000). To achieve electropolishing of a rough surface, the protruding parts of a surface profile must dissolve faster than the recesses. This process, referred to as anodic levelling, can be subject to incorrect analysis when measuring the surface topography(Lopes, Elias et al. 2010). Anodic dissolution under electropolishing conditions deburrs metal objects due to increased current density on corners and burrs. Most importantly, successful electropolishing should operate under diffusion limited constant current plateau, achieved by following current dependence on voltage, under constant temperature and stirring conditions. One of the benefits of electropolishing for stainless steel is that it removes iron from the surface and enhances the chromium/nickel content for the most superior form of passivation for stainless steel(Lee and Lai 2003). Electropolishing also provides a clean and smooth surface that is easier to sterilize, while improving the surface finish by levelling micro-peaks and valleys. It can be used to reduce the size of some parts. Another benefit of electropolishing is that it removes a small amount of material (typically 20-40 micrometre in depth in the case of stainless steel from the surface of the parts, while also removing small burrs or high spots(Magaino, Matlosz et al. 1993).

2.2 Recent Research in Machining of *AISI 4140* Alloy Steel

Recently, there has been several remarkable research in machining *AISI 4140* alloy steel at Karlsruhe Institute of Technology (KIT) in Germany. One of KIT research projects by Schulze (Schulze, Zanger et al. 2013) presented the influence of three machining parameters, including cutting edge radius, depth of cut and cutting speed on the generation of nanocrystalline in orthogonal cutting in *AISI 4140* alloy steel by broaching machine. All compared data and analyzed results provided profound experienced work in the low cutting speed for this material. In order to improve the characteristics of surface layer, some modified parameters had been analyzed on the nanocrystalline surface layer’s generation in an orthogonal finishing of *AISI 4140* alloy steel. Based on the experiments with *AISI 4140 alloy steel* in the process of orthogonal cutting, the developing approach of a 2D finite element simulation model analyzed the mechanisms of temperature increase and distribution during the cutting process, including the mechanisms causing transformation of the work piece microstructure (Schwenk, Hoffmeister et al. 2013). Moreover, friction effects between the tool and work piece in simulation has been considered because it has influence on the heat production and resulting surface layer (Schulze, Michna et al. 2011). The simulated temperatures, cutting forces and phase transformations were compared to orthogonal cutting experiments. This approach has been proven to agree with experiment results, and succeed in simulating the martensitic start and finishing temperatures, and modeling the volume of martensitic.

Moreover, a study of cutting tool plays an important role in machining *AISI 4140* alloy steel. The effect of coating systems on the cutting tool performance was analyzed by applying uncoated and four differently coated cemented carbide inserts in turning process (Aurich, Eyrisch et al. 2012). The uncoated cemented carbide cutting tool served as a reference for the capability of the coating systems. The cutting performance of two tungsten carbide tools with multilayer chemical vapor deposition in high speed range was also investigated in dry machining. From research of the influence of the tool surface roughness on the contact condition both on the rake and flank face of the cutting tool during orthogonal cutting of *AISI 4140* alloy steel (Arrazola, Arriola et al. 2009), it is necessary to understand the tribology conditions between the work piece and the cutting tool to create more accurate models of the machining process. As the research show by (Chavoshi and Tajdari 2010), the application of the 3D FEM model on the effects of cutting tool's geometry including nose radius and edge radius during the turning process, which provided a fundamental understanding of cutting mechanics of the turning operation of *AISI* 4140 alloy steel.

2.3 Effect of Cooling Condition in Machining

Most of previous machining *AISI 4140* alloy steel without any lubricant focus on the effect of machine parameters in tool wear and tool life. Some researchers studied on minimum quantity lubrication during machining process. Based on their results, most lubrication conditions lead to a large beneficial effect on cutting tools and surface states. By applying Cryo-cooling technology, the correlation between machining parameters especially in cutting edge radius and surface layer states has been investigated in Cryo-cooling machining and dry machining of *AISI 4140* alloy steel (Ambrosy, Zanger et al. 2014). By induced Cryo-cooling machining *AISI 4140* alloy steel, compared with other processes, significantly contribute to surface analysis characteristics of machined components by improving the surface quality of machined components, generating much smoother surface topography, producing much smaller grains on the surface and subsurface of machined components, increasing hardness on the surface, and in the subsurface leading to improved wear resistance, generating compressive residual stress, and therefore increasing the fatigue life of machined components, and developing preferred basal structures leading to improved corrosion resistance. Cryo-cooling machine ng has been investigated in the academic and industry area for over twenty years. The Cryo-cooling plays an important role in machining were defined by Hong and Zhao (Hong and Zhao 1999) as removing heat effectively from the cutting zone, lowering cutting temperatures, modifying the frictional characteristics at the tool-workpiece interfaces, and changing the properties of the workpiece and the tool material. Application of Cryo-cooling in grinding processes can be seen in the jet of liquid nitrogen is delivered at the grinding zone which, is between the grinding wheel and the workpiece (Hong 2006).The cooling applications is critical factor in machining operations and many operations cannot be carried out efficiently without cooling. Due to excessive heat and consequently tool-wear and sometimes poor surface quality are the most important factors affecting performance and productivity of metal processing operations, the application of a coolant in the cutting process can increase tool-life and dimensional accuracy, decrease cutting temperatures, surface roughness and the amount of power consumed in a process and thus improve the productivity. In machining of some materials, reductions in tool flank wears up to five fold were obtained with Cryo-cooling (Wang and Rajurkar 1997). The tool-wear increased with the length of cut and the surface roughness increased with tool-wear (Wang and Rajurkar 2000). They employed a hybrid Cryo-cooling machining method with plasma heating enhanced during machining of Inconel *718* and their results indicated an improvement of 156% in tool-life and a 250% improvement in surface roughness when compared with conventional machining (Wang, Rajurkar et al. 2003). Zurecki (Zurecki, Ghosh et al. 2003) made a tool-life comparison between liquid nitrogen cooled Al_2O_3-based cutting tools and conventionally cooled CBN tools in machining of hardened steel. They applied Cryo-cooling coolant by spraying with a nozzle to the rake surface of the tool and found that Cryo-cooling cooled Al_2O_3-based cutting tools endured longer than the conventionally cooled CBN tools. The beneficial effects of Cryo-cooling machining on tool life, where liquid nitrogen was sprayed from the rake and flank side of the cutting tools, were reported on different materials such as steels (Zurecki, Ghosh et al. 2003) and titanium alloys (Dhananchezian and Kumar 2011). Another study showed results that the Al_2O_3 ceramic inserts cooled by Cryo-cooling cooling method significantly outperformed conventional dry PCBN operations (Ghosh, Seshaiah et al. 2005). Kumar and Choudhury (Kumar and Choudhury 2008) investigated dry cutting conditions and Cryo-cooling liquid nitrogen spraying by a nozzle in machining of stainless steel *202* with a carbide insert in terms of tool-wear. They observed about 37.39% advantage in the flank wear with Cryo-cooling machining over the dry cutting. In application of indirect Cryo-cooling, the surface roughness of materials machined with liquid nitrogen cooling was found to be much better than the surface roughness of materials machined without liquid nitrogen cooling. The large differences were attributed to the variation in the tool-wear. In machining of *AISI 304* stainless steel using Cryo-cooling, tool-life was increased more than four times (Khan and Ahmed 2008). The capability of reducing the tool-wear is one of the most remarkable contributors in the utilization of liquid nitrogen delivery during machining processes. Kaynak et al. (Kaynak, Karaca et al. 2013) demonstrated the improvement of tool-wear performance in Cryo-cooling machining of *NiTi* shape memory whose machinability is generally very poor limiting its application in the aerospace industry. By contrast to dry and MQL machining, both the flank and notch wear were improved by controlling the progressive tool-wear and tool-wear rate in the case of Cryo-cooling machining. For the aerospace-based material Inconel *718*, Cryo-cooling machining also provided the enhanced machining performance in terms of tool-wear, temperature, surface analysis(Kaynak 2014). The interpretation given was that Cryo-cooling machining reduces the tool wear compared with conventional cooling, which has a larger tool-wear. These findings also proved that the number of nozzles used to deliver liquid nitrogen played a significant role to control the cutting forces and power consumption. According to Hong et al. (Hong and Ding 2001), by applying liquid nitrogen from the rake face of inserts, chip breakability can be improved due to the enhanced brittleness of the chips at a lower temperature resulting from the rapid cooling effect. A fluid cushion is formed between the chip insert contact area, and it helps to reduce the material stickiness thus mitigating or eliminating the introduction of built-up edge. Moreover, the hardness of the tool insert material is also improved in the environment of lower temperature. Combining all the effects, the tool-life/tool-wear of inserts used in Cryo-cooling machining can be enhanced. Moreover, delivering liquid nitrogen from the clearance side of the insert will benefit the surface analysis of the manufactured components. The study conducted by Hong et al. (Hong, Markus et al. 2001) was to investigate the effects of Cryo-cooling machining by a combination of two nozzles delivering liquid nitrogen._They found that optimizing the position of the nozzles could enhance the performance of the chip breaker. In addition, the tool-life was increased up to 5 times compared with the ones used in dry machining. Another systematic study was carried out to investigate the influence of Cryo-cooling machining on the cutting temperature of *Ti-6Al-4V* alloy (Hong, Ding et al. 2001). The temperatures under various cooling methods were measured by thermo-couples, imbedded in the carbide tool insert and compared with the predicted results obtained from a FEM-based predictive model. According to the experimental results and theoretical predictions, they concluded that the cutting temperature was in the increasing trend following this order: simultaneous Cryo-cooling on the rake and flank sides, Cryo-cooling on the rake side, Cryo-cooling on the flank side, precooling the work material, flood-cooling and dry condition. From this study, the lowest temperature could be achieved when liquid nitrogen was delivered from the rake and flank sides simultaneously. In another research (Dhar, Paul et al. 2002), the cutting temperatures of machining *AISI 1040* and *AISI 4320* steels were found to be lowered by Cryo-cooling, the cutting forces were also reduced due to the lower temperatures and it also helped to maintain the sharpness of the cutting edges of the tool inserts. Cryo-cooling machining and burnishing of magnesium alloys (Pu 2012) was carried out for surface analysis and FEM simulation. James C.et al. (Caudill, Huang et al. 2014) explored the surface analysis of *Ti-6Al-4V* alloy in Cryo-cooling burning process. Shape memory alloys of enhancing surface analysis(Kaynak, Karaca et al. 2014) was investigated in Cryo-cooling machining. The effect of Cryo-cooling on machining performance measures such as tool-wear, cutting temperature, force components and friction were studied extensively for various work material such as *Inconel 718* (Courbon, Pusavec et al. 2013). It was reported that Cryo-cooling machining contributes to improved machining performance in various materials (Senevirathne and Fernando 2012).

2.3.1 Hardness

The hardness has been investigated by several research of machining in different materials. The research of machining *AZ31B* Mg alloy found the hardness had higher value at about 10 mm below the machined surface after Cryo-cooling machining using the larger cutting edge radius tool (Pu, Outeiro et al. 2011). Using the same edge radius tool, the hardness-increasing tendency was slightly smaller under dry condition. The similar results also was shown the investigation of surface analysisin Cryo-cooling machining *Ti-6Al-4V* alloy (Caudill, Huang et al. 2014). The maximum surface hardness was obtained under cryo-cooling condition. Moreover, both Cryo-cooling and flood cooled burnishing presented a trend of increasing surface hardness with increasing preload. Subsurface microhardness variation for Cryo-cooling, dry and flood were shown in this research with constant preload as well. Higher hardness values were measured in Cryo-cooling machining throughout the burnished layer when compared with flood-cooled and dry burnishing.

More severe plastic deformation at lower temperature results in increased work hardening (Quan and Ye 2003). Since Cryo-cooling machining reduces the cutting temperature remarkably, in comparison with dry machining, a few researchers have investigated the effect of Cryo-cooling machining on microhardness on the surface and subsurface of the machined components. Pu et al. (Pu, Caruso et al. 2011) studied the microhardness variation beneath the machined surface in Cryo-cooling machining *AZ31 Mg* alloy, and measured results were compared with those from dry machining, and as received material as shown in Figure 2.1.

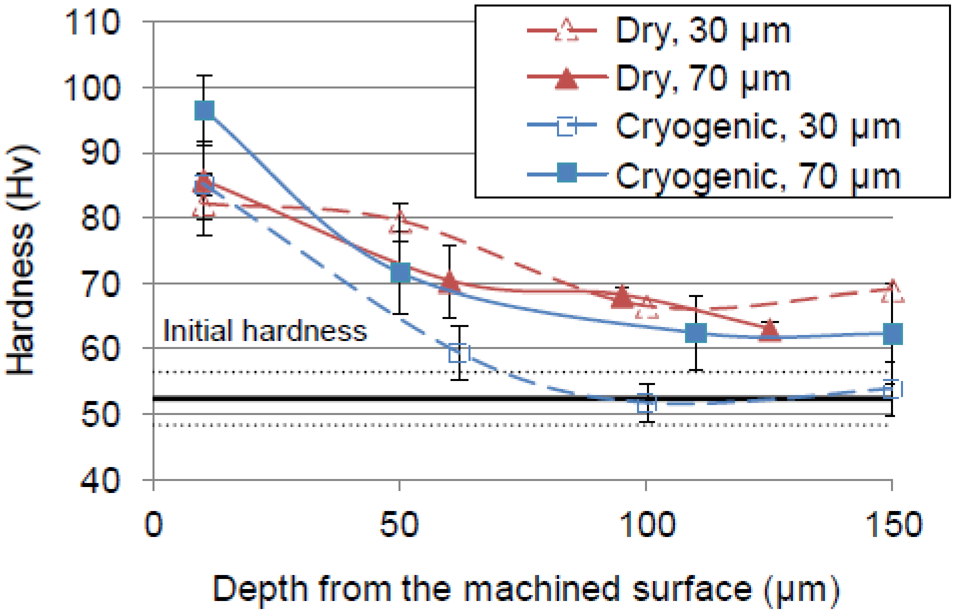


Figure 2.1 Hardness Variation with Depth below Machined Surface under Different Conditions (Pu, Caruso et al. 2011)

It's reported that the hardness values near the surface on these four profiles increased at different rates. It's easy to find that the hardness increases in the dry machined disc using a 30-μm edge radius tool is similar to the increase of the initial disc. The hardness at about 5μm from the surface increased by about 60% compared with the bulk material. Therefore, the actual hardness increases on the machined surface can be even larger than 60%. This large increase in hardness show that the severe plastic deformation formed on Cryo-cooling machined *AZ31 Mg* alloy. Jiang et al. (Jiang, Chen et al. 2010) reported that Cryo-cooling machining led to increased hardness of *AZ31 Mg* alloy as well. Besides light materials, in Cryo-cooling machining of difficult-to-machine materials such as *NiTi* shape memory alloys, it was found that a slightly harder subsurface in comparison with dry cutting was measured (Kaynak, Karaca et al. 2014). The effect of Cryo-cooling on microhardness of machined specimen in the further research was much more obvious in orthogonal cutting of austenitic *NiTi* alloy, it's shown in Figure 2.2.

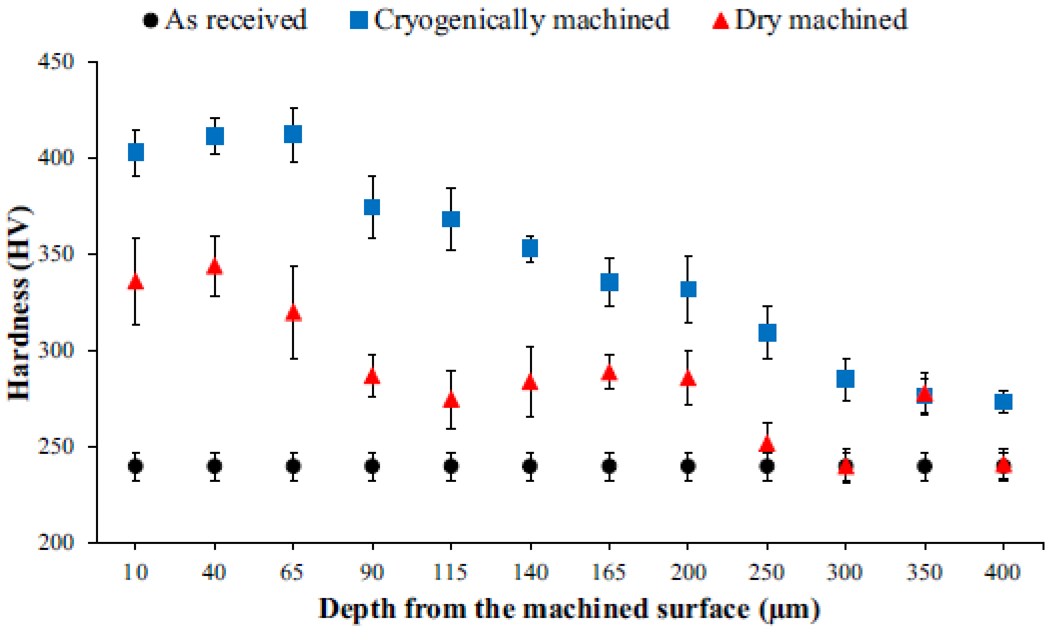


Figure 2.2 Subsurface Microhardness of as Received and Machined Specimens of *NiTi* alloy (Kaynak, Karaca et al. 2014)

The obtained difference in Cryo-cooling machining was attributed to high density of twins observed in microstructure, much higher subsurface microhardness was obtained due to small grains. The experimental findings show that the grain refinement, increased density of twins and increased subsurface hardness resulting from Cryo-cooling machining.

The surface modification including hardness variation beneath surface layer in dry and Cryo-cooling machining of AA7075 alloy was investigated recently. (Rotella and Umbrello 2014). In Cryo-cooling machining *Aluminum* alloys, an increased hardness on the surface and subsurface was observed (Rotella, Dillon et al. 2012). Figure 2.3 shows the hardness variations in selected samples from the machined surface to 600µm. The results clearly demonstrate that Cryo-cooling conditions allow the material to reach a higher surface hardness and a deeper hardness variation is also noted comparing the results with the dry tests. As a result, Cryo-cooling machining will create a more favorable machined surface in terms of hardness.

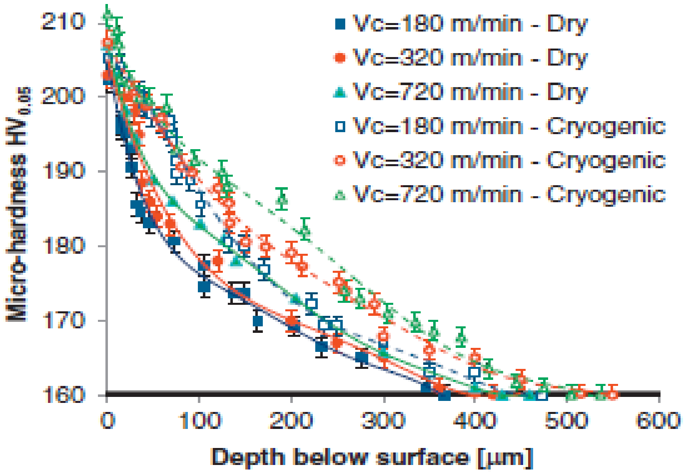
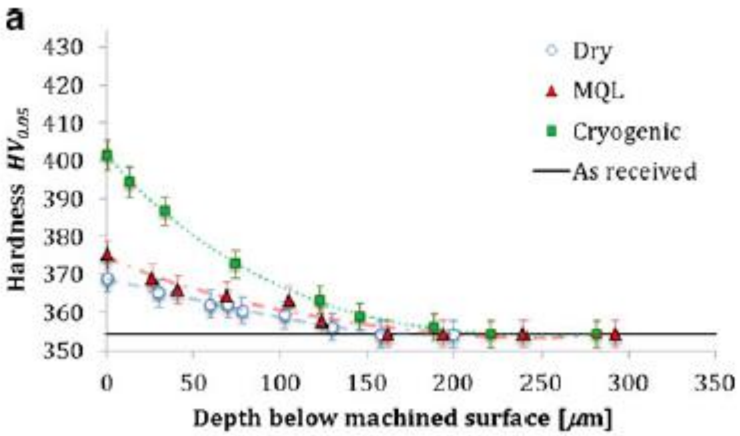


Figure 2.3 Measured Hardness Variation with Different Cutting Speed under Dry and Cryo-cooling Machining AA7075 Alloy (Rotella and Umbrello 2014)

The comparison between flood condition and Cryo-cooling condition in hardness measurement beneath surface layer was investigated in several research as well. Highest surface hardness was achieved in Cryo-cooling machining *AISI* 304 stainless steel in comparison with wet and oil based cooling, but the depth of work hardening was lower than flood condition (Fredj and Sidhom 2006). And Cryo-cooling machining in titanium alloy slightly enhanced the subsurface hardness compared with other Cryo-cooling in machining. Figure 2.4 shows the hardness variation of machined *Ti-6Al-4V* alloy samples at 0.1 mm/rev from the surface to the bulk material (Rotella, Dillon Jr et al. 2014). A deeper hardness alteration was observed in all Cryo-cooling ally machined_samples. MQL performs better than dry machining by exhibiting a higher surface hardness and maintaining it up to_a greater depth. Cryo-cooling machining of *Ti-6Al-4V* alloy with its lower temperatures promotes the hardness_increase during the cutting process. In fact, a combination of reduced thermal softening effect and greater grain refinement_results in a higher surface hardness in the machined samples. In the dry machining, it tends to create softer and rougher surface due to the lack of_coolant. From the results, the MQL cooling effect is not a comparable methods compare with Cryo-cooling _machining due to its significantly reduced thermal impact.



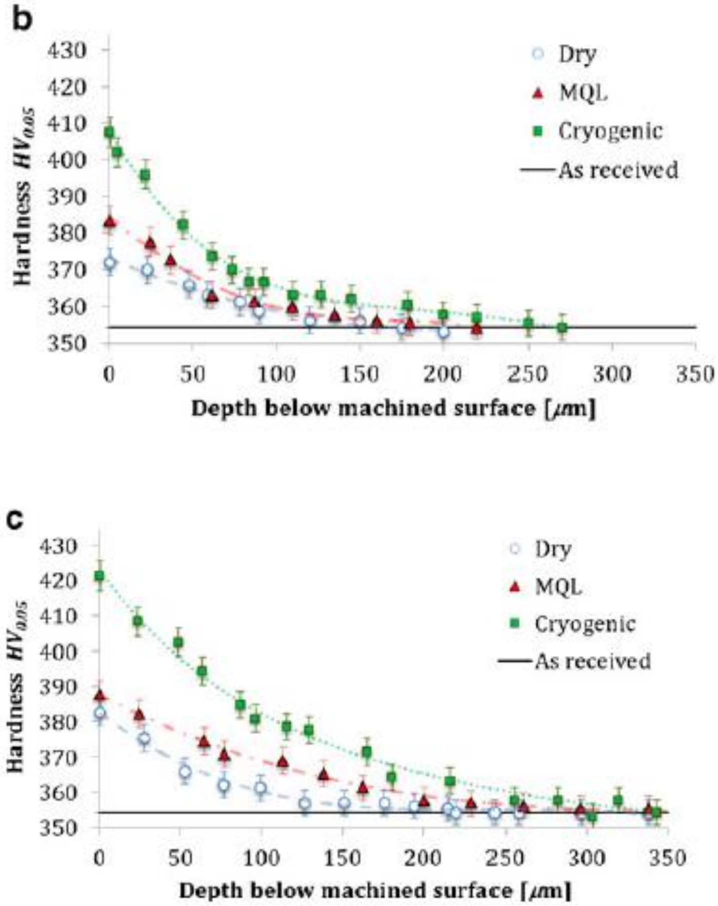


Figure 2.4: Hardness Variation in Machining Ti-6Al-4V alloy (Rotella, Dillon Jr et al. 2014)

Therefore, literature review of hardness as above show that the application of Cryo-cooling results in strain hardening, and less thermal effect on surface and subsurface of machined specimens. However, it has to be noted that the occurring work hardening depends on many parameters during deformation, including cutting temperature, machining force and cutting speed etc. The thermal and mechanical properties of machined material are also major factors in determining whether work hardening or thermal softening will take place in the process of machining. Initial conditions of material such as heat treatment, annealing, etc., are also key parameters affecting the response of the work material to high strain, strain-rate, and temperatures during the machining process. In sum, Cryo-cooling machining increases surface and subsurface hardness caused by reducing the cutting temperature, and decreasing thermal softening on surface and subsurface of machined samples. Due to low temperature, it leads to strain hardening on the surface and subsurface of machined samples. From the view of microstructure change, the grain refinement occurs to achieve a smaller grain, and increases the hardness on the surface and subsurface of work materials. Cryo-cooling machining also results in twinning deformation by reducing deformation temperature, which leads to formation of high density twins.

During the Cryo-cooling machining of *AISI 4140* alloy steel (Ambrosy, Zanger et al. 2014), the correlation of Martens hardness on depth of workpiece surface layer at cutting speed 75 m/min, cutting edge radius 30μm and depth of cut 30μm were measured, and shown in Figure 2.5 as below.

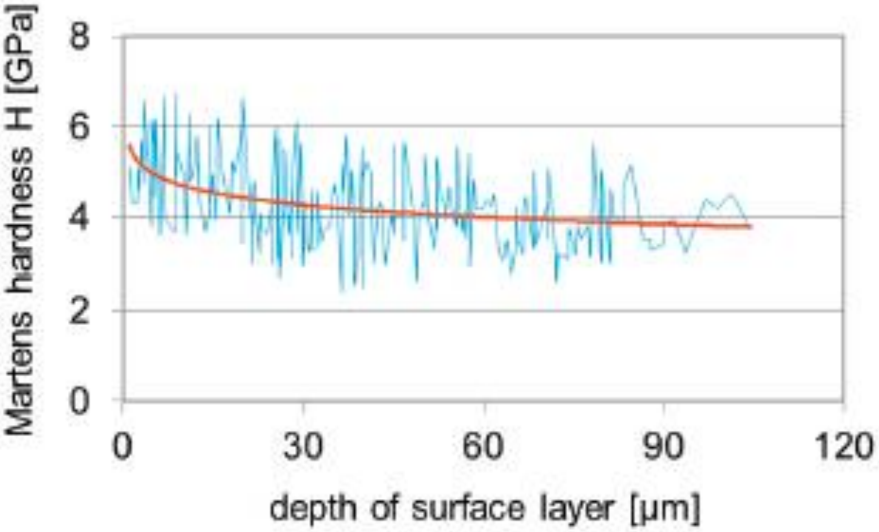


Figure 2.5 The correlation of Marten Hardness on Depth of Workpiece Surface Layer with cutting Speed 75m/min and cutting edge radius 30 μm (Ambrosy, Zanger et al. 2014)

The hardness of the machined surface after Cryo-cooling machining with a ratio of cutting edge radius and depth of cut with 1 was increased on the basis of the hardness value within the workpiece bulk material. The hardness measured in the depth of affected workpiece surface layer and on the workpiece surface after dry and Cryo-cooling machining with two different cutting edge radius are shown in Figure 2.6 and Figure 2.7**.**

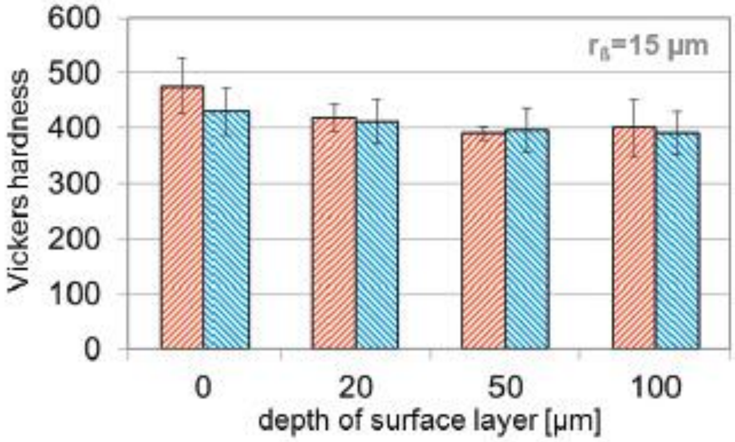


Figure 2.6 The hardness in the depth of affected workpiece surface layer and on the workpiece surface after dry and Cryo-cooling machining with 15µm (Ambrosy, Zanger et al. 2014)

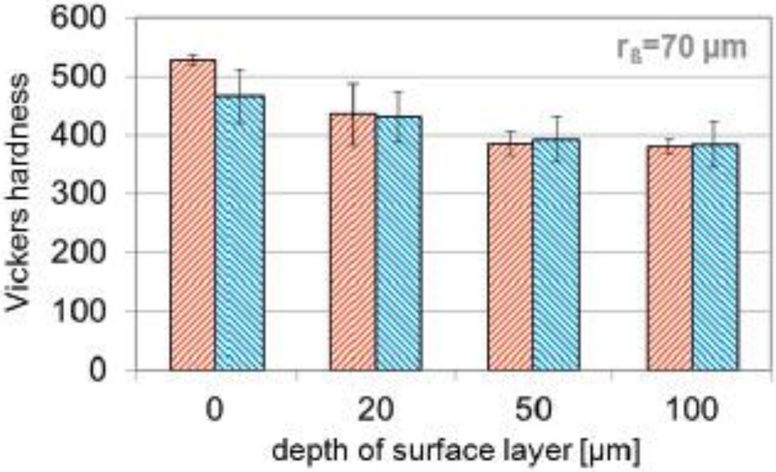


Figure 2.7 The hardness in the depth of affected workpiece surface layer and on the workpiece surface after dry and Cryo-cooling machining with 70µm (Ambrosy, Zanger et al. 2014)

At the same cutting edge radius, the hardness increased slightly at the workpiece surface during Cryo-cooling machining. Larger edge radius caused higher value of hardness in the same depth of surface layer. This experiment aimed to prove the value of surface hardness could be much larger during Cryo-cooling machining and higher cutting edge radius due to more severe plastic deformation.

2.3.2 Surface roughness

The effect of machining parameters including feed rate, cutting speed and Cryo-cooling on surface roughness has been explored for many years. The Cryo-cooling on surface quality especially surface hardness factor is key research for achieving desirable surface quality. As the result of better surface finish, the influence of Cryo-cooling machining on surface roughness in machining of different materials has been studied recently. In the recent studies of surface roughness, it's been reported that in machining of various materials such as *Ti-6Al-4V, Inconel 718* and Tantalum, Cryo-cooling machining substantially reduced the surface roughness in comparison with dry machining and other Cryo-cooling. Surface roughness on the machined surface was found to be reduced by Cryo-cooling cooling compared with dry and flood cooling on *AISI 52100* steel (Zurecki, Ghosh et al. 2003, Fredj and Sidhom 2006) and *AISI 4037* steel (Dhar and Kamruzzaman 2007).

Puˇsavec et al. (Pusavec, Hamdi et al. 2011) also reported that Cryo-cooling machining helps to reduce the surface roughness by preventing mechanical and chemical degradations of the machined surface in comparison with dry and MQL conditions in machining of *Inconel 718*.

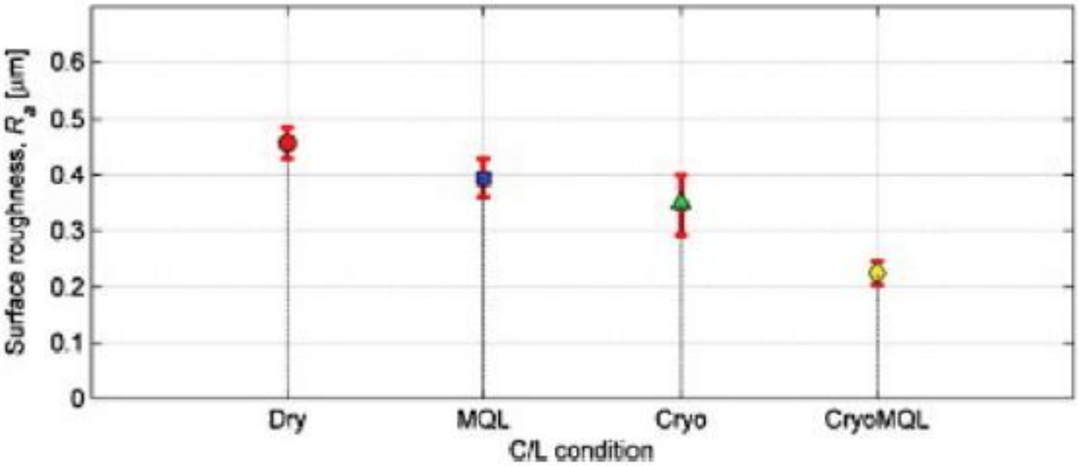


Figure 2.8 Surface Roughness of Machining Inconel 718 under Different Conditions (Pusavec, Hamdi et al. 2011)

In this research show in Figure 2.8 above on machining *Inconel 718* alloy, better surface roughness value was obtained in Cryo-cooling machining with same parameters compare to dry machining. A decrease in surface roughness was achieved by using Cryo-cooling machining as against conventional dry and MQL machining processes.

The lower value of surface roughness was obtained in Cryo-cooling machining of *AZ31B* Mg alloy in Figure 2.9 (Pu, Outeiro et al. 2011). The application of liquid nitrogen cooling led to about 20% decrease in surface roughness for both 30 and 70 µm edge radius tools compared with dry machining.

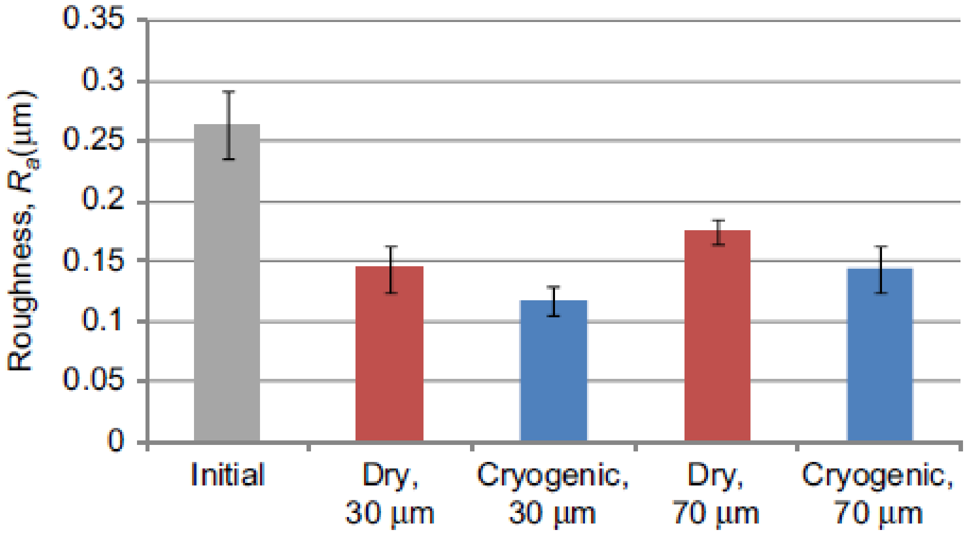


Figure 2.9 Surface Roughness of Machining AZ31B Mg Alloy in Dry and Cryo-cooling Machining (Pu, Outeiro et al. 2011)

The following Figure 2.10 shows surface roughness data was obtained by machining *NiTi* memory alloys (Kaynak 2014) under dry and Cryo-cooling machining process. The liquid nitrogen helped to improve the surface quality of machined components more than the dry machining. For the low cutting speed of 12.5m/min, there was not too much difference between dry and Cryo-cooling machining. However, the Cryo-cooling technology led to a significant reduction in roughness when machining using high cutting speed.

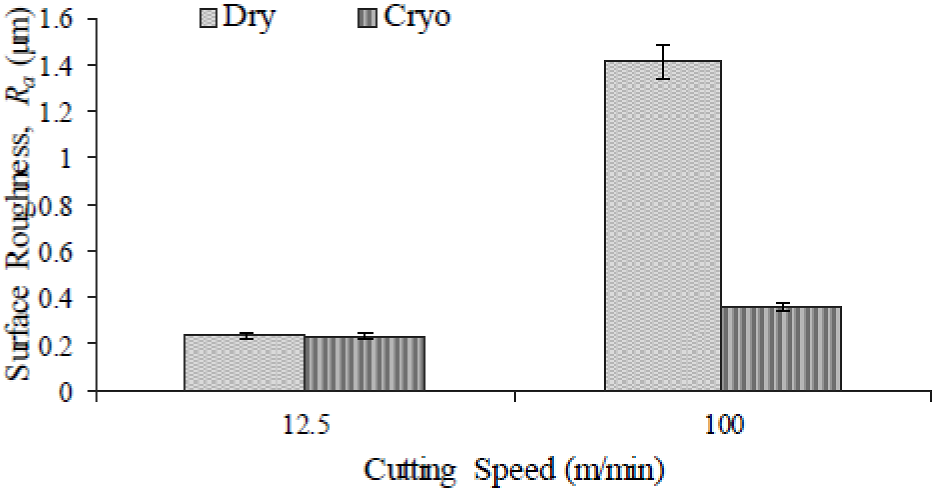


Figure 2.10: Surface Roughness as a Function of Cutting Speed under Dry and Cryo-cooling (Kaynak 2014)

The Cryo-cooling machining of *AISI 4140* alloy steel was investigated for surface roughness as well. But before Cryo-cooling machining in this material, some research focused on different Cryo-cooling on surface roughness. The surface roughness was investigated by using minimum quantity lubricant (MQL) during machining *AISI 4140* alloy steel (Sundaram and Lambert 1979). The reduction of tool wear, surface roughness and improving dimensional accuracy was successfully conducted using clean machining processes with MQL.It showed superior performance compared to dry turning. The hard turning test was carried out to investigate tool wear reduction and surface quality improvement of machined hardened steel *AISI4140* alloy steel when using MQL. There were 16 groups of experiments by four different Nanoparticle concentration levels to show that the MQL could reduce the surface roughness compare with dry and wet machining. Surface roughness can be enhanced. Minimal quantity lubrication oil mixed with a nanoparticle additive is feasible for augmenting the machining process. The surface roughness was also studied during the MQL turning process in another research (Chavoshi and Tajdari 2010). The oil mist was supplied from both nozzles to the rake and flank faces. The surface roughness has been significantly reduced when both nozzles were working. Some of researchers have been working on using different cutting tools to improve the surface roughness (Arrazola, Arriola et al. 2009). The results indicated that the surface roughness obtained with the wiper ceramic insert significantly improved when compared with conventional ceramic insert. Cryo-cooling and dry machining of AISI 4140 *alloy steel* by applying two different types of cutting inserts in comparison with surface roughness show in Figure as below (Dhar, Paul et al. 2002).

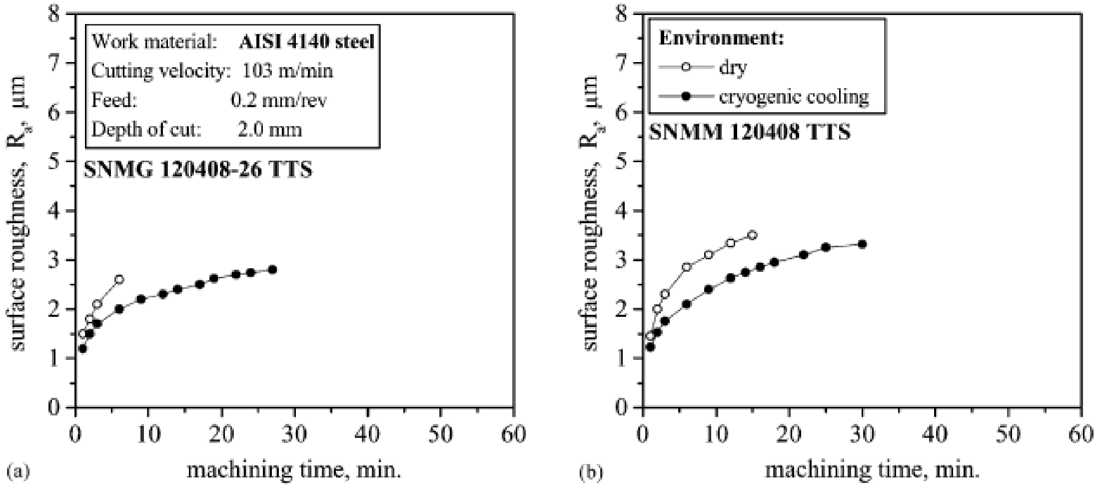
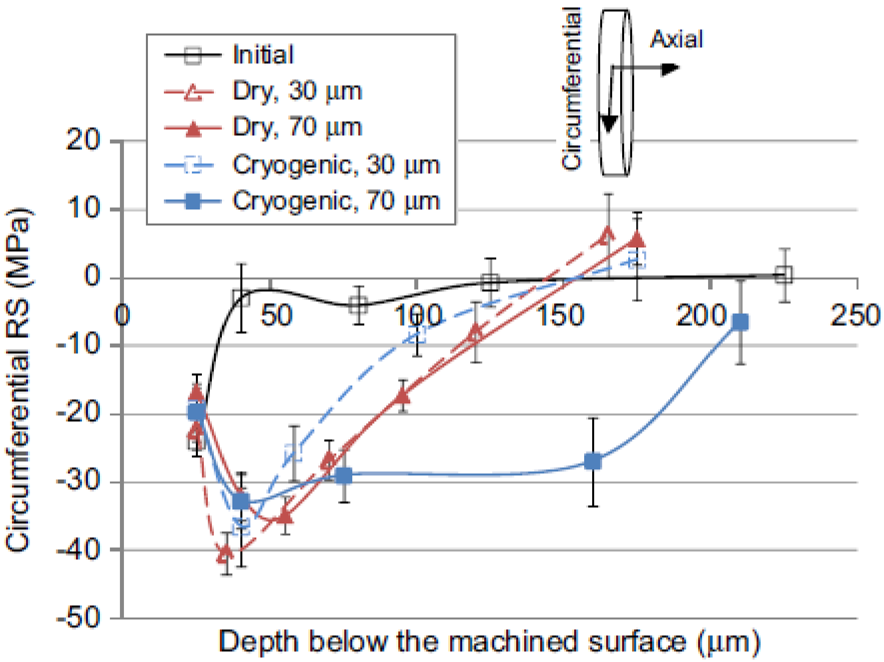


Figure 2.11: Surface Roughness Data of Machining AISI 4140 Alloy Steel with Time under Dry and Cryo-cooling Conditions (Dhar, Paul et al. 2002)

The surface roughness was increased gradually with time, but it’s noted that the reducing of surface roughness was observed under Cryo-cooling even though two different inserts were applied.

2.3.3 Residual stress

The analysis of residual stress is an essential study in the research of surface analysisand functional performance for various materials. The basic mechanism of machining-induced residual stresses was studied by many researchers. The functional behavior of a machined component is substantially determined by the physical state of its surface including the residual stress distribution near the surface (Brinksmeier, Schneider et al. 1984). The residual stress plays a key role in surface analysis(Capello 2005). The influence of residual stress may be either beneficial (compressive residual stress) or detrimental (tensile residual stress), depending upon its magnitude, pattern, and distribution (Guo, Anurag et al. 2009)._The nature of residual stresses depends not only on machining parameters such as the cutting speed, feed rate, depth of cut, but also on the tool geometry, the lubricating and Cryo-cooling (M'saoubi, Outeiro et al. 1999). Considering cooling as one of the important factors that affects the distribution and pattern of residual stress is reasonable. One of the residual stress generation mechanisms is the mechanical deformation mechanism, which results in compressive residual stress on the surface and subsurface of the machined components, due to limited thermal effect and dominant mechanical effect. Eliminating the thermal effect helps to generate the desired residual stress on the surface and subsurface of the machined component. To achieve this, the key parameter is to reduce the temperature during material removal processes. In this regard, Cryo-cooling machining has the potential to improve the functional performance of machined parts through the induced compressive residual stress. Therefore, many researchers focus on the effect of Cryo-cooling machining on the residual stress state of machined components. One of research published recently on the effect of Cryo-cooling machining on the residual stress state of the surface and subsurface of *AISI 52100* steel (Umbrello 2011). The results show that residual stresses are more compressive and deeper penetration depth in Cryo-cooling machining. Bicek et al. (Biček, Dumont et al. 2012) also presented that Cryo-cooling machining of *AISI 51200* steel reduces the thermal stress inducements compared to conventional dry machining, and therefore has higher compressive stresses on the surface and subsurface. Cryo-cooling machining-induced residual stress state on the surface and subsurface of machined light materials such as *AZ31* magnesium alloys was investigated by researchers (Pu, Outeiro et al. 2012), and it was reported that Cryo-cooling machining generates compressive residual stresses, and this extended to greater depths in both axial and circumferential directions, in comparison with dry cutting show in Figure 2.12 as below. The residual stresses in the axial direction and circumferential direction were more compressive and extended to greater depths during Cryo-cooling machining than those created during dry machining.



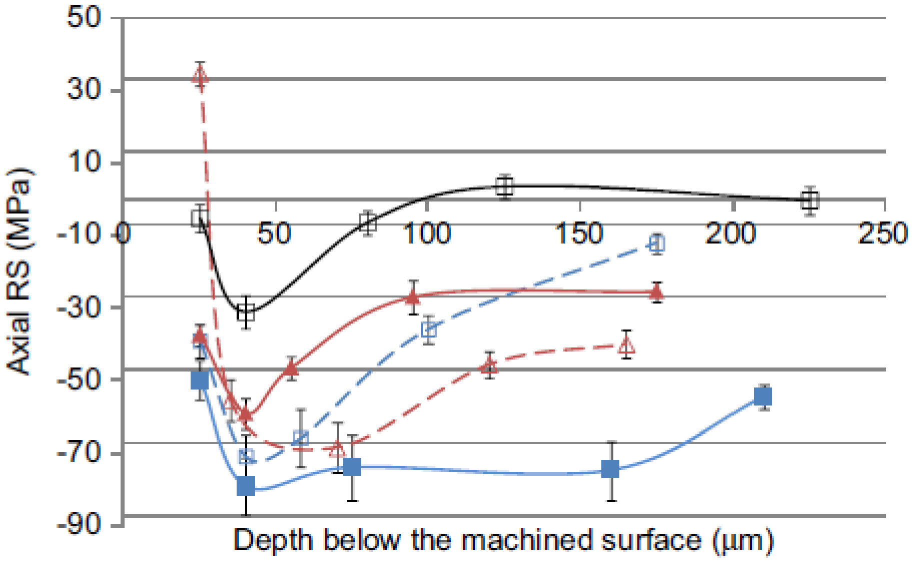
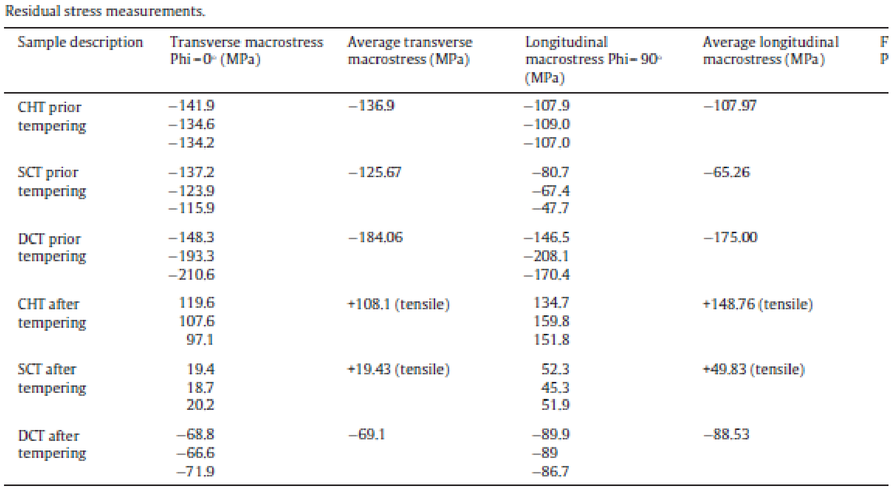


Figure 2.12 Residual Stress after Machining AZ31 Mg Alloy with Different Cutting Edge Radius under Dry and Cryo-cooling conditions (Pu, Outeiro et al. 2012)

It was concluded that Cryo-cooling machining minimizes the thermal effect and maximizes the mechanical effect, induces a greater compressive residual stress compared to other conditions. For another research, it was found that residual stress depends on Cryo-cooling in machining *Inconel* 718 (Pusavec, Hamdi et al. 2011). In the different Cryo-cooling including dry, MQL, Cryo-cooling and Cryo-cooling with MQL during machining process of *Inconel 718*, this study shows the typical residual stress data in axial and hoop directions, and the Cryo-cooling machining produced a much larger compressive residual stresses beneath the machined surface, as well as thicker compressive zone of material beneath the surface.

According to the reviewed literature, compared with other machining cooling approaches such as dry and wet, Cryo-cooling machining significantly contributes to improve a product's performance by generating more compressive residual stresses. The influence of residual stresses on fatigue life and corrosion resistance of manufactured components was reported in recent years. Less tensile residual stresses was generated on the machined surface under Cryo-cooling compared with dry machining. Achieving desired residual stresses on the surface and subsurface of machined components to improve the functional performance of components is very important work in study. Therefore, the contribution of Cryo-cooling machining on residual stress to enhance the performance of components is key work in machining area. It was also emphasized by researchers that a thicker compressive zone of material beneath the surface was obtained in Cryo-cooling ally machined samples and these two entities in general improve the machining quality, and present an upgraded characteristic (Kenda, Pusavec et al. 2011).

Based on previous study on residual stress under Cryo-cooling in various materials, the contribution of Cryo-cooling machining on the enhancement of residual stress distributed on the machined surface of the manufactured components was comprehensively studied by many researchers. In a recent work, the effect of Cryo-cooling treatment on the residual stresses of *AISI 4140* alloy steel was studied _(Senthilkumar, Rajendran et al. 2011). The Table 2.2 show two kinds of Cryo-cooling treatment, shallow (- 80 ºC × 5 h) and deep Cryo-cooling treatment (-196 ºC × 24 h) in comparing with Hot treatments were carried out between quenching and tempering in conventional heat treatment process.



Residual stress measurements.

Sample description	Transverse macrostress Phi = 0° (MPa)	Average transverse macrostress (MPa)	Longitudinal macrostress Phi = 90° (MPa)	Average longitudinal macrostress (MPa)
CHT prior tempering	−141.9 −134.6 −134.2	−136.9	−107.9 −109.0 −107.0	−107.97
SCT prior tempering	−137.2 −123.9 −115.9	−125.67	−80.7 −67.4 −47.7	−65.26
DCT prior tempering	−148.3 −193.3 −210.6	−184.06	−146.5 −208.1 −170.4	−175.00
CHT after tempering	119.6 107.6 97.1	+108.1 (tensile)	134.7 159.8 151.8	+148.76 (tensile)
SCT after tempering	19.4 18.7 20.2	+19.43 (tensile)	52.3 45.3 51.9	+49.83 (tensile)
DCT after tempering	−68.8 −66.6 −71.9	−69.1	−89.9 −89 −86.7	−88.53

Table 2.1: Measured Residual Stress in Longitudinal and Transverse Directions for Pretreatment in *AISI 4140* Alloy Steel (Senthilkumar, Rajendran et al. 2011)

The results showed that an increasing of compressive residual stress in *AISI 4140* alloy steel were subjected to Cryo-cooling pretreatment before tempering. In addition, conventional heat treatment and shallow Cryo-cooling treatment promoted a tensile state of residual stress, while deep Cryo-cooling treatment generated a compressive residual stress. However, this thesis show the detailed analysis of residual stress in machining *AISI 4140* alloy steel in chapter 4.

2.4 Summary

The literature review presented in this chapter clearly shows that recent development of numerical studies in s polishing methods and surface analysis changes, such as residual stresses, hardness, and surface roughness. The mechanical polishing and electropolishing have different benefits for specimen preparation work before surface analysis. In these research of machining process, surface analysis can be remarkably changed by cooling condition. These changes will have a critical influence on the functional performance of machined components. Another important topic reviewed is the previous work on machining of *AISI 4140* alloy steel. Some have been made to understand the changes of surface analysis induced by Cryo-cooling machining of *AISI 4140* alloy steel. However, most of them focused on the effect of cutting tool's geometry on surface analysis such as surface hardness and surface roughness in conventional machining process. The possibility of using 3D machining to improve functional performance of manufactured products through inducing desirable surface analysis has not been adequately investigated. The experimental and numerical results presented in the following chapters will demonstrate the potential of using turning process, to improve the surface analysis characters of *AISI 4140* alloy steel through inducing desirable surface analysis factors. The two polishing approaches will show the detailed attributes for surface analysis.

Chapter 3 Experimental Setup and Procedure

In this chapter, the details of experimental setup and procedure to carry out the investigations are discussed, including the setup of turning used to conduct the experiments, and the configuration of PC-based data acquisition system to measure the cutting force and temperature. The cooling techniques and equipment applied to carry out the experiments are introduced. The most innovative part is the electropolishing technology in removing surface material consistently along with depth of *AISI 4140* alloy steel sample before residual stress measurements. And X-ray diffraction (XRD) technic was employed to measure residual stress in tangential (cutting speed) and radial (feed) directions of machined samples. The instruments and methods used to measure hardness, surface roughness and chip microstructure are also discussed in this chapter.

3.1 Experimental Setup

3.1.1 Work Material

The material investigated in this study was *AISI 4140* alloy steel. The basic chemical composition of this *AISI 4140* alloy steel is shown in Table 3.1 as below (Schulze, Hoffmeister et al. 2011). *AISI 4140* alloy steel bar was used to prepare disc samples which have a diameter of 144.3 mm and a thickness of 3mm.

Element	**Fe**	**Cr**	**Mn**	**C**	**Si**	**Mo**	**S**	**P**
Content (%)	96.79-97.77	0.80-1.10	0.75-1.0	0.38-0.43	0.15-0.30	0.15-0.25	0.040	0.035

Table 3.1: Chemical Composition of *AISI 4140* Alloy Steel (Schulze, Hoffmeister et al. 2011)

3.1.2 Cutting Tool

The cutting tool is CVD coated carbide from Kyocera Company. The geometry of grooved cutting tool is CNMG HQ515. The detailed parameter is shown in Table 3.2 as below.

C	**N**	**M**	**G**	**HQ**	**5**	**1**	**5**	**CVD**
Shape	Relief Angle	Tolerance	With Holes	Chip breaker	Inscribe Circle size	Thickness	Corner Radius	Coated Carbide
80º Rhombic	0º		Two Sides	Finishing Applied	5/8inch	1/16 inch	1/64inch	TiN layer Al_2O_3 layer TiCN layer

Table 3.2: The Geometry of Cutting Tool in Machining *AISI 4140* Alloy Steel

3.1.3 Experimental Matrix

As shown in Figure 3.1, a HAAS CNC machine, equipped with an Air Products ICEFLY® liquid nitrogen delivery system, was employed to conduct turning experiments of the *AISI 4140* alloy steel. A machining using a coated carbide insert was conducted at a feed rate of 0.1 mm/rev and a depth of cut of 0.2 mm in order to standardize initial turning.

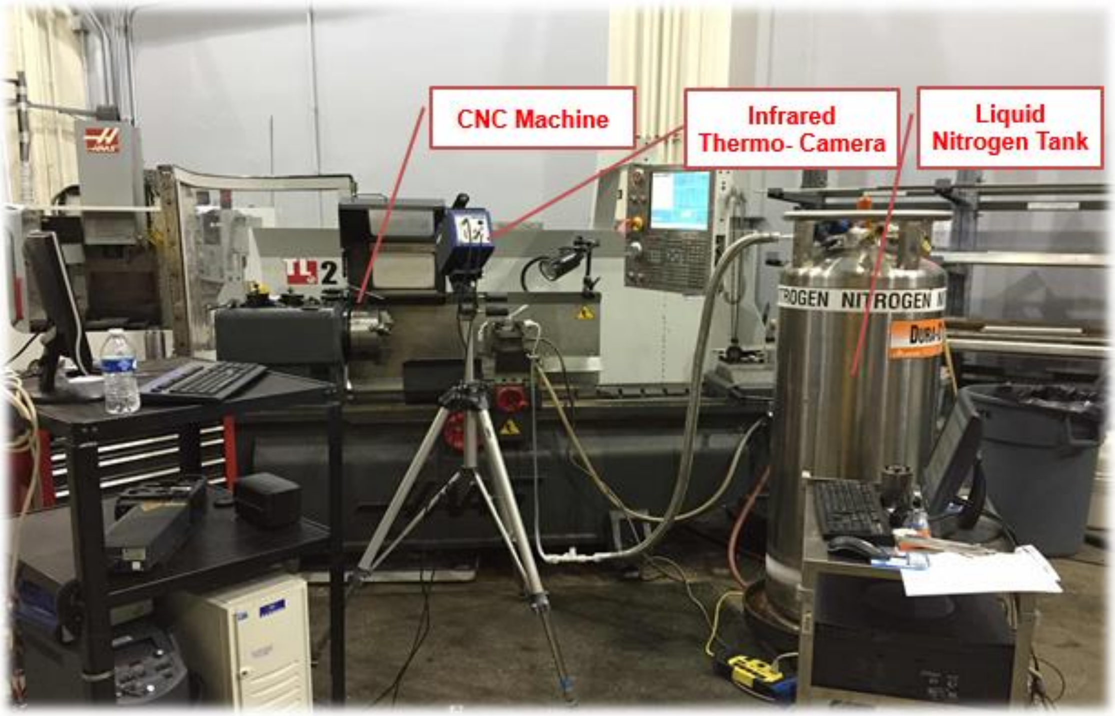


Figure 3.1 HAAS CNC Machining Center Equipped with Liquid Nitrogen Delivery System and Infrared Thermo- Camera

The machining experimental matrix is shown in Table 3.3 as below.

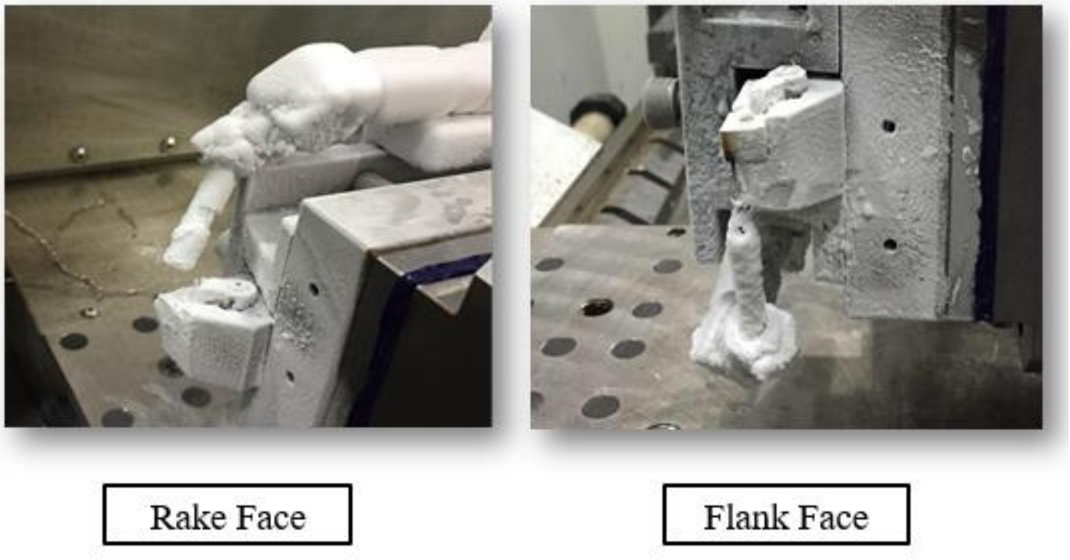
NO.	Cutting Speed (m/min)	Depth of Cut (mm)	Feed Rate (mm/rev)	Cryo-cooling
1	80	0.2	0.1	Dry
2	150	0.2	0.1	Dry
3	250	0.2	0.1	Dry
4	350	0.2	0.1	Dry
5	80	0.2	0.1	Flood-cooled
6	150	0.2	0.1	Flood-cooled
7	250	0.2	0.1	Flood-cooled
8	350	0.2	0.1	Flood-cooled
9	80	0.2	0.1	Cryo-cooling : Rake Face
10	150	0.2	0.1	Cryo-cooling : Rake Face

11	250	0.2	0.1	Cryo-cooling : Rake Face
12	350	0.2	0.1	Cryo-cooling : Rake Face
13	80	0.2	0.1	Cryo-cooling : Flank Face
14	150	0.2	0.1	Cryo-cooling : Flank Face
15	250	0.2	0.1	Cryo-cooling : Flank Face
16	350	0.2	0.1	Cryo-cooling : Flank Face

Table 3.3: Experimental Matrix for Machining *AISI 4140* Alloy Steel

3.2 Cooling Technics

For dry machining, no cooling method was used; for Cryo-cooling machining, liquid nitrogen was sprayed to the tool-workpiece interface. Liquid nitrogen was used as coolant in this research in order to reach the Cryo-cooling temperature during the machining. Internal pressure building tank of 250 liters capacity filled with liquefied nitrogen gas was chosen to supply the cooling liquid nitrogen and to keep the Cryo-cooling supply constant for every machining test. Valves were built on the liquid nitrogen tank, and also on the hose connecting the cylinder and the tool holder mentioned early. Both valves were opened up to the maximum turn to allow the liquid nitrogen go through the tool holder and the coolant supply holes and thus apply Cryo-cooling cooling internally during turning experiments. Liquid nitrogen tank with hose is shown in Figure 3.1 before. As shown in Figure 3.2, liquid nitrogen was sprayed to the machined surface from rake side or flank side of the cutting tool with constant flow rate during Cryo-cooling machining.



Rake Face

Flank Face

Figure 3.2 The Nozzle Position in Cryo-cooling Machining

3.3 Infrared Thermal-Camera Setup

A FLIR ThermaCAM PM695 infrared thermo-camera was used during the experiments to record the whole disc thermal field and temperature history of the *AISI 4140* alloy steel during processing. The accuracy of the camera was ± 2 °C according to the manufacturer‘s manual. As shown in Figure 3.1, the infrared camera did not move during cutting process. The distance between the workpiece and the camera was around 0.5 m. When using the infrared camera, the emissivity of the material is a critical parameter, and its choice will greatly influence the accuracy of the measurements. For Infrared thermography using IR camera to assess cooling effects, include the following references which report the IR thermography technique to identify defects of final products including stamping, welding and machining(Omar, Hassan et al. 2005, Omar, Hassan et al. 2005, Omar, Hassan et al. 2006). Good temperature measurement results were obtained on *AISI 4140* alloy steel when the emissivity was set to be 0.8. Therefore, an emissivity of 0.8 was applied for this study.

3.4 Cutting Force Measurement

A KISTLER 3-Component Tool Dynamometer was used to monitor the forces during machining. In the turning process, three directions of force components including cutting force (tangential), radial feed force, and axial force were measured in specific channels.

3.5 Measurement of Surface analysis

3.5.1 Hardness

The hardness variation with depths from the surface was measured using a Vickers indenter on a CSM Micro-Combi Tester as shown in Figure 3.3. It’s also used for chip hardness measurement. Measured samples were cut from the machined discs, hot mounted, ground and polished. The load used was 100 mN and the duration time was 15s. Five indentations were measured on machined samples and chips in single experiment in which mean value was considered.

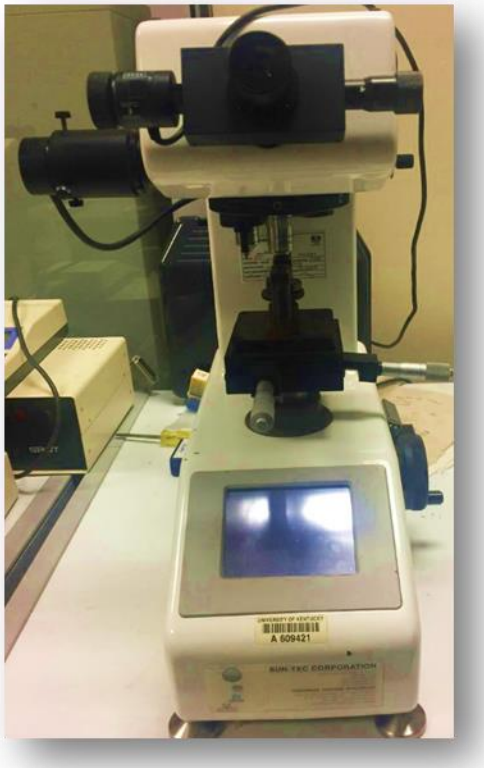


Figure 3.3 Vickers Indenter in Hardness Measurement for Machined Sample and Chip

3.5.2 Surface Roughness

The surface roughness after machining was measured using Zygo New View 7300 measurement system shown in Figure 3.4 which was based on white light interferometry.

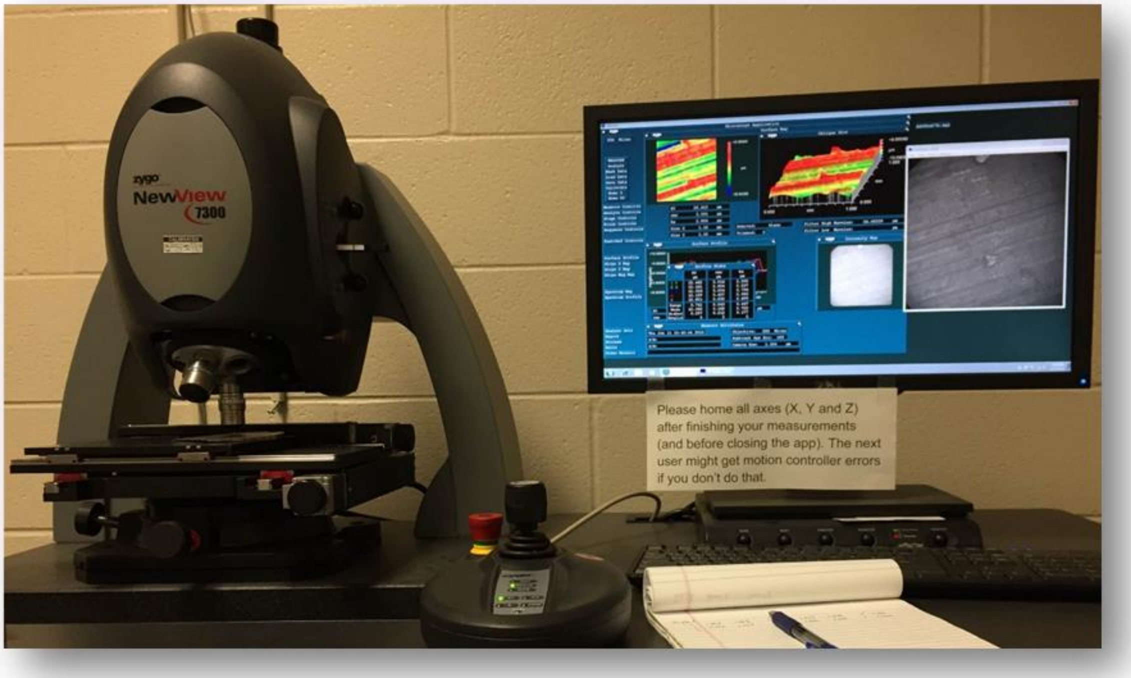


Figure 3.4 Zygo New View 7300 Measurement System in Surface Roughness

3.5.3 Polishing and XRD technics

Mechanical polishing included grinding and polishing. The grinding paper for the *AISI 4140* alloy steel were used as below.

- Silicon Carbide Grinding Paper Grit 80. 200 mm (8") dia.
- Silicon Carbide Grinding Paper Grit 220. 200 mm (8") dia.

- Silicon Carbide Grinding Paper Grit 800. 200 mm (8") dia.

- Silicon Carbide Grinding Paper Grit 1200. 200 mm (8") dia.

The lubricant is DP-Lubricant Blue. The polishing was applied in DiaDuo-2, 3 μm diamond suspension for routine materialographic specimen preparation. For final grinding and polishing of 150 rpm are used for both grinding/polishing disks and specimen holders for *AISI 4140* steel alloy. They are also both turning in the same direction. The force is set up constantly for 80N.

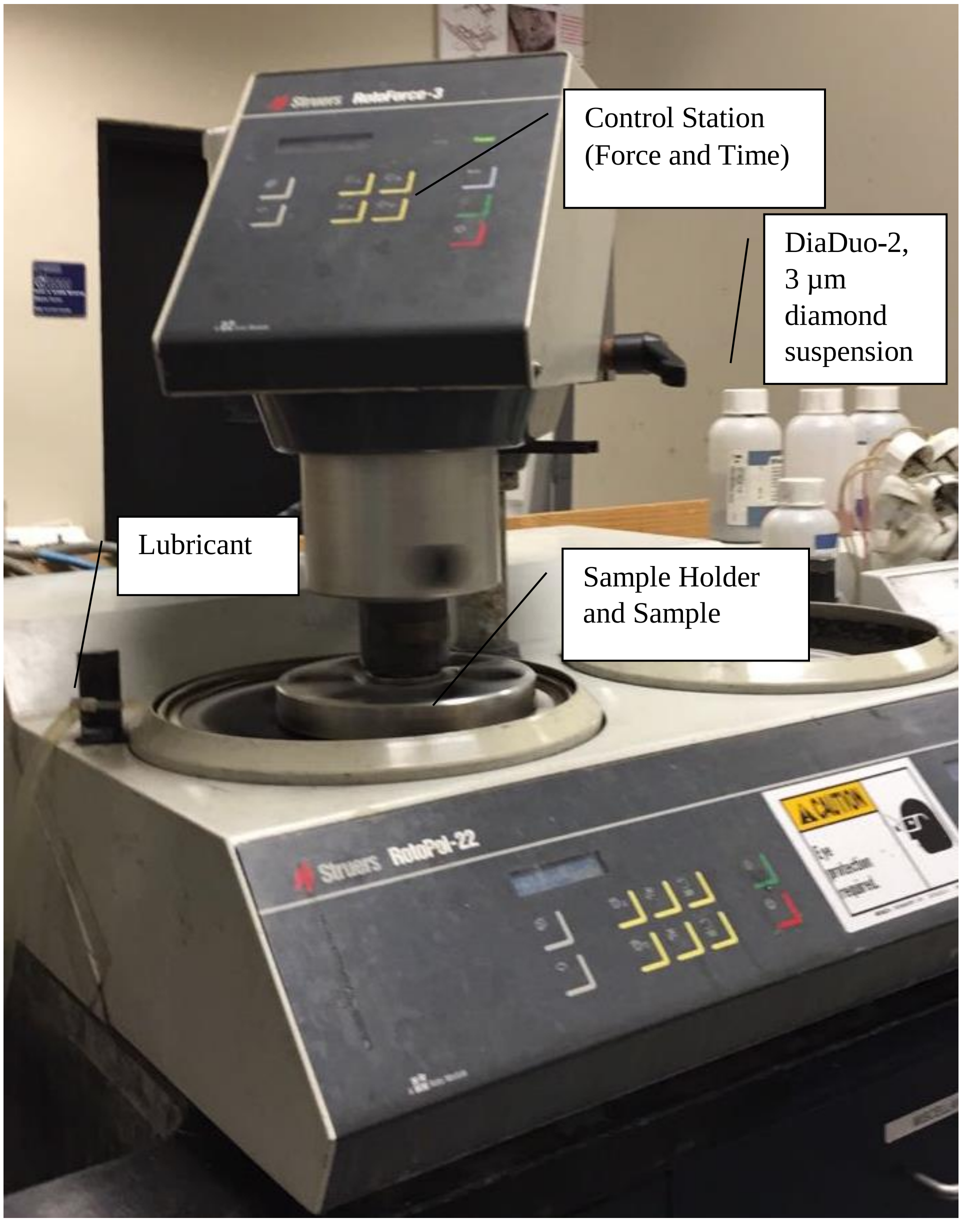


Figure 3.5 Mechanical Polishing Equipment Struers RotolPol-22

The residual stress state in machined *AISI 4140 alloy steel samples* was analyzed by X-ray diffraction technique using Bragg's law method. The experiments were conducted at the SeCat lab of University of Kentucky. The equipment used is Rigaku XRD machine, and the Figure 2.5 shows the experimental setup for residual stress measurements.

Figure 3.6 SeCat Lab XRD Machine for Residual Stress Measurements

The measured sample was cut from disc and cold mounted to avoid possible changes of residual stresses during sample preparation. XRD is the most non-destructive way of evaluating surface residual stresses. This method was first proposed by Lester and Aborn in 1925. In 1930, Sachs and Weerts showed that the accuracy obtained was similar to other methods. The method was improved in 1934 by Barret and Gensamer which was used to measure sum of eigenstresses. In 1935, Glocker showed that it was possible to evaluate each of the eigenstresses. Since then, because of both technological improvements and better understanding of the deformation of the crystal lattice, especially influence of anisotropy and crystallographic texture, a remarkable progress made on the method. Nowadays, it is one of the most common techniques that is used to measure residual stresses. The basic principle is based on Bragg's law shown in Figure 3.6, which states that when a monochromatic X-ray beam with wavelength λ is projected onto a crystalline material at an angle θ, diffraction occurs only when the distance traveled by the rays reflected from successive planes. This can be expressed using $n\lambda = 2dsin\theta$, where n is an integer, λ is the wavelength of a beam of X-rays incident on a crystal with lattice planes separated by distance d, and θ is the Bragg angle. XRD relies on the elastic deformation of a material to measure internal stresses in a material. The deformation cause changes in the spacing of the lattice planes from their stress free value to a new value that corresponds to the magnitude of the applied stress. Because the wavelength is constant, the unknown parameters in Bragg's equation are the interplanar spacing d and Bragg angle θ. Thus, if θ becomes known, the d value can be obtained using Bragg's law.

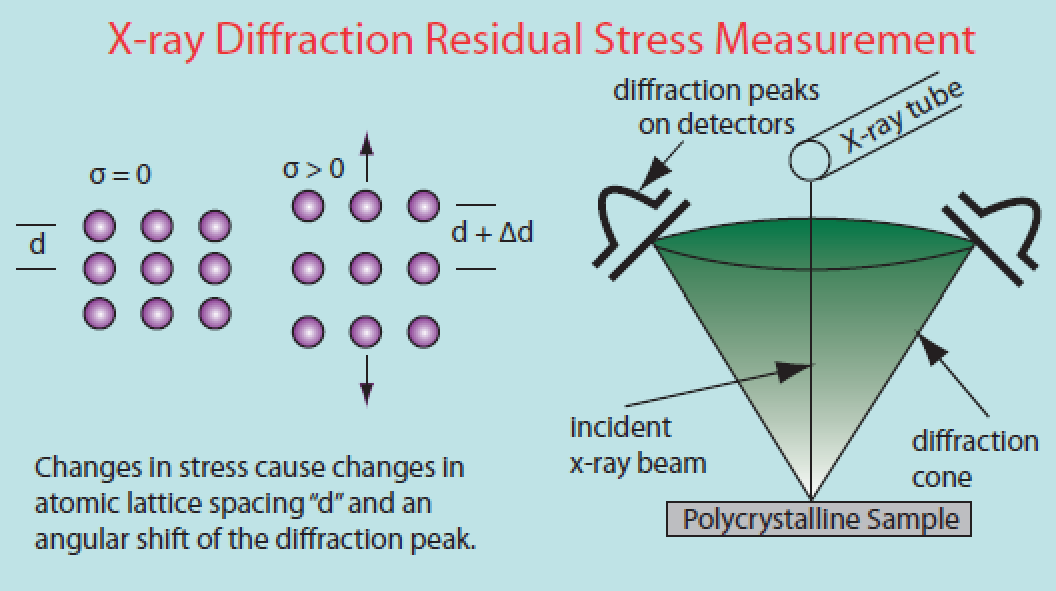


Figure 3.7: XRD Measurement Methods (Anderoglu 2005)

Complete theories and procedures for residual stress measurements by using XRD method can be found in this study (Hua, Umbrello et al. 2006). The parameters used in the X-ray analysis for this work are shown in Table 3.4.

Young Modulus	190GPa
Radiation Bar	Cu
Voltage	18V
Bragg Angle 2θ	116.4

Table 3.4: XRD Parameters for Residual Stress Measurement of *AISI 4140* Alloy Steel

The absolute intensity of the diffracted X-rays detected by the detector was different in each XRD pattern. Before the measurement of residual stress, the test of bulk material sample provided the information of XRD 2θ scan from for *AISI 4140* alloy steel in this research. Therefore, the peak angle was to achieve better results of residual stress. The cold mounted samples were selected at cutting speed of 150m/min and 350m/min, they are measured in two directions with tangential (cutting speed) direction and axial (feed) direction.

To determine the in-depth residual stress profiles, successive layers of material were removed by electropolishing to avoid the modification of machining-induced stresses. The BUEHLER

ELECTROMET 4 shown in Figure 3.7 was applied to remove material along with depth of machined specimen's surface of *AISI 4140* alloy steel.

Figure 3.8 Electropolishing Equipment for Removing Surface Layer of *AISI 4140* Alloy Steel

Moreover, the most important step is selecting the appropriate electrolyte for removing this material. And the solution used in present study must have constant removal rate. The detailed of solution employed and parameters for electropolishing of *AISI 4140 alloy steel* is shown in Table 3.5.

Electrolyte	Phosphoric Acid	230 ml
	Sulfuric Acid	200 ml
	Water	200 ml
Electropolishing Parameters	Voltage	18 V
	Current	7.6 A
	Removal Rate	20 μm/min

Table 3.5: Electropolishing Solution and Parameters for Removing Surface Layer of *AISI 4140* Alloy Steel

After several tests of bulk material, it should be noted that the temperature of solution impacted removal rate significantly. Thus, solution always has to be completely cool down until to room temperature before electropolishing. The first data of residual stress was measured on the surface, then started from at 20 μm beneath the machined surface to 300 μm.

In addition, materialographic mounting can be regarded as a helping process assisting the mechanical preparation process as well as the final test. Understanding the different characteristics of mounting resins and being able to evaluate the need for mounting is the key to have specimens that are easy to handle and clean and gives a good image of a coating or an edge.

Hot mounting for mechanical polishing is ideal for large numbers of specimens coming to the lab successively. The resulting mounts will be of high quality, uniform size and shape, and require a short process time. Hot mounting requires a mounting press that combines pressure with a high temperature. This mounting method could be used for surface analysis in surface roughness and hardness measurements. Cold Mounting is suitable for a large series of specimens coming to the lab simultaneously, and for single specimens. Cold mounting by vacuum impregnation is used to reinforce and protect materials such as ceramics, plasma sprayed coatings, and specimens for failure analysis that require special care during preparation. The residual stress measurement after machining process is not allowed introduced stress in mounting samples. Therefore, cold mounting is suitable approach for residual stress measurement in surface analysis.

3.6 Summary

Machining *AISI 4140* alloy steel at four cutting speeds in dry, flood and Cryo-cooling conditions were conducted by applied 16 turning experiments presented in this chapter. The surface analysis characteristics including surface roughness, hardness and residual stress were pretested and measured on each mounted sample. The introduction for surface layer removal knowledge involved in electroploshing technics before subsurface residual stress measurement was explored in details, and provided invaluable experience for study of *AISI 4140* alloy steel.

Chapter 4 The Effects of Machining Process in *AISI 4140* Alloy Steel Surface Analysis

4.1 Introduction

In this chapter, it presents the results of an experimental investigation of the effect of machining conditions including cutting speed and cooling method on the surface analysis of *AISI 4140* alloy steel. The surface analysis factors investigated include hardness, surface roughness, and residual stresses. The cutting speed were found to have remarkable influences on the surface analysis of machined *AISI 4140* alloy steel. Also the influence of Cryo-cooling on surface analysis is one of the most important topics investigated in this chapter. The results show that Cryo-cooling machining with high cutting speed leads to significantly enhanced surface analysis in terms of: significant hardness value; improved surface finish of roughness on the machined surface; much larger compressive areas in the residual stress profiles. These changes should notably improve the functional performance of machined *AISI 4140* alloy steel components. The experimental results presented here serve as a development of surface analysis on machining of *AISI 4140* alloy steel.

4.2 Experimental Results and Discussion

4.2.1 Cutting Forces Analysis

The research of the cutting force is a necessary part for cut assessment. In order to know the mechanical output of a machine and tool, it is important to know what is the cutting power taken by the tool and therefore to have information on the cutting forces. The value of the cutting forces also serves to dimension the organs of machines and to foresee the deformations of the pieces. During 3D turning process of *AISI 4140* alloy steel, there are three forces components including tangential cutting force, axial force and radial feed force in different directions. The turning process and force components measured by the dynamometer are shown in Figure 4.1 as below.

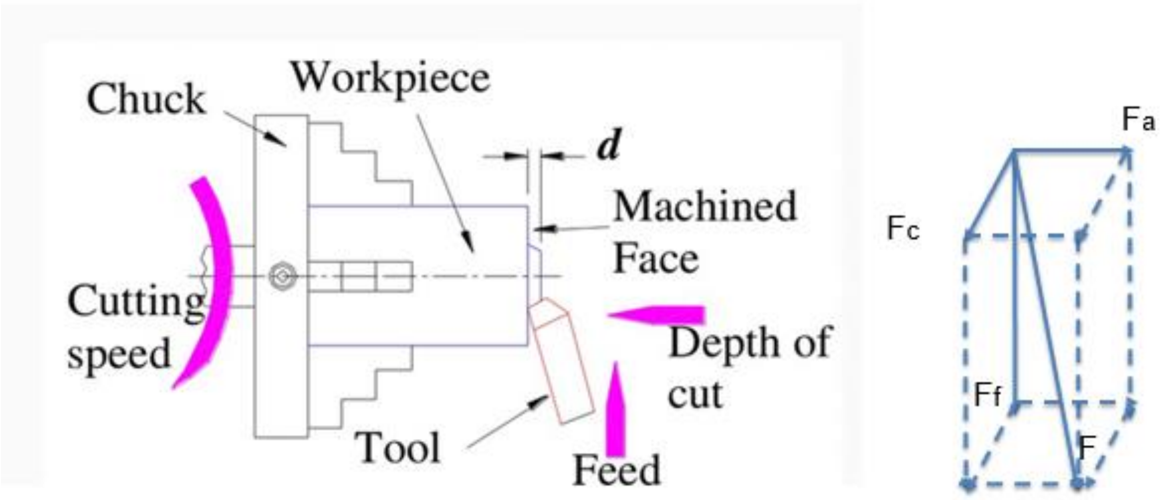


Figure 4.1: Machining Process and Cutting Force Components in Turning *AISI 4140* Alloy Steel

It is necessary to determine the correlation between cutting speed and achieved forces. Increasing the cutting speed generated more heat and led to higher temperature, thus thermal effect dominated to reduce the forces. The major cutting force data was measured as shown in Figure 4.2. The reduction in the cutting force was very significant at a higher cutting velocity in any Cryo-cooling because of thermal softening effect increased with cutting speed. When the cutting speed was increased, the cutting temperature also increased considerably was shown in Figure 4.5, thereby softening the work piece. The lowest cutting force of 60.27N was achieved at speed of 350m/min under dry machining. The decrease of forces under this condition can be due to the fact that thermal softening outweighed notably the work hardening effect. Moreover, the decrease at high cutting speed is essentially owed to the reduction of the rubbing between chip and cutting tool, limited by the stabilization of the temperature at high speeds. At high cutting velocities the plastic deformation decreases and the angle of shearing increases permitting the reduction of the area or section of shearing. However, when we amplify the cutting speed, the angle of shearing increase and the section will be reduced. The increase cutting speed at the same reduce a considerable the cutting force.

Meanwhile, the Cryo-cooling affected the cutting speed as shown in Figure 4.2 as well. Then the cooling method applied in this thesis also influenced cutting force notably at the same speed. In dry turning compare to flood condition, the softening of the chips due to high temperature at the primary cutting zone makes the chips become adhere to the tool rake face. Therefore, the friction is higher in between the chip-tool interface during the chip shearing process. However, the flood condition results in prevention of adhesion of the chips to the tool rake face hence reduced the friction between the chips and the tool, makes the sliding of the chips easier. It's noted that cutting force increased in Cryo-cooling machining of *AISI 4140* alloy steel at the same cutting speed. Increasing force normally was influenced by overwhelmed mechanical effect than thermal effect during the machining process. The low temperature of liquid nitrogen removes the heat in the cutting zone, making the work piece brittle, which certainly increases the cutting forces. On another hand, increased strain-rate leads to stronger work hardening and increases the forces. In addition, cutting force increased due to the shearing area increased under Cryo-cooling on the application of low temperature cooling fluids. For the flank face of nozzle position achieving larger cutting force, the liquid nitrogen led more cutting force may be due to the fact that the liquid nitrogen was sprayed to the machined surface more effectively. It has little influence on the temperature of cutting zone. Compared with data obtained under dry machining, the cutting force for Cryo-cooling machining with rake face and flank face was increased 8.7% and 11.43%, respectively. The increase is due to the effective cooling from the liquid nitrogen jet which enhances the mechanical properties of the material. On the contrary, cutting force deceased and maintain lowest value under flood machining at same speed machining. The maximum difference in cutting force between flood and dry machining was 13.7%.

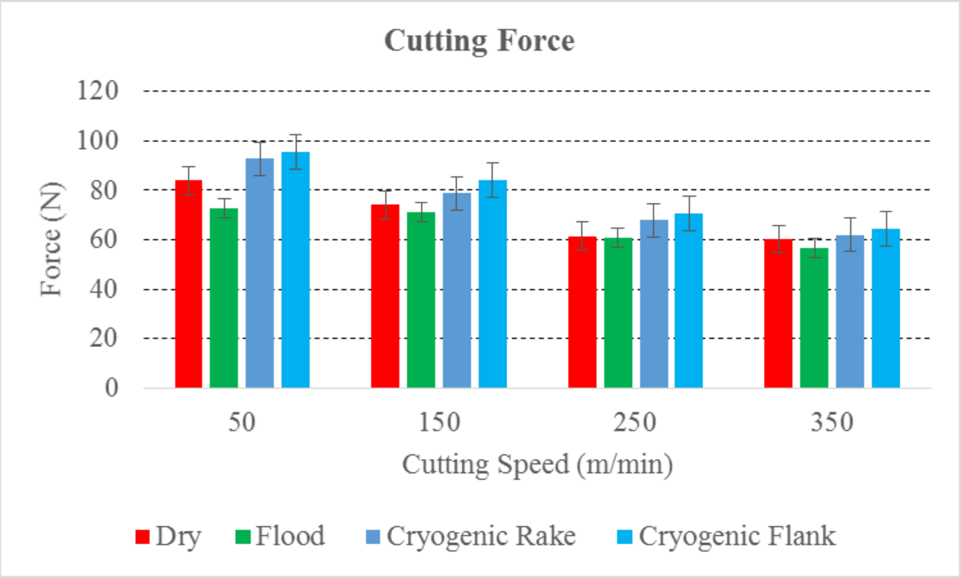


Figure 4.2: Cutting Force in Machining *AISI 4140* Alloy Steel

Similar trends as the cutting forces were observed in axial force and radial feed force as shown Figure and Figure. They show the influence of cutting speed on axial feed force and radial feed force for both all Cryo-cooling s was significant, when cutting speed of 350m/min was achieved lowest value as well. The application of liquid nitrogen have more influence on both forces. There were 66.3% and 102.4% maximum increases respectively in the radial feed force Cryo-cooling rake and Cryo-cooling flank compare to dry machining when the cutting speed was increased from 50 m/min to 350 m/min. under flood condition, The increase in the axial direction was much smaller, the largest increase which was 22.6% under Cryo-cooling conditions. The smaller force in the two feed forces compared to cutting direction may be due to the fact that only a small concentration of material occurred by cutting.

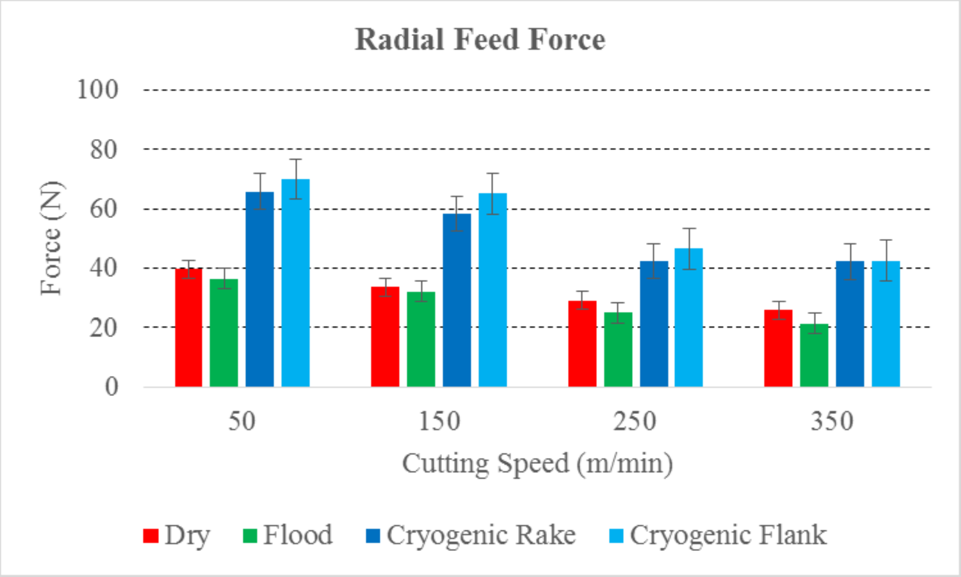


Figure 4.3 Radial Feed Force in Machining *AISI 4140* Alloy Steel

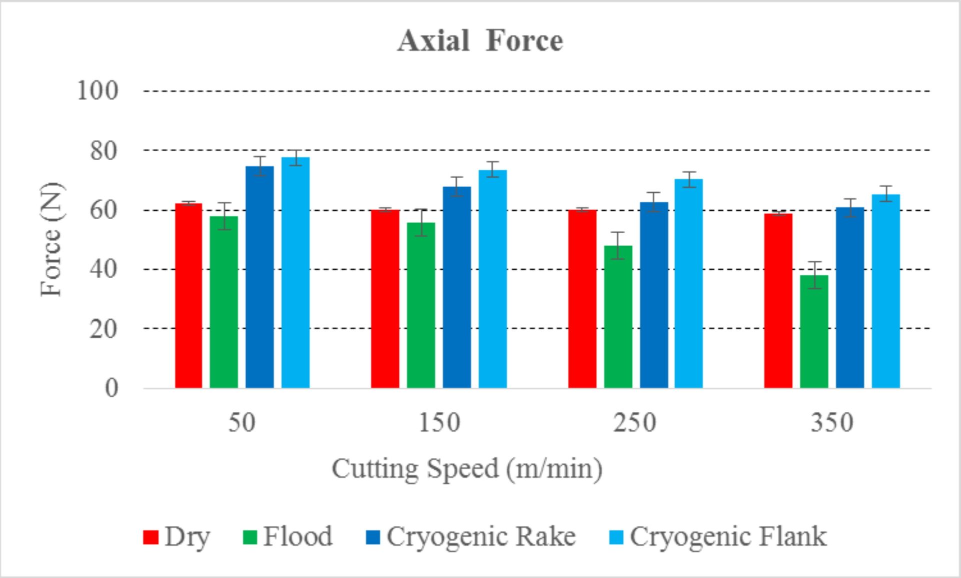


Figure 4.4 Axial Force in Machining *AISI 4140* Alloy Steel

4.2.2 Temperature

The temperature was measured by following the procedure described in Chapter 3. The emissivity value of *AISI 4140* alloy steel was 0.8 for the setup of infrared camera. As shown in the Figure 4.5, the highest temperatures under dry and Cryo-cooling machining of *AISI 4140* alloy steel were achieved. Larger cutting speed generated more heat during dry machining process, and it's easily found that the induced liquid nitrogen could reduce the machining temperature significantly compare to dry machining, and more decreasing of cutting temperature was obtained when Cryo-cooling machining in flank face of cutting tool. Compared with dry machining, the highest temperature was decreased by 21.1% and 23.7%, 17.7% and 26.2%, 16.3% and 18.1%, 16.7% and 18.4% respectively for Cryo-cooling machining at cutting speed of 50m/min, 150m/min, 250m/min and 350m/min.

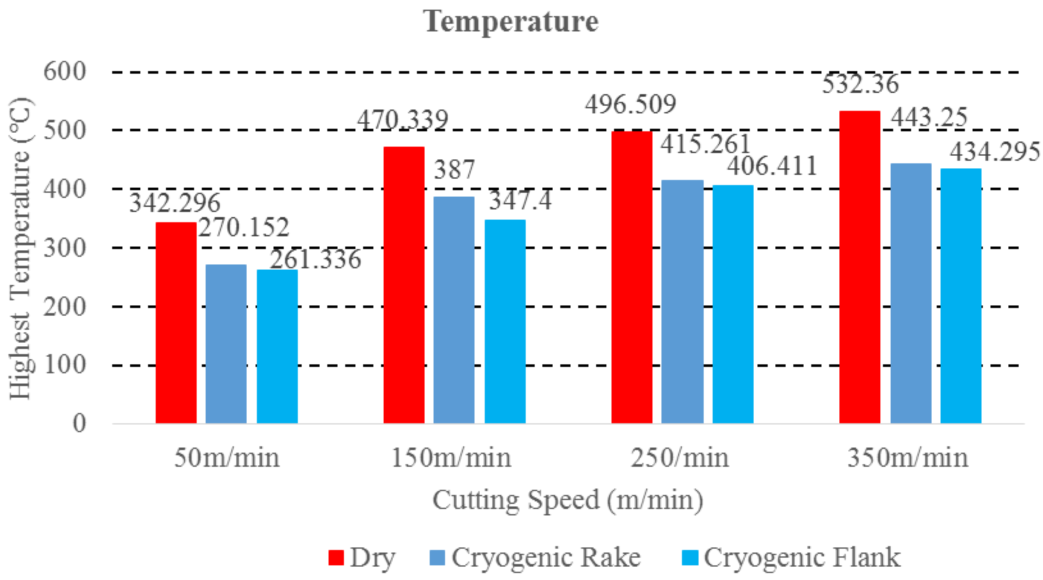


Figure 4.5 Highest Temperature in Dry and Cryo-cooling Machining *AISI 4140* Alloy Steel

4.2.3 Surface Roughness

Surface roughness measurements were carried out by a ZYGO© NewView 7300 scanning white light interferometer. Figure 4.6 shows comparison of the obtained surface roughness resulting from various cooling and lubricating conditions in machining *AISI 4140* alloy steel under two different cutting speeds. Flood machining generates much desired surface quality by considerably reducing surface roughness compared to other conditions.

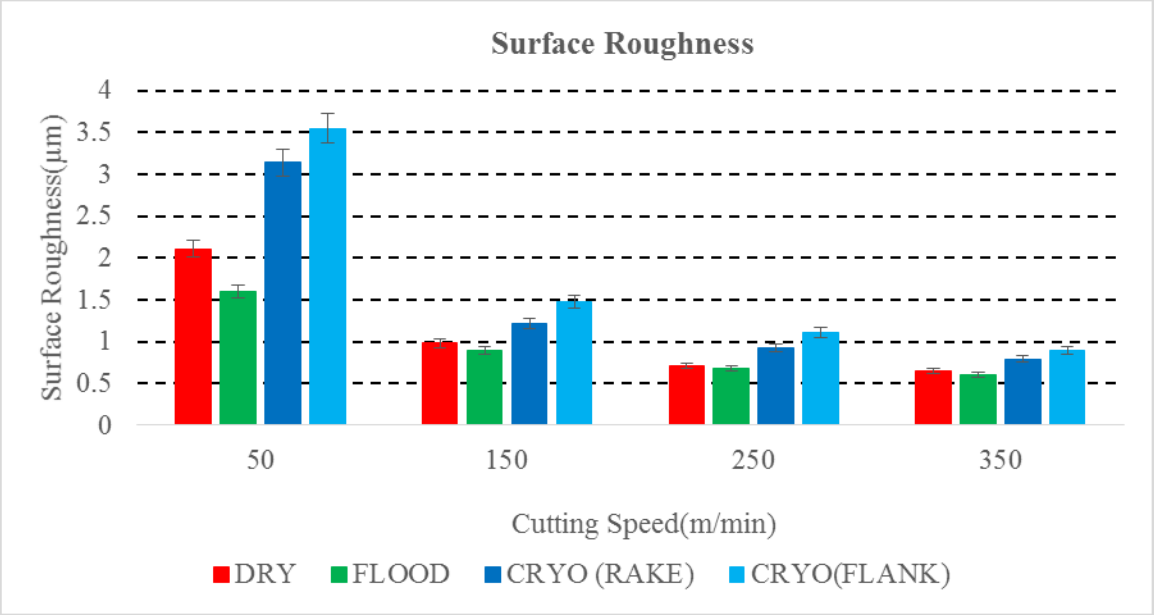


Figure 4.6: Surface Roughness Data in Machining *AISI 4140* Alloy Steel under dry, flood and Cryo-cooling

One study of turning process in surface finish presented the influence of cutting speed on the surface roughness (Öktem, Erzurumlu et al. 2005). According to this paper, the cutting speed had the greatest influence on the roughness followed by the feed rate. The depth of cut had no significant influence on the roughness. Similar results were found by Feng (Feng 2001) that also observed that in addition to feed rate, nose radius, work material and speeds, the rake angle has a significant influence on the surface roughness. The surface analysisin finishing hard turning of hardened steels was analyzed by Rech and Moisan (Rech and Moisan 2003). These authors observed that the roughness increases with both cutting speed and feed rate. However, in the dry machining and Cryo-cooling machining shown in Figure 4.6, high speed achieve better surface finish in roughness of *AISI 4140* alloy steel because larger thermal softening effect on material surface with less vibration during machining process. The surface roughness was improved four times especially in Cryo-cooling machining compared to low cutting speed. The cutting tools was observed without any built-up edge after machining under dry and Cryo-cooling condition in high speed machining. It has same trend in flood condition, even has better surface roughness in low speed.

Besides cutting speed, the Cryo-cooling of machining *AISI 4140* alloy steel is also important factor in the development of the surface roughness improved surface quality in flood machining is due to much smoother surface topography as shown in Figure 4.7 and Figure 4.8, yet in dry and Cryo-cooling, the feed marks are much more visible. When feed marks are visible on the surface of machined sample, much worse surface was obtained. The difference between peak and valley on the surface profile was much larger in dry and Cryo-cooling compared with flood cooling. There is no big difference on the topography of the flood and Cryo-cooling machined samples in high speed range from 150m/min. Moreover, the low temperature liquid nitrogen removes the heat and makes the work piece brittle, which certainly increases the surface roughness.

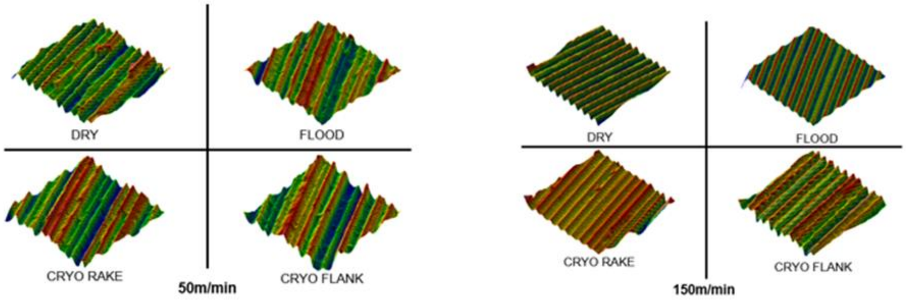


Figure 4.7 3D Topography at 50m/min and 150m/min in dry, flood and Cryo-cooling machining of *AISI 4140* Alloy Steel

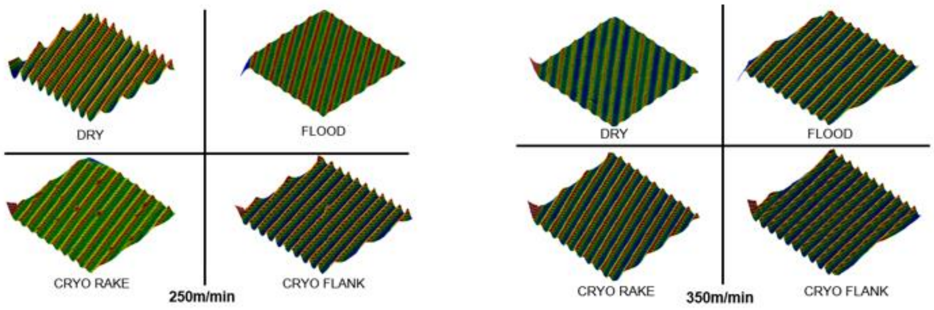


Figure 4.8 3D Topography at 250m/min and 350m/min in dry, flood and Cryo-cooling machining of *AISI 4140* Alloy Steel

Considering the relationship between surface quality and performance of machined products, particularly its contribution to the risk of failure of functional products. It is a well-known that failure or crack generally starts on the surface or subsurface where these deep feed marks could result in stress concentration at the surface and initiate the fracture and failure. In general, a smoother and high quality surface is desired from machining processes. Flood and Cryo-cooling machining meets this demand in high speed range better than the dry machining.

4.2.4 Microhardness

The hardness variation with depth below the machined surface with 600 μm under different machining conditions is shown in Figure 4.9, and each hardness data point presented in this figure was calculated by averaging five measurements taken. It shows the average values of microhardness at four different cutting speeds for dry, flood and Cryo-cooling machining of *AISI 4140* alloy steel. Beneath surface layer, every processed sample were measured by the Vickers indenter. The average value of the measured bulk material is 203 HV. The factors influencing hardness variation in this study in machining of *AISI 4140* alloy steel are considered to be thermal softening and work hardening. Machining is an effective process to induce high strain ranging on the machined surface. Hardness on the machined surface was found to improve because of work hardening effect during machining of magnesium_*Al 7075* alloy (Rotella and Umbrello 2014). Both the effects of thermal softening and work hardening need to be understood for a specific material being machined, as the properties vary from one material to another. Due to work-hardening the deformed layer, the hardness at the surface is much higher than in the base metal, and it was shown to exponentially reduce with increasing depth from the surface until it reaches the bulk material hardness value at a certain depth (Che-Haron and Jawaid 2005). Work hardening is another important factor that influences the hardness of a material. The work hardening effect has to be taken into account to explain the hardness variation in previous research. The amount of work hardening was successfully estimated by several researchers using the peak breadth measured from X-ray diffraction technique (Outeiro and Dias 2006). As shown in Figure 4.9, a general trend in this study, the hardness decreases significantly with the distance below the surface. The highest hardness found in all sixteen hardness curves corresponding to the eight different conditions in which four cutting speeds were used in dry and Cryo-cooling machining, was located on the machined surface. It is likely that hardness decreased specially in the machined surface layers within the depth of 120μm due to the thermal softening effect resulting from. Also the effect of work-hardening can only be kept stable under a certain temperature (Quan and Ye 2003). During or after the plastic deformation process, if the temperature rises up to the material’s restoration point, the effect of work-hardening will be weaken.

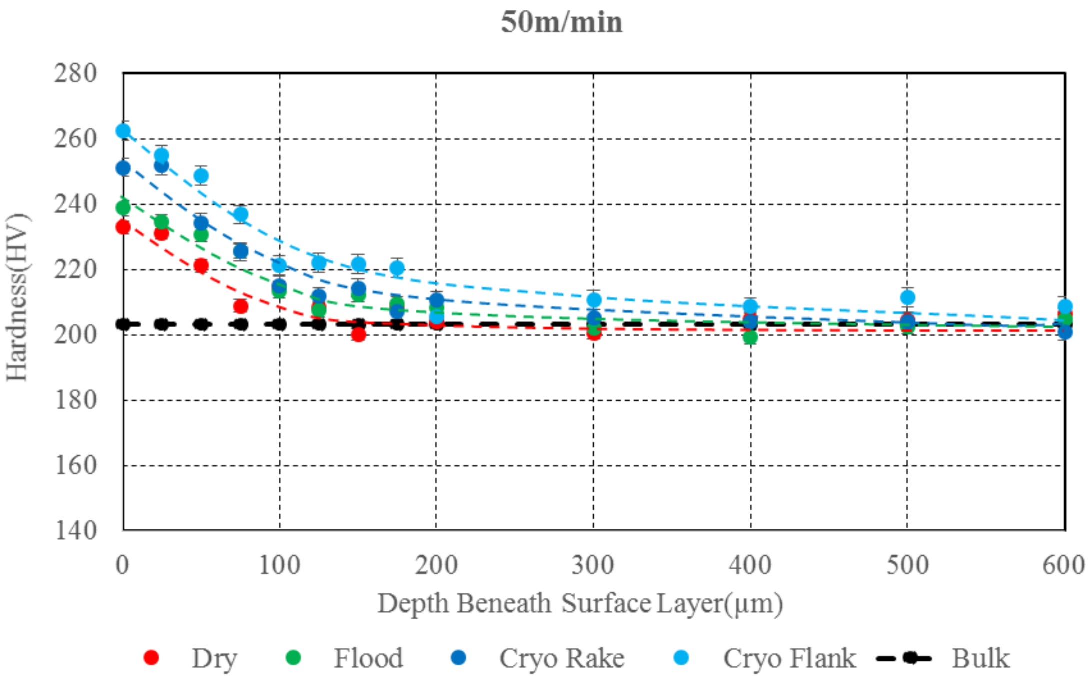


Figure 4.9: Hardness Variation at 50m/min in Machining *AISI 4140* Alloy Steel

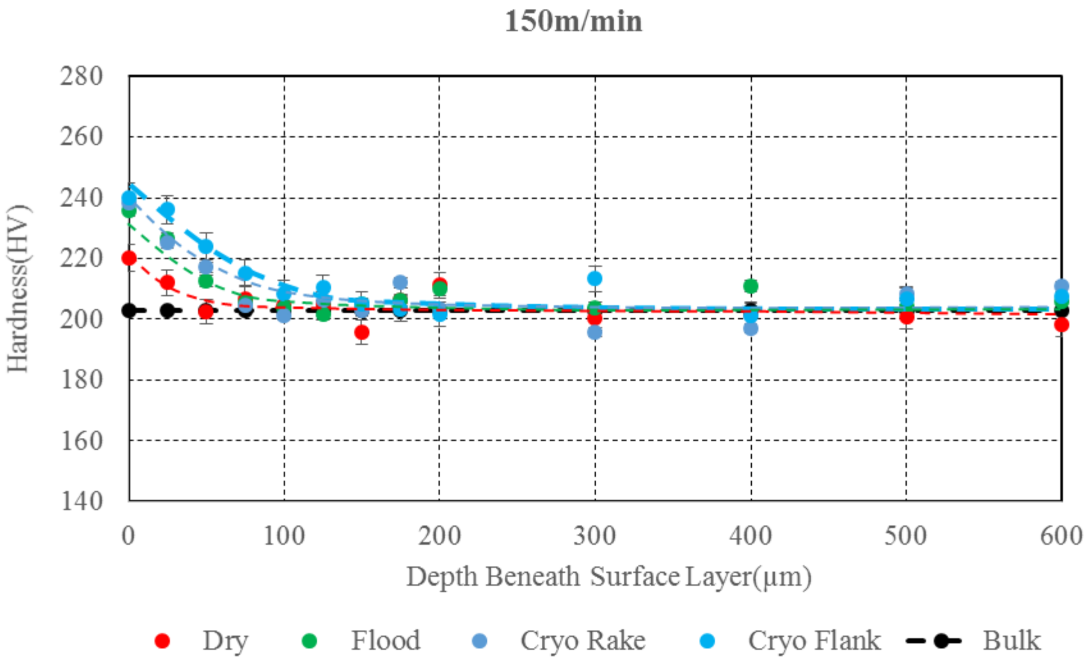


Figure 4.10: Hardness Variation at 150m/min in Machining AISI 4140 Alloy Steel

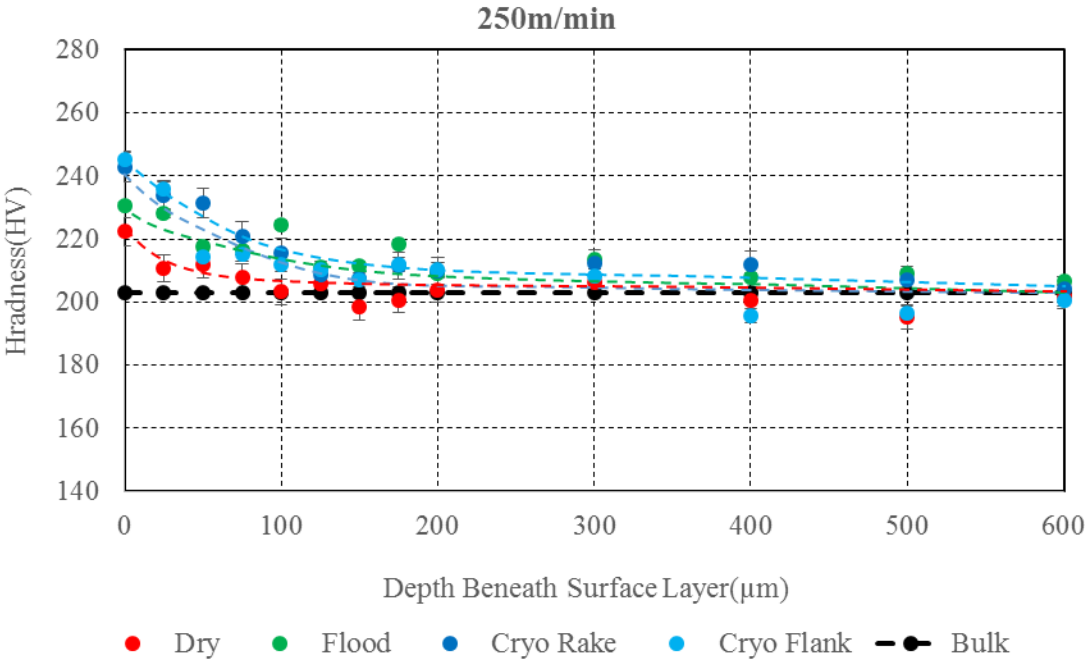


Figure 4.11: Hardness Variation at 250m/min in Machining AISI 4140 Alloy Steel

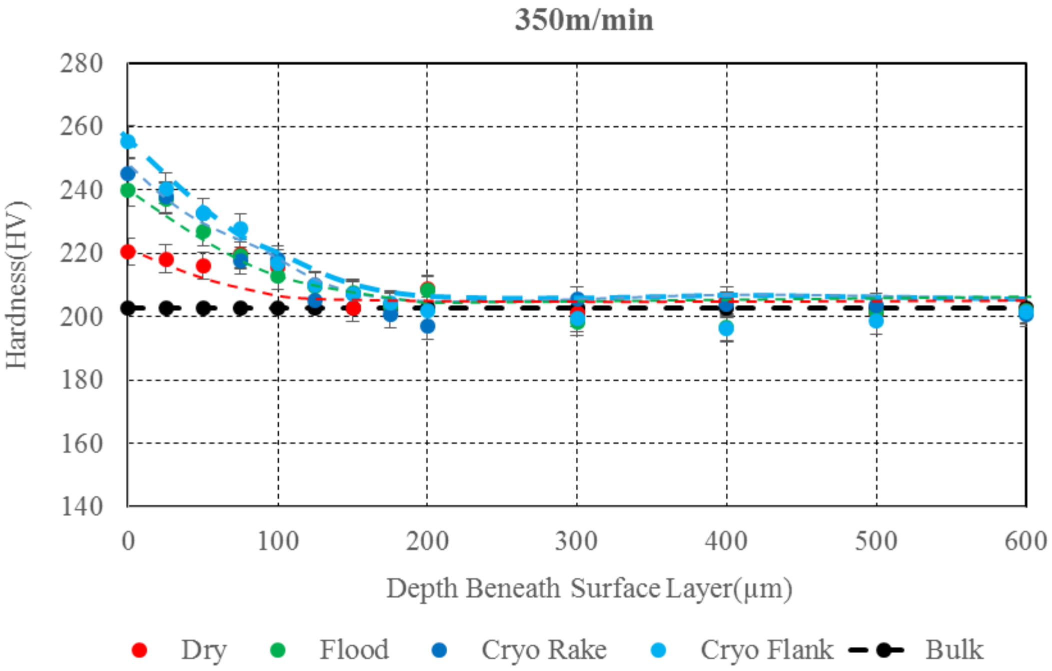


Figure 4.12: Hardness Variation at 350m/min in Machining AISI 4140 Alloy Steel

As shown from all Figures of hardness above, dry machining generally lead to lower surface hardness especially at higher cutting speed. The reason can be attributed to the effects of high temperatures generated during machining process, which would increase the thermal softening effect by improving machined surface temperature. The application of the liquid nitrogen coolant increases the work material surface hardness due to work hardening effect caused by its extreme low temperature, which could be the reason for an increase in the cutting force. For Cryo-cooling machining of *AISI 4140* alloy steel, higher hardness was observed in the machined surface layers compared with dry and flood condition, particularly at 50 and 350 m/min cutting speeds. It is seen in Figure that higher hardness was obtained in Cryo-cooling experiments than other condition as liquid nitrogen lowered the temperature. The surface hardness increased 29% from 203 HV in the bulk material to 262 HV the machined surface after Cryo-cooling machining in flank face with cutting speed of 50m/min, but the surface hardness increase was smaller under dry conditions. The liquid nitrogen delivered during Cryo-cooling machining effectively lowered the temperature in the machined surface to reduce the effect of thermal softening, and because of this phenomenon, the work hardening effect could improve the hardness in the machined surface at lower cutting speeds in Cryo-cooling machining. The highest hardness value could be achieved when the cutting speed was 50 m/min for dry, flood and Cryo-cooling conditions. The thermal softening significantly affected surface hardness in most cases. However, the temperature was lower to reduce the thermal softening effect, especially 50 m/min cutting speeds was used in the Cryo-cooling machining. The work hardening was more dominant to make the material harder. Based on the temperature measured in the machining experiments in this chapter, lowest temperature was achieved in Cryo-cooling machining on the machined surface.

For the machined surface layers closer to the bulk material between 200 and 600μm, thermal softening and work hardening balanced with each other, therefore the hardness was approximately the same as the bulk material. It is clearly visible that Cryo-cooling machining led to greater hardness values and a deeper influenced layer than the ones from dry machining. It caused by the higher temperature within the tool-workpiece contact zone which reduces the Severe Plastic Deformation effect as well as the higher temperature outside the tool-workpiece contact zone which prompts the dynamic recovery process during dry machining. The application of liquid nitrogen on the contact region effectively suppressed the temperature rise during and after machining and helped retain the SPD effects from processing. Therefore, it could be concluded that the increased mechanical deformation outweighed the thermal effects during dry machining when using high cutting speed and this led to similar amount of work hardening with the Cryo-cooling condition. This could be due to the decreasing temperature from the surface to the bulk material. The high temperature at the surface outweighed the mechanical deformation effects.

In sum, by reducing the cutting temperature and decreasing thermal softening on surface and subsurface of machined samples, due to low temperature, Cryo-cooling machining led to strain hardening on the surface and subsurface of machined *AISI 4140* alloy steel specimens.

4.2.5 Residual Stress

The major problems is high temperature during the machining of *AISI 4140* alloy steel, it will impact surface analysisby inducing tensile residual stress on surface and subsurface (Lienert, Hoffmeister et al. 2014). As shown from Figure 4.13 to Figure 4.16, shows the residual stresses along with depth in the tangential and radial directions after machining with two high cutting speeds under both dry and Cryo-cooling conditions were measured. The residual stresses were influenced significantly by cutting speed and Cryo-cooling. To analyze the residual stress on the surface and subsurface, tensile and compressive stress depend on both mechanical effect and thermal effect. Based on the reviewed literature, compared with other machining approaches such as dry, flood and Cryo-cooling. Cryo-cooling machining significantly eliminates the thermal effect and helps to achieve the desired residual stress on the surface and subsurface of the machined component. Therefore, the compressive residual stress results in limited thermal effect and dominant mechanical effect. On the contrary, the mechanism affects more on tensile residual stress on machined specimen. The distribution of residual stresses induced in the surface layers during the manufacturing processes. The nature of the residual stresses will enhance or impair the ability of a component to withstand fatigue, creep, stress, corrosion cracking, etc (Caruso, Outeiro et al. 2014). Residual stresses can have a detrimental effect on structural integrity and are an important consideration in failure assessment of all structures. It has been reported that the application of liquid nitrogen could introduce a favorable residual stress distribution in the surface layer, which may further improve the functional performance of metallic materials. Compared with conventional oil-based cooling, Ben Fredj and Sidhom found that Cryo-cooling led to about 50% reduction of tensile residual stress in the parallel direction of the disc workpiece (Fredj and Sidhom 2006), and the residual stress in the perpendicular direction was reduced to nearly zero from 200 MPa tensile, which substantially improved the fatigue life of *AISI 304* steel specimens subjected to high cycle fatigue loading. It was found that the residual stress distribution in machined *AISI 52100* steel was significantly improved by using Cryo-cooling (Zurecki, Ghosh et al. 2003). The compressive area which is the area defined by the compressive portion of the residual stress profile and the depth axis has been reported to be an important influencing factor on the fatigue life and corrosion performance of different materials (Pu 2012).

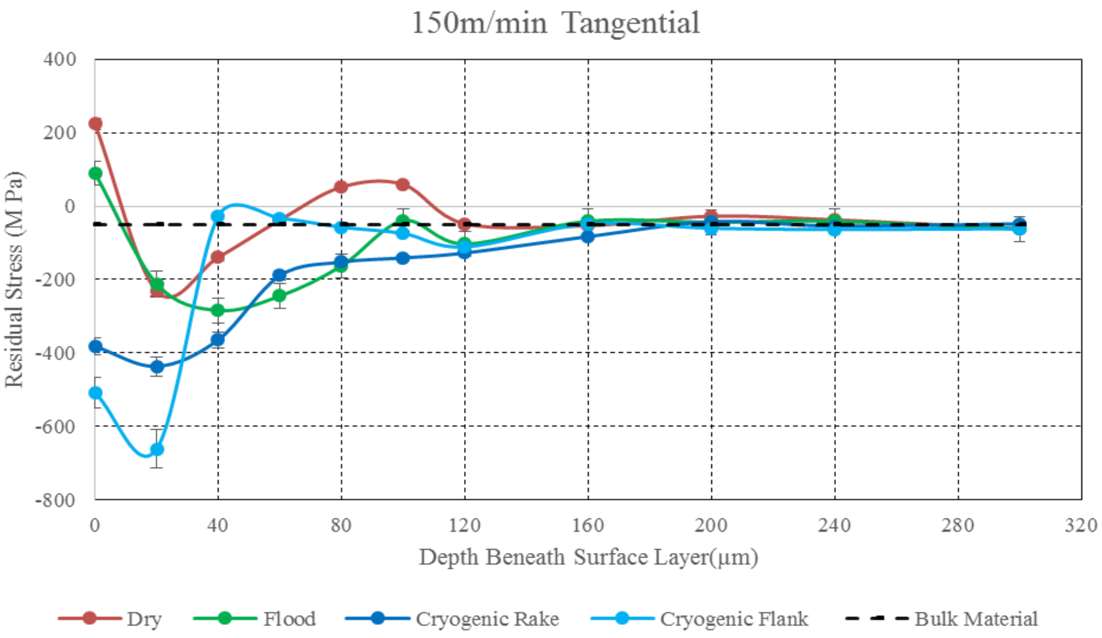


Figure 4.13 : Measured Residual Stress in Machining AISI 4140 Alloy Steel in Tangential Direction (cutting speed) at 150m/min

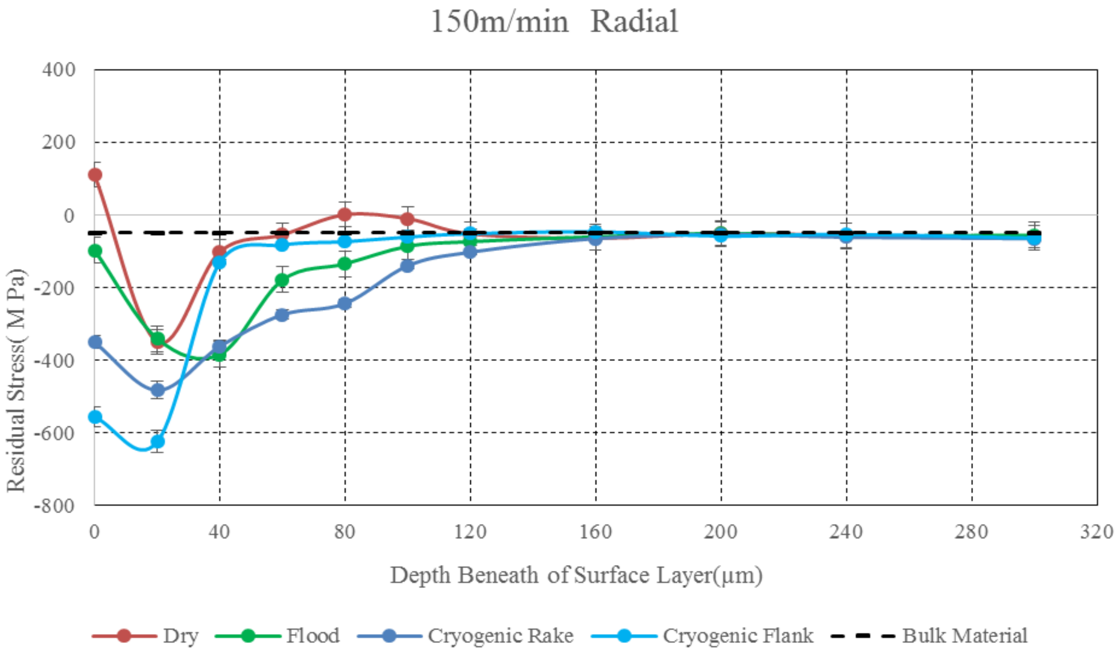


Figure 4.14 Measured Residual Stress in Machining AISI 4140 Alloy Steel in Radial Direction (feed) at 150m/min

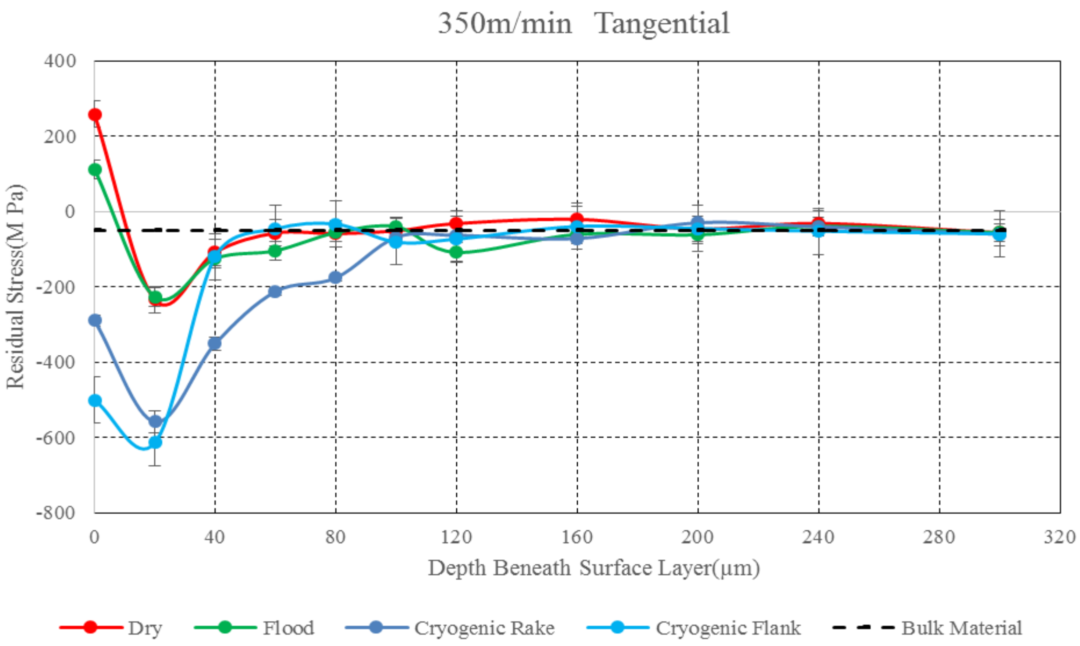


Figure 4.15 Measured Residual Stress in Machining AISI 4140 Alloy Steel in Tangential Direction (cutting speed) at 350m/min

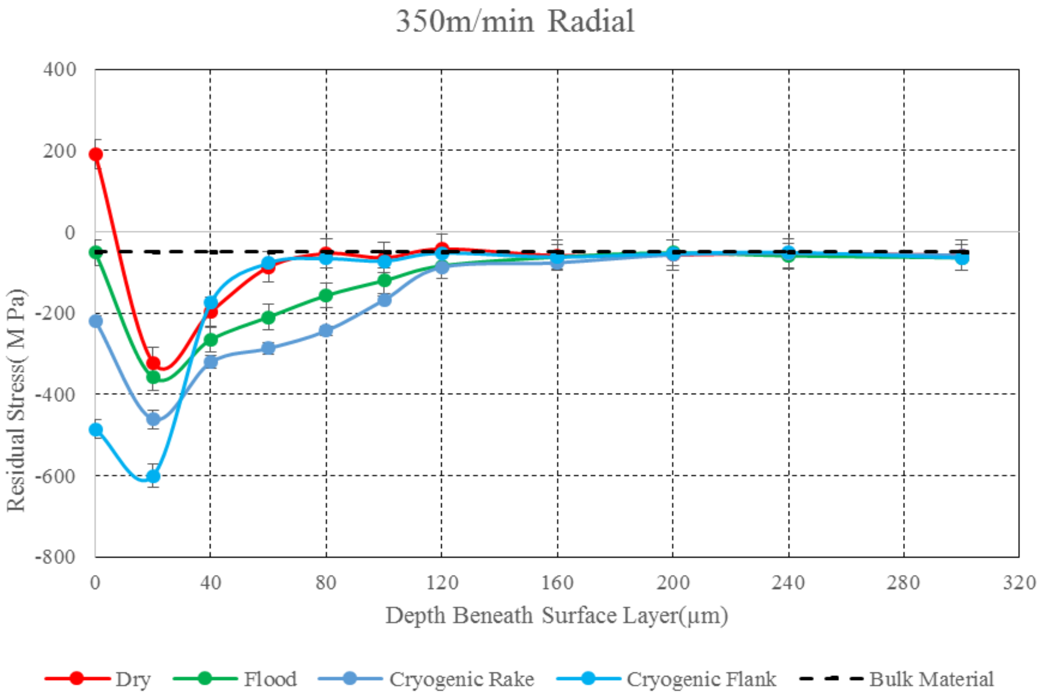


Figure 4.16 Measured Residual Stress in Machining AISI 4140 Alloy Steel in Radial Direction (feed) at 150m/min

The statement of machined surface is the first key of residual stress analysis. Ideally, the initial surface residual stresses in both directions were closed to zero due to the stress relief annealing process. But after machining, the residual stresses on machined surface under dry and flood conditions were becoming tensile stresses in tangential direction due to dominated thermal effect, especially in the cutting speed of 350m/min generated more heat during machining process lead to larger tensile residual stresses up to 258.55 M Pa in both directions. The higher speed will increase the tensile residual stress on surface layer because of lager thermal effect. However, the induced Cryo-cooling especially liquid nitrogen obviously influenced the residual stress statement on surface. With the same cutting speed, the residual tress was reduced by flood condition, the most important is that Cryo-cooling machining generated larger compressive residual stress on surface than dry and flood conditions in both directions. The value of surface compressive stress value under Cryo-cooling condition was below -200MPa. In the two different nozzle positions of Cryo-cooling machining, Figure shows significant compressive residual stresses on machined surface in the axial direction and tangential direction because induced liquid nitrogen suppressed the thermal effect in the machining procedure. It’s not hard to conclude that the nozzle position at flank face has more desirable compressive residual stress up to -556.79 M Pa on surface layer due to as a more effective Cryo-cooling method on the interface between tool and machined material.

Moreover, it’s critical work to analyze the penetration depth of compressive residual stress under different cutting conditions. In addition to the surface residual stresses, the depth distribution of the residual stresses along the sub-surface is sometimes more important to the component performance. Greater compressive depth with larger compressive values along the sub-surface is claimed to be desirable to the functional performance of many materials (Wilson, Grandt et al. 2009). For the dry condition, Figure shows the penetration depth of compressive residual stress is from around 10μm to 50μm with both speed of 50m/min and 150m/min in axial direction as well in tangential direction. And the peak compressive stress for dry condition was about -349.4 MPa at a depth of 20 µm below the surface in axial direction of 150m/min. In the flood condition, the depth of compressive residual stress was extremely consistent through 10 µm to 160 µm then close to bulk material. The peak value of compressive residual stress was -358.27 MPa with 350m/min in axial direction. However, much larger differences were found in the axial direction between dry and Cryo-cooling machining with the same cutting speed. By the comparison, large increases in compressive areas were obtained by Cryo-cooling machining in rake face. With both 150m/min and 350m/min cutting speeds, compressive residual stress was induced under Cryo-cooling condition extended to 200 µm below the machined surface compared to 50µm in two directions. The nozzle position also impacted on penetration depth significantly. When the liquid nitrogen was applied in flank face, liquid nitrogen was sprayed on material surface before cutting, cooling the work material completely to achieve larger compressive residual stress on machined surface. Even though the peak values at 20 µm were larger than Cryo-cooling machining in rake face, the compressive area was less influenced by liquid nitrogen due to machining process was based on Cryo-cooling work material surface. Smaller cooling effect on interface between cutting tools and machining material. Therefore, a thicker compressive zone of material beneath the surface was obtained in Cryo-cooling in rake face machined samples.

The results suggest that more significant heat generation occurs when the high cutting speed and this tends to induce more tensile residual stresses on machined surface. The residual stresses were also more compressive on machined surface during Cryo-cooling machining than those created during dry and flood condition. It also reveals that using Cryo-cooling in rake face achieved large and deep compressive residual stresses below the machined surface, which should enhance the functional performance of the components such as fatigue life and wear/corrosion resistance. The compressive area which is the area defined by the compressive portion of the residual stress profile and the depth axis was claimed to have a notable influence on the fatigue life (Shibata, Irie et al. 2009). Generating desired residual stresses on the surface and subsurface of machined components to improve the fatigue performance of components is of great interest. In this regard, the contribution of Cryo-cooling machining to enhance the performance of components is vital contributes to improving a product’s performance by generating more compressive residual stresses.

4.3 Summary

In this chapter, the effect of cutting speed and cooling method were analyzed separately in surface analysis characteristics including surface roughness, microhardness and residual stress. The liquid nitrogen has notable influence on reducing surface roughness in high speed range even though the flood condition could produce better surface finish in machining *AISI 4140* alloy steel at any speed. To achieve better surface states, high cutting speed was highly recommended. The Cryo-cooling machining improved microhardness profile significantly. The results of residual stresses were also more compressive on machined surface during Cryo-cooling machining than those created during dry and flood condition. It also show that using Cryo-cooling in rake face achieved large and deep compressive residual stresses below the machined surface.

Chapter 5 Conclusion and Future Work

In the current research, experimental studies on the influence of cutting speed, Cryo-cooling and Cryo-cooling nozzle position on surface analysis of machined *AISI 4140* alloy steel , including surface roughness, hardness, and residual stress. In addition, the analysis of polishing methods had been presented for correlation with machining conditions and surface analysis. For this Chapter, the primary findings and results of research are summarized with conclusion remarks from chapter 3 and chapter 4. Based on the current results and observations of present research, the possible future work are discussed briefly eventually.

5.1 Concluding Remarks

These conclusions are summarized in chapter 4 and chapter 5 for Cryo-cooling machining of *AISI 4140* alloy steel for improving the surface analysis as below:

1. The surface roughness and hardness measurement were successfully achieved by mechanical polishing process. The electropolishing method removed surface layer consistently, and it was applied for residual stress measurement without any introduced stress.
2. In dry machining, decreased cutting force was achieved when the machining speed increased due to more thermal softening effect. Compared to dry machining, Cryo-cooling machining led higher cutting force because the work materials became harder due to the liquid nitrogen cooling effect. The two feed forces from axial direction and radial direction had the same trend as cutting force.
3. The hardness data in the surface and sub-surface of Cryo-cooling machined specimens was higher than the dry one, because work hardening effect was more dominant compared with the thermal softening effect where the heat could be taken away in a relatively short time during Cryo-cooling machining. Microhardness measurements

indicated that the hardness close to the surface in the burnishing-influenced layer was increased to varying extents. The most significant hardness increase was achieved when using Cryo-cooling machining at 100 m/min machining speed, an increase of up to 87% relative to the bulk value. However, the hardness was not only dependent on the microstructures, but also on the phase composition and residual stress values.

4. Compared to dry machining, application of liquid nitrogen in the low speed of 50m/min show the surface roughness was very large due to dominated mechanical effect on surface finish. In the high speed range from 150m/min to 350m/min, the flood and Cryo-cooling machining improved the surface finish significantly.
5. Generally, the application of liquid nitrogen during machining *AISI 4140* alloy steel led to the formation of more compressive residual stresses in both directions. Detail about electropolishing and XRD technics provided more experience in removing surface layer of *AISI 4140* alloy steel. Without the application of liquid nitrogen, the surface residual stresses became more tensile under all conditions when compared with the virgin material as well as the ones with Cryo-cooling cooling. The residual stresses became more tensile in dry machining, when compared with the initial data, and became compressive when Cryo-cooling was employed. Compressive residual stresses are induced in the surface and sub-subsurface of the work materials produced by Cryo-cooling machining, and it is very beneficial to improve the fatigue life of the manufactured components. The measurement of residual stresses is very critical to verify the effects of Cryo-cooling machining *AISI 4140* alloy steel.

Overall, the results suggest that correct polishing method was accomplished for surface analysis. The appropriate machining process can significantly modify the surface/subsurface properties of *AISI 4140* alloy steel, leading to potential performance improvement of critical components in various applications.

5.2 Future Work

The major findings presented above will provide good information to the academic and industry communities in certain degrees due to the novelty and scientific contribution of this work. Nonetheless, there is a need for more future work that need to be done in order to extend the current research of machine process to fill the voids of the unfinished work existing in this thesis. Detailed future work that can be done are shown as below:

1. Grain size and Microstructure characterization of machined surface are needed to better understand the influence of various machining conditions on microstructural changes near the surface. It will also reveal useful information on the transition of microstructures within the relatively thin featureless layers produced by machining. The results on surface analysis suggest that optical microscopy is a necessary part for the further research on machining *AISI 4140* alloy steel under different machining conditions.
2. It is recommended that the influences of flow rate, precooling, and both nozzle applied in cooling condition, on surface analysis of machined *AISI 4140* alloy steel should be investigated.
3. Establishing the FEM simulation on machining process and surface analysis for a comparison work with experimental machining *AISI 4140* alloy steel.

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VITA

Name

Qiang Qi

Place of Birth

Lianyungang, Jiangsu, China

Education

B.S in Mechanical Engineering, Beijing University of Chemical Technology, Beijing, China

Experience

Research Assistant (07/2006-07/2007) Non-destructive Testing Lab, Beijing University of Chemical Technology, Beijing, China

Project Engineer (09/2007-01/2012) Minol Ennergy Inc., Beijing, China