Journal of Applied Sciences Research, 8(9): 4880-4890, 2012
ISSN 1819-544X
This is a refereed journal and all articles are professionally screened and reviewed

ORIGINAL ARTICLES

The Effect of Cryogenic Application on Surface Integrity in Manufacturing Process: A Review

[1,2]A.R. Natasha, [1]J.A. Ghani, [1]C.H.C. Haron, [1]J. Syarif

[1]Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia.
[2]Department of Manufacturing and Materials, Faculty of Engineering, International Islamic University Malaysia, P.O.Box 10, 50728 Kuala Lumpur, Malaysia

ABSTRACT

The quality of work material's surfaces after undergone various manufacturing processes is very important in determining the functional performance of a component throughout the services. Application of coolant and lubricant in manufacturing operations such as turning, milling, grinding, rolling, etc. has been proven to improve the surface integrity of the work materials. In this review, application of cryogenic coolant in manufacturing operations was investigated in terms of its effects on surface integrity of the work materials which includes surface finish, microstructural changes, refinement of grain size, formation of white layer, residual stresses of internal subsurface layer, and surface hardness. Cryogenic application is able to reduce the value of surface roughness, allow for more comprehensive martensitic transformation, reduce the grain size, prevent the formation of white layer at the subsurface, reduce the tensile residual stresses and increase compressive stresses area, and finally increase the hardness of the work material. In conclusion, cryogenic application in a lot of manufacturing processes has been determined to be able to enhance and improve the quality of the workpiece surface, consequently, boost the functional performance of the components.

Key words: cryogenic application; surface integrity; manufacturing processes; surface finish; microstructural changes; grain size; white layer; residual stresses; surface hardness.

Introduction

Functional performance of a work material such as fatigue strength, corrosion rate, fracture toughness, and tribological behavior (such as friction, wear and lubrication, and accuracy of dimensions) are highly dependent on the surface properties. The integrity of the external surface topography (surface finish), and also the microstructure, mechanical properties and residual stresses of internal subsurface layers are among the properties of a machined surface that affecting the functional performance (Grzesik *et al.*, 2010). Therefore, surface integrity has been a subject of interest to many researchers in order to enhance the functional performance of work materials.

Many techniques have been investigated for the purpose of improving the quality of surface integrity in machining. Gentle machining is claimed to be able to enhance the surface integrity of machined surface compared to abusive and conventional machining (Grzesik *et al.*, 2010). Gentle machining can be defined as machining in a "low stress conditions" which will result in little heat generated at the cutting zone. In order to achieve the low stress conditions in machining, many attempts have been explored, and application of cutting fluid is among one of them.

Cutting fluid applied during machining has a function as coolant and lubricant. Coolant is important to cool the heat generation zone in machining process; meanwhile lubricant is used to minimize the friction between the tool, chip, and workpiece interface. Methods of cutting fluid application include flood machining, near-dry machining and also cryogenic machining. Cryogenic acts more as coolant to reduce the temperature generated in machining process. Cryogenic coolant uses liquid gaseous such as liquid nitrogen (LN_2) or liquid carbon dioxide (CO_2), which have very low melting temperature, to reduce the temperature at the cutting zone. Cryogenic machining is more advantageous compared to the usage of conventional cutting fluid in term of environmental friendly in such a way that the liquid gas used will evaporate into the air and become part of the atmosphere (Nalbant and Yildiz, 2011). The evaporation of the gaseous also eliminate the cost of cutting fluid disposal (Umbrello *et al.*, 2012).

A lot of researches have been conducted to study the benefits of cryogenic application in manufacturing process. Cryogenic application is claimed to improve process sustainability, increase material removal rate

---

Corresponding Author: A.R. Natasha, Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia.

(MRR), enhance the tool life, improve product quality of machined parts and enhance surface integrity (Umbrello *et al*., 2012).

Therefore, this paper is aimed to review the effect of cryogenic application in manufacturing processes on surface integrity of work materials. Among surface properties usually being analyzed are external topography of surface (surface roughness), microstructure of internal subsurface layer, surface hardness, grain size, residual stresses and white layer formation. A general evaluation of this review was given in Table 1.

Table 1: The evaluation of surface integrity studies in cryogenic application in manufacturing operations.

Cryogenic operation	References	Work material	Cutting tool	Investigation topics
Cryogenic turning	(Umbrello *et al*., 2011; 2012)	Hardened 52100 steel	CBN	Surface roughness, white layer, residual stress, grain size, phase transformation, surface hardness
Cryogenic turning	(Xavier *et al*., 2010)	Hardened AISI 52100	PCBN	Surface roughness, white layer, tool wear
Cryogenic turning	(Pu *et al*., 2012)	AZ31B Mg alloy	Uncoated carbide	Grain size, crystallographic orientation, residual stress, cutting force, cutting temperature
Cryogenic turning	(Jerold and Kumar, 2011)	AISI 1045	Multicoated carbide	Cutting temperature, chip thickness, surface roughness, cutting force
Cryogenic turning	(Ahmed *et al*., 2007)	AISI 4340	SNMG 120408-26 carbide	Tool wear, tool life, surface roughness
Cryogenic parting, grooving and threading	(De Chiffre *et al*., 2007)	AISI 304L	Coated carbides	Tool life, cutting force, surface roughness
Cryogenic slot milling	(Ravi and Kumar, 2011)	Hardened AISI H13 tool steel	TiAlN PVD coated carbide	Cutting temperature, flank wear, surface roughness, cutting force
Cryogenic milling	(Nalbant and Yildiz, 2011)	AISI 304 stainless steel	Uncoated cementite carbide	Cutting force, tool wear, microstructure
Cryogenic micromilling	(Kakinuma *et al*., 2012)	PDMS polymer	Tungsten carbide	Surface finish, chip formation, surface roughness, cutting energy
Cryogenic grinding	(Fredj and Sidhom, 2006)	AISI 304	99A60M7V10N with V shape grinding wheel	Surface roughness, surface hardness, residual stress, fatigue lifetime, work hardening
Cryogenic grinding	(Fredj *et al*., 2006)	AISI 304	99A46M7V10N grinding wheel	Grinding temperature, grinding force, surface roughness, work hardening, residual stress, corrosion resistance
Cryogenic rolling	(Nageswara rao and Jayaganthan, 2012)	Al 6061 alloy	-	Microstructural features, tensile strength, ductility, grain refinement
Cryogenic rolling	(Panigrahi and Jayaganthan, 2011)	Al 7075 alloy	-	Surface hardness, tensile strength, grain size
Cryogenic deep rolling	(Meyer, 2012)	AISI D3 (X210Cr12)	-	Surface roughness, surface hardness, phase transformation
Cryogenic abrasive jet machining	(Gradeen *et al*., 2012)	PDMS polymer	-	Microstructure, surface evolution, erosion rate
Cryogenic treatment	(Liu *et al*., 2012)	Mg-1.5Zn-0.15Gd alloy	-	Microstructure, microhardness, wear rate
Cryogenic treatment	(Bensely *et al*., 2008; 2009)	En 353	-	Hardness, fatigue behavior, microstructure
Deep cryogenic treatment	(Baldissera, 2009; Baldissera and Delprete, 2009)	Carburized 18NiCrMo5 steel	-	Fatigue behavior, carbides precipitation, residual stress, hardness, tensile strength
Deep cryogenic treatment	(Leskovšek and Podgornik, 2012; Podgornik *et al*., 2012)	S390 high-speed steel	-	Surface hardness, wear resistance, galling resistance, microstructure
Deep cryogenic treatment	(Akhbarizadeh *et al*., 2012a; 2012b; (Amini *et al*., 2012)	1.2080 tool steel	-	Microstructural changes, carbide distribution, carbide percentage, microhardness
Deep cryogenic treatment	(El Mehtedi *et al*., 2012)	X30 CrMoN 15 1 steel	-	Microstructural changes, hardness
Cryogenic cooling welding	(Amuda and Mridha, 2012)	AISI 430 stainless steel	-	Grain refinement, microstructure, hardness, ductility.
Cryogenic wear test	(Jain *et al*., 2010)	High purity Ti	-	Wear rate, grain size

Surface finish / surface roughness:

Surface finish is one of the most important aspects that usually been analyzed because the affect it has on product performance and life cycle, besides the residual stresses and the occurrence of surface and subsurface micro cracks (Xavier *et al*., 2010). These aspects are very vital, especially when the product would be fit with other parts or used under dynamic loading. It is also reflected the quality of surface integrity on work materials (Yazid *et al*., 2011).

Some researchers have proven that the surface roughness measurement, R_a, gave some improvement when machining with cryogenic application compared to dry and wet machining (Jerold and Kumar, 2011; Pu *et al*., 2012; Ravi and Kumar, 2011; Umbrello *et al*., 2012). Smaller R_a measurements reflect better surface quality of the work parts. Surface finish is largely influenced by the cutting force, tool wear and chip formation. Figure 1 shows improvement of surface roughness value in cryogenic machining compared to dry and wet machining.

The improved surface finish resulted in cryogenic machining is due to lower cutting temperature generated during the machining process, hence lowering the cutting forces and tool wear (Kumar and Choudhury, 2008; Ravi and Kumar, 2011; Zhang *et al*., 2012). Similar findings were reported by Dhar & Kamruzzaman (2007) who also obtained a reduction in tool wear in turning AISI 4037 steel bar with cryogenic jet application. Effective reduction of cutting temperature had been attained when the LN_2 jet was aimed to the main cutting edge, maintaining the tool's sharpness (Ravi and Kumar, 2011) and hardness hence lessen the abrasion wear as well as adhesion and diffusion wear (Dhar and Kamruzzaman, 2007).

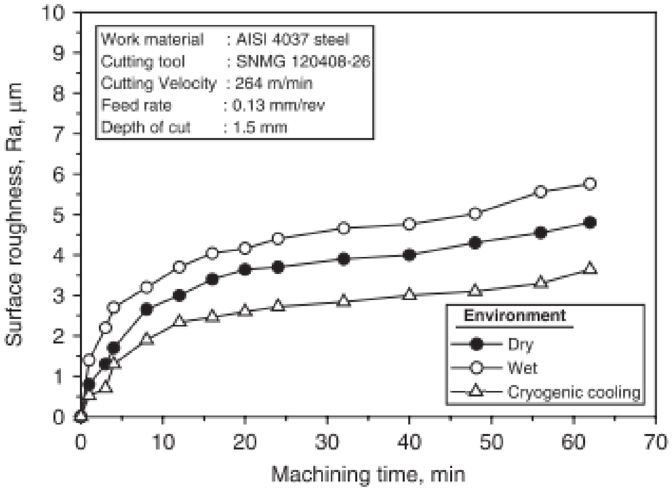

Fig. 1: Comparison of surface roughness between cryogenic, dry and wet machining (Dhar and Kamruzzaman, 2007).

However, the authors observed that the reduction of average cutting temperature is less effective when higher cutting speed and feed rate were used as shown in Figure 2. This is possibly contributed by the chip-tool contact becomes almost fully plastic or bulk at higher cutting speed, therefore preventing the LN_2 from penetrating efficiently between the interface (Dhar and Kamruzzaman, 2007). Deformation on the flank face, micro-cracks and formation of built-up edge may occurred hence resulting in rough surface finish (Khan and Ahmed, 2008; Yazid *et al*., 2011). This condition may also caused by the chipping occurred at the cutting edge due to high tool pressure when machining with higher cutting speed and feed rate, consequently increase the wear rate (Ibrahim *et al*., 2011), therefore, resulting in bad surface roughness.

Besides, cryogenic condition also enhances the chip breakability during machining and reduces the tendency of chip's adhesion to the tool resulting in less scratch on the surface finish (Jerold and Kumar, 2011; Stanford *et al*., 2009). In grinding process, cryogenic cooling helps in preventing the wheel loading, preserving the grit's sharpness and reducing the chip's size (Paul, 1995; Paul and Chattopadhyay, 1995), therefore improve the surface finish (Fredj and Sidhom, 2006). These were due to improvement of tangential and normal grinding forces, and also the specific energy under cryogenic cooling (Paul and Chattopadhyay, 1995b).

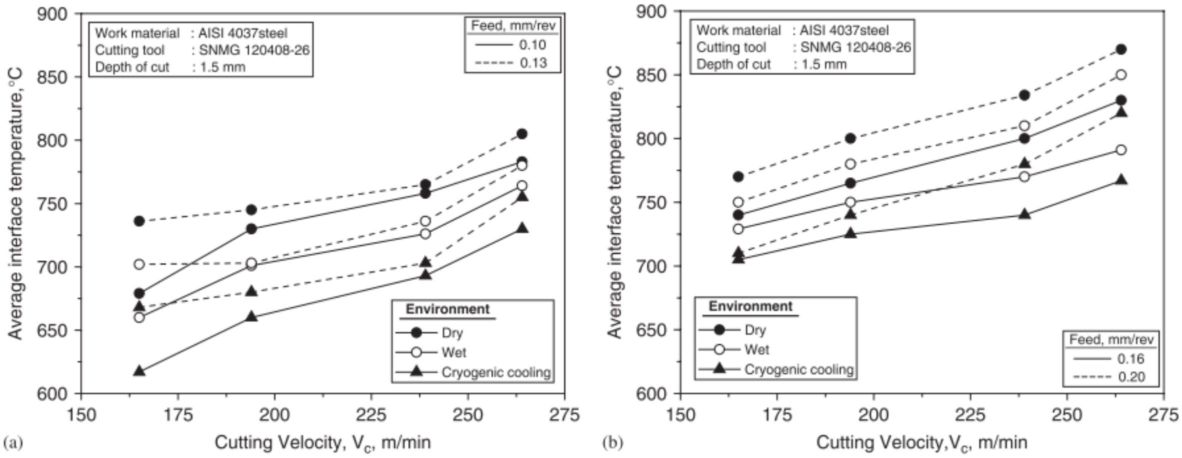

Fig. 2: Variation in average chip-tool interface temperature with V_c under different cutting conditions at (a) lower and (b) higher feed (Dhar and Kamruzzaman, 2007).

However, application of cryogenic cooling in deep rolling operation resulted in increase of surface roughness value compared to deep rolling at room temperature (Meyer, 2012; Meyer *et al*., 2011). This is because of embrittlement of material at lower temperature which decreases the plasticity and causes poorer deformability (Meyer, 2012; Meyer *et al*., 2011).

Microstructure of internal subsurface layers:

Phase Transformation:

Retained austenite is a form of microstructure that is not favorable due to the effect it has on the properties of steel such as decrease of tensile strength and yield strength, and reduction of maximum attainable surface compressive stresses, consequently impairing its fatigue resistance (Bensely *et al*., 2008). Therefore, reduction of the amount of retained austenite in a material is very desirable.

Martensite is a very hard form of microstructure. Application of cryogenic in manufacturing process is reported to allow for more comprehensive martensitic transformation (Bensely *et al*., 2008; Meyer, 2012). High amounts of martensite are shown in cryogenically deep rolled sample. Similar observations has been made by Zhirafar *et al*. (2007) in cryogenically treated AISI 4340 steel, in which small reduction of retained austenite has been obtained. Figure 3 shows contents of retained austenite and the micrograph after deep rolling process of AISI D3.

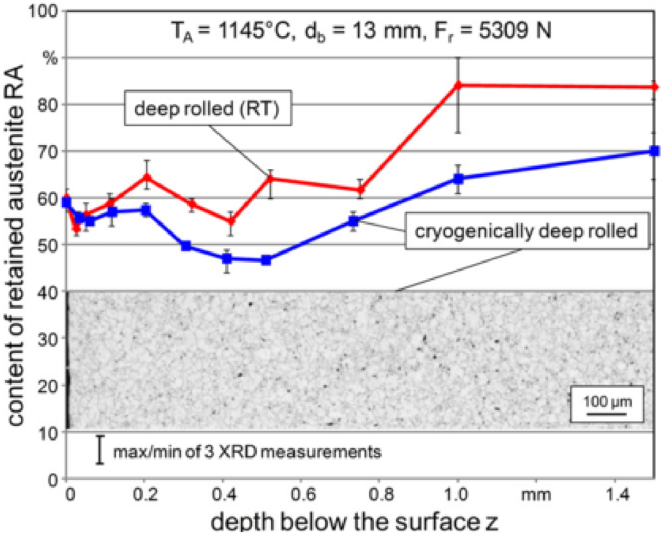

Fig. 3: Contents of retained austenite and micrograph after deep rolling of AISI D3 under varied thermal conditions (Meyer, 2012)

Meyer (2012) explained the martensitic transformation is induced by thermal effects of cryogenic combined with mechanical loads in deep rolling process. The author's explanation is based on the theory discussed by Tamura (1982) which stated that microstructural transformation usually occurs as a specific activation energy (in a function of Gibb's free energy) is achieved due to thermal effects. Figure 4 shows a diagram showing how mechanically and thermally induced differences of Gibbs free energy being applied in cryogenic deep rolling (Meyer, 2012). The comprehensive martensitic transformation allows for more stable microstructures application without deteriorating the surface and subsurface properties. This statement is also supported by Bensely *et al*. (2008) who observed that the structure of cryogenically cooled materials were found to be more uniform and dense, hence increasing the stability of the component.

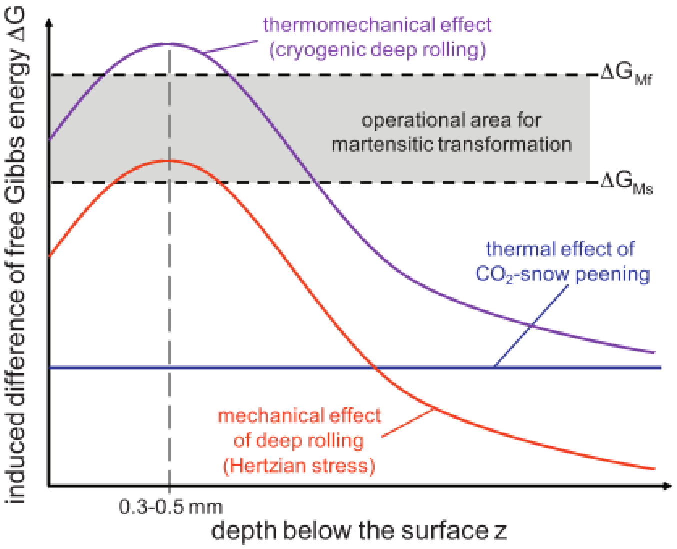

Fig. 4: Schematic diagram of superposition of mechanically and thermally induced difference of Gibbs free energy in cryogenic deep rolling (Meyer, 2012).

In addition, the relation between cryogenic treatment-induced and deformation-induced is also suggested in order to further explain the martensite transformation in cryogenic treated specimens (Shimojo *et al*., 2001). When the material experienced plastic deformation as a result of dislocation motion, below certain temperature, martensite transformation occurs. However, increment of austenitizing temperature, T_A of heat treatment results in higher stability of the microstructures, therefore lowering the percentage of formed martensite as shown in Figure 5 (Meyer, 2012).

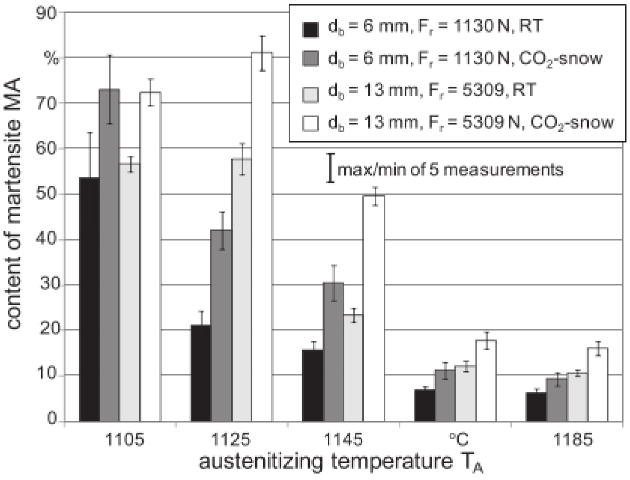

Fig. 5: Contents of martensite in the surface and subsurface layers after deep rolling under varied mechanical loads and thermal conditions (Meyer, 2012).

Grain size:

Size of the grain of subsurface layer influences the properties of the materials. Fatigue life of materials can be extended by prolonging the nucleation phase by mean of pinning the dislocation with the formation of nano-sized martensite at the intersected dislocations (Shimojo *et al*., 2001). Cryogenic application in manufacturing process is proven to be able to reduce the grain size (Panigrahi and Jayaganthan, 2011; Umbrello *et al*., 2012). Umbrello *et al*. (2012) had shown that nano-scale grain size of cryogenically turned AISI 52100 steel can be achieved as shown in Figure 6 below. Cryogenic conditions also help to retain the grain size smaller after recrystallization phase.

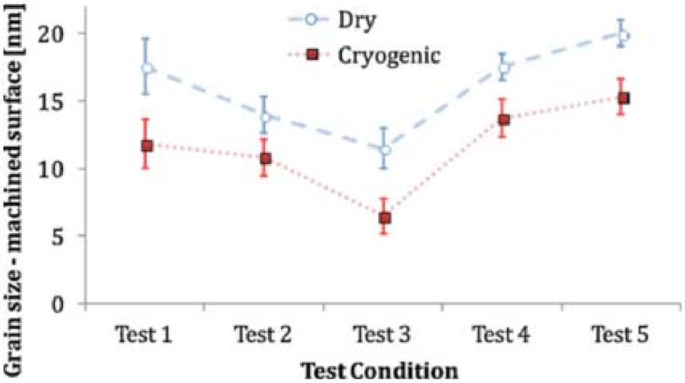

Fig. 6: Experimental grain size obtained under cryogenic and dry machining of 52100 steel (Umbrello *et al*., 2012).

The adventitious balance of the driving force in phase transformation and the restrainment of grain's growth caused by high dislocation density may be a factor of formation of nano-sized martensite (Shimojo *et al*., 2001).

Grain refinement may also be caused by dynamic recrystallization (DRX). Pu *et al*. (2012) had used an empirical formula in equation below to predict the grain's size produced after machining of AZ31B Mg alloy with the application of LN_2.

$$\frac{d_{rec}}{d_{init}} = 10^3 \times Z^{-1/3} = 10^3 \left[\dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \right]^{-1/3}$$

where d_{rec} is the recrystallised grain size; d_{init} is the initial grain size; Z is the Zener–Hollomon parameter; $\acute{\varepsilon}$ is the strain-rate; Q is the activation energy; R is the gas constant; T is the temperature.

Based on the equation above, low temperature resulted from cryogenic application and high strain rate during the machining process will produced very fine grain size. This is verified by the AFM tapping mode phase image of a featureless layer about 2 mm from the machined surface in Figure 7 showing some grain-like features with an average size of 31 nm (Pu *et al*., 2012).

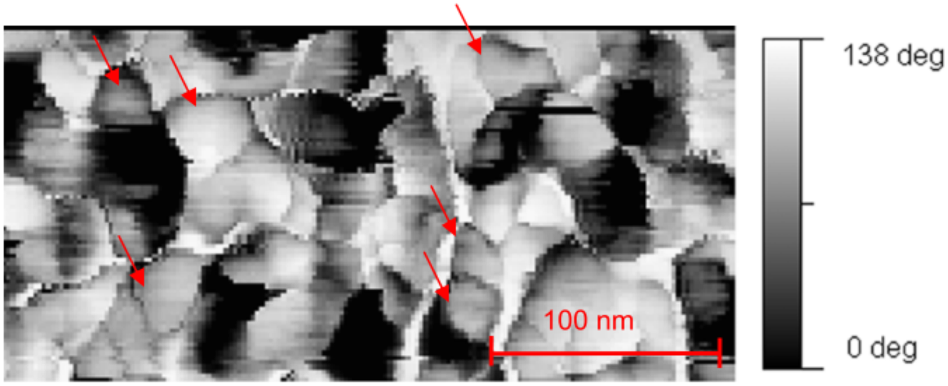

Fig. 7: AFM tapping mode phase image of the featureless layer from the machined surface after machining under cryogenic condition (Pu *et al*., 2012).

White layer:

The effect of white layer formation on the properties of materials is not yet well understood (Jawahir *et al*., 2011). Several recent studies of white layer found that it composed of very fine grains up to nano-scale size (Bushlya *et al*., 2011; Herbert *et al*., 2011) and contained fresh martensite along the depth (Li *et al*., 2007). According to Bushlya *et al*. (2011), there are several mechanisms that may contribute to the formation of white layer. They are; phase transformation due to rapid heating and cooling; grain refinement due to severe plastic deformation (SPD); and reactions of the surface with environment.

From the literature, white layer formed under the machined surface is undesirable in most applications (Pu *et al*., 2012), because white layer usually is very hard and brittle, thus gives negative impact to the life of the components (Bushlya *et al*., 2011; Umbrello *et al*., 2011). However its presence can be beneficial in some applications where wear resistance is desirable in the absence of impact loading (Jawahir *et al*., 2011). White layers are also associated to the increase of hardness and decrease of adhesive wear of the specimens (Askari *et al*., 2011; Herbert *et al*., 2011), which eventually increase the wear resistance (Larbi *et al*., 2005).

Cryogenic application in machining is able to reduce the thickness (Umbrello *et al*., 2011; 2012) or even preventing (Xavier *et al*., 2010) the formation of the white layer compared to dry machining as shown in Figure 8. This is most probably because huge decrement in cutting temperature by LN_2 application, since white layer formation is happening because of localized thermal softening by the work material due to high temperature generated at the cutting zone (Umbrello *et al*., 2012). Another factor contributing to the white layer formation is rapid heating and quenching that influences the formation of untempered martensite structure, hence, low heat generated in cryogenic machining may prevent this from happening (Umbrello *et al*., 2011).

Formation of white layer has also been related to the increase in cutting temperature, which is resulted by the wear of the cutting tool, and high cutting speed and lack of coolant during the machining operation (Bushlya *et al*., 2011). Therefore, by applying cryogenic coolant, the decrease in cutting temperature and tool wear may also be contributing factor in preventing or reducing the thickness of the white layer.

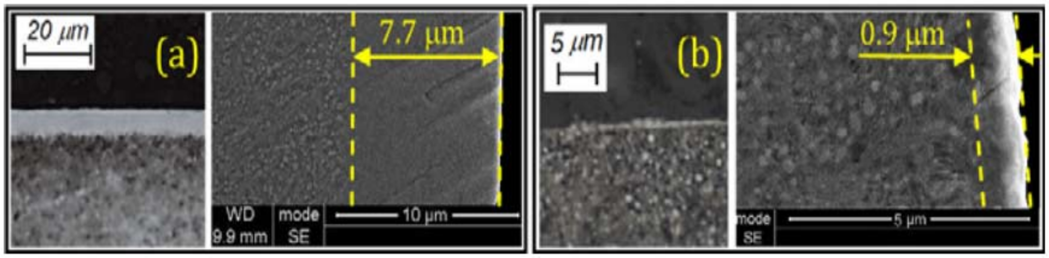

Fig. 8: White layer formed under machined surface in (a) dry and (b) cryogenic machining (Umbrello *et al*., 2012).

Residual stresses of internal subsurface layers:

Residual stresses are the stresses that remain within the subsurface layers after the original cause of the stresses such as external loads or thermal gradients, have been removed. Tensile residual stresses are undesirable, since it may reduce static strength and fatigue life, disseminate cracking in sensitive materials and enhance chemical and stress corrosion (Bensely *et al*., 2008; Paul and Chattopadhyay, 1995). On the other hand, compressive residual stresses are favorable because of the positive impact it has on the component's fatigue properties and dimensional stability (Bensely *et al*., 2008; Umbrello *et al*., 2011).

Cryogenic cooling application in grinding is able to reduce the magnitude of tensile residual stresses compared to dry and wet grinding (Fredj and Sidhom, 2006; Fredj *et al*., 2006). This is also supported by the data collected by Baldissera and Delprete (2010) that showed deep cryogenic treated AISI 302 stainless steel improves the fatigue limit and fatigue life of the specimen. It is also able to increase the compressive stresses area (Pu *et al*., 2012; Umbrello *et al*., 2012). As discussed in sub-section 3.3, the effective cooling ability of cryogenic coolant reduced the thickness of the white layer, consequently, higher compressive area machined components after the post removal operation can be achieved (Umbrello *et al*., 2012).

In addition, the compressive area measured under cryogenic machining increases with increasing of the cutting speed (Umbrello *et al*., 2012) and increment of cutting edge radius (Pu *et al*., 2012). This is probably because of more severe plastic deformation occurred on the machined surface during cutting with higher cutting speed or larger tool's edge radius resulting in larger compressive area (Pu *et al*., 2012). Another factor affecting the compressive stress area is the amount of retained austenite after the manufacturing operation (Bensely *et al*., 2008). As discussed in Section 3.1, in cryogenic coolant application, the percentage of retained austenite has been reduced; therefore larger compressive residual stresses area is induced. However, the percentage value of retained austenite reduction also affecting this phenomena. A very small percentage of retained austenite reduction does not induce compressive residual stresses as compared to remarkable increase of compressive stresses when most of retained austenite had been transformed into martensite (Bensely *et al*., 2008).

Figure 9 shows significant increment of compressive area in cryogenic machining using different cutting edge radius. From the result, the author suggested that the combination of cryogenic cooling and large tool's edge radius may induce large and deep compressive residual stresses in machined surface, which consequently improve the functional performance of machined components. However, smaller compressive area is measured when combination of lower workpiece initial hardness and the use of honed tools is used in the experiment (Umbrello *et al*., 2012).

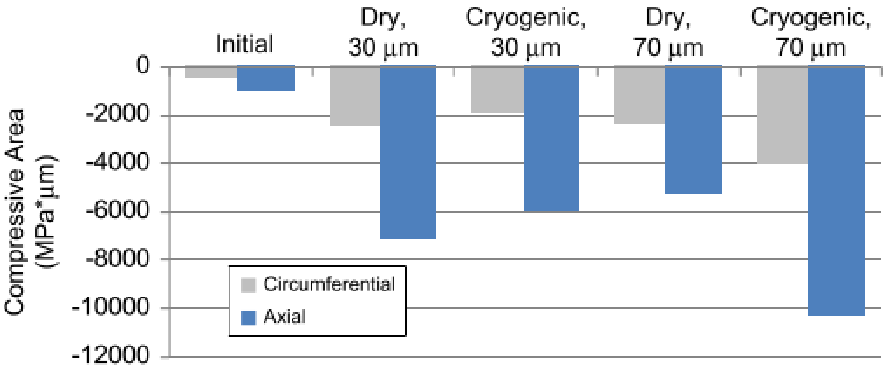

Fig. 9: Compressive areas of the residual stress profiles before and after machining under different cutting conditions (Pu *et al*., 2012).

Surface hardness:

Several studies on cryogenic application in manufacturing operation have proven that the hardness of the work materials is increased (Meyer, 2012; Pu *et al*., 2012; Zhirafar *et al*., 2007). Surface hardness is closely related to grain size, work hardening process occurred during the operation and also microstructural changes within the subsurface layers (Askari *et al*., 2011; Pu *et al*., 2012).

Meyer (2012) had shown in his research of cryogenic deep rolling that the hardness of subsurface layers has been increased significantly compared to deep rolling at room temperature. Besides, the hardness penetration depth was also higher for cryogenic deep rolling operation.

The increment of the hardness can be related to the microstructural changes as mentioned in previous section. At cryogenic temperature, small amount of retained austenite is transformed to martensite hence improving the hardness if the treated specimens (Zhirafar *et al*., 2007). In addition, the author also suggested that carbide formation during tempering could have been induced in cryogenic treated samples (Zhirafar *et al*., 2007).

Work hardening or strain hardening that occurred during manufacturing operation is the strengthening of a metal by plastic deformation. Low temperature in cryogenic operation induced the plastic deformation during the machining process, therefore, increases the surface hardness of the work material (Pu *et al*., 2012). Yazid *et al*. (2011) also mentioned that high value of hardness is an indicator that high work hardening induced by plastic deformation had taken place during the machining operation and it appeared as white lines on surface topography, as shown in Figure 10.

In addition, cryogenic cooling is also claimed to induce the carbide precipitation in which, very fine carbides particles appeared and lodged into the micro voids in the microstructure thus increase the density and coherence of the metals (Bensely *et al*., 2008). This very fine carbides, which can be considered as nano-sized particles may improve the wear resistance of a material by enhancing the strength and toughness of martensite matrix (Meng *et al*., 1994). This is parallel with the phenomenon of carbide formation during precipitation hardening which increased the work material's hardness (Salleh *et al*., 2009).

Conclusion and Future Works Recommendation:

The aim of this paper is to review and analyze the effect of cryogenic cooling application in manufacturing operations on surface integrity of the work materials. There are tremendous studies have been conducted to observe the resulting surface integrity in various manufacturing operations such as turning, milling, grinding, deep rolling, etc. Several conclusions can be drawn from this review.

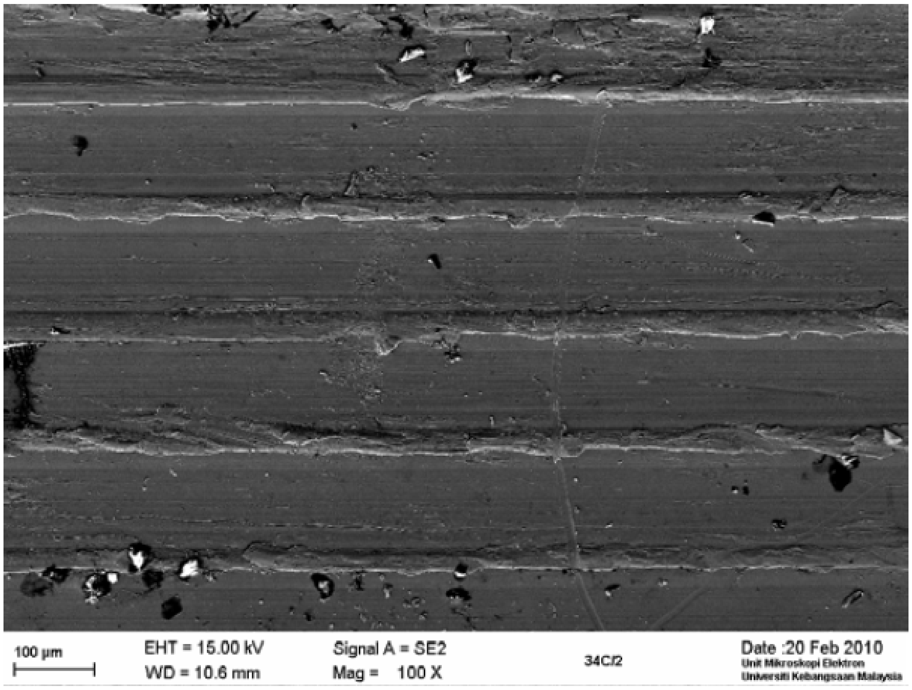

Fig. 10: White lines on surface topography of machined surface of Inconel 718 indicating plastic deformation occurrence (Yazid *et al*., 2011).

Surface integrity of the work materials has been a subject of interest since it has direct effect on the properties and performance of a component. Many approaches have been investigated in order to enhance the integrity of the workpiece surfaces. One of the promising approaches is by applying cryogenic cooling in manufacturing operations. It is proven that cryogenic application in manufacturing operations may enhance the surface integrity of the work materials. Among the improvements are better surface finish, reduction of the volume of retained austenite as well as white layer thickness, refinement of grain size, larger compressive residual stress area, and increment of surface hardness. These enhancements of surface properties by cryogenic is mainly due to the reduction of temperature during the operation.

However, from this review, there are still a few gaps that can be further explored and investigated. A lot of researches being conducted involved the treatment or pre-cooling by cryogenic liquid gaseous of either the workpiece or the cutting tool prior to manufacturing processes. Nevertheless, direct application of cryogenic liquid gaseous during various manufacturing operations substituting the conventional cutting fluid should be further explored. In addition, there is also lack of studies on the effect of the direction of cryogenic gaseous application on the machining output parameters.

Besides, almost all type of materials with different properties has been used in cryogenic cooling researches. However, more researches should be conducted on cryogenic machining of materials particularly alloy steel that usually been surface hardened. The combination of several surface properties such as phase transformation, grain size and also surface hardness may result in a good quality of hardened surface as achieved in conventional surface hardening process.

References

Ahmed, M.I., A.F. Ismail, Y.A. Abakr and A.K.M.N. Amin, 2007. Effectiveness of cryogenic machining with modified tool holder. Journal of Materials Processing Technology, 185(1-3): 91-96.

Akhbarizadeh, A., K. Amini and S. Javadpour, 2012a. Effect of simultaneous magnetic field and deep cryogenic heat treatment on the microstructure of 1.2080 tool steel. Materials & Design, 35: 484–490.

Akhbarizadeh, A., K. Amini and S. Javadpour, 2012b. Effects of applying an external magnetic field during the deep cryogenic heat treatment on the corrosion resistance and wear behavior of 1.2080 tool steel. Materials & Design, 41: 114-123.

Amini, K., A. Akhbarizadeh and S. Javadpour, 2012. Investigating the effect of holding duration on the microstructure of 1.2080 tool steel during the deep cryogenic heat treatment. Vacuum, 86(10): 1534-1540.

Amuda, M.O.H. and S. Mridha, 2012. Comparative evaluation of grain refinement in AISI 430 FSS welds by elemental metal powder addition and cryogenic cooling. Materials & Design, 35: 609-618.

Askari, M., H. Khorsand and S.M.S. Aghamiri, 2011. Influence of case hardening on wear resistance of a sintered low alloy steel. Journal of Alloys and Compounds, 509(24): 6800-6805.

Baldissera, P., 2009. Fatigue scatter reduction through deep cryogenic treatment on the 18NiCrMo5 carburized steel. Materials & Design, 30(9): 3636-3642.

Baldissera, P. and C. Delprete, 2010. Deep cryogenic treatment of AISI 302 stainless steel: Part II – Fatigue and corrosion. Materials & Design, 31(10): 4731-4737.

Baldissera, P. and C. Delprete, 2009. Effects of deep cryogenic treatment on static mechanical properties of 18NiCrMo5 carburized steel. Materials & Design, 30(5): 1435-1440.

Bensely, A., L. Shyamala, S. Harish, D. Mohan Lal, G. Nagarajan, K. Junik and A. Rajadurai, 2009. Fatigue behaviour and fracture mechanism of cryogenically treated En 353 steel. Materials & Design, 30(8): 2955-2962.

Bensely, A., S. Venkatesh, D. Mohan Lal, G. Nagarajan, A. Rajadurai and K. Junik, 2008. Effect of cryogenic treatment on distribution of residual stress in case carburized En 353 steel. Materials Science and Engineering: A, 479(1-2): 229-235.

Bushlya, V., J.M. Zhou, F. Lenrick, P. Avdovic and J.E. Ståhl, 2011. Characterization of White Layer Generated when Turning Aged Inconel 718. Procedia Engineering, 19: 60-66.

De Chiffre, L., J.L. Andreasen, S. Lagerberg and I.B. Thesken, 2007. Performance testing of cryogenic CO2 as cutting fluid in parting/grooving and threading austenitic stainless steel. CIRP Annals - Manufacturing Technology, 56(1): 101-104.

Dhar, N.R. and M. Kamruzzaman, 2007. Cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-4037 steel under cryogenic condition. International Journal of Machine Tools and Manufacture, 47(5): 754-759.

El Mehtedi, M., P. Ricci, L. Drudi, S. El Mohtadi, M. Cabibbo and S. Spigarelli, 2012. Analysis of the effect of Deep Cryogenic Treatment on the hardness and microstructure of X30 CrMoN 15 1 steel. Materials & Design, 33: 136-144.

Fredj, N.B. and H. Sidhom, 2006. Effects of the cryogenic cooling on the fatigue strength of the AISI 304 stainless steel ground components. Cryogenics, 46(6): 439-448.

Fredj, N.B., H. Sidhom and C. Braham, 2006. Ground surface improvement of the austenitic stainless steel AISI 304 using cryogenic cooling. Surface and Coatings Technology, 200(16-17): 4846-4860.

Gradeen, A.G., J.K. Spelt and M. Papini, 2012. Cryogenic abrasive jet machining of polydimethylsiloxane at different temperatures. Wear, 274-275: 335-344.

Grzesik, W., B. Kruszynski and A. Ruszaj, 2010. Surface Integrity of Machined Surfaces. In Surface Integrity in Machining, Ed., J. P. Davim. London: Springer London, pp: 143-179.

Herbert, C.R.J., D.A. Axinte, M.C. Hardy and P.D. Brown, 2011. Investigation into the Characteristics of White Layers Produced in a Nickel-Based Superalloy from Drilling Operations. Procedia Engineering, 19: 138-143.

Ibrahim, G.A., C.H. Che Haron, J.A. Ghani, A.Y.M. Said and M.Z. Abu Yazid, 2011. Performance of PVD-Coated Carbide Tools When Turning Inconel 718 in Dry Machining. Advances in Mechanical Engineering, 2011: 1-7.

Jain, A., B. Basu, B.V.M. Kumar and J. Sarkar, 2010. Grain size–wear rate relationship for titanium in liquid nitrogen environment. Acta Materialia, 58(7): 2313-2323.

Jawahir, I.S., E. Brinksmeier, R. M'Saoubi, D.K. Aspinwall, J.C. Outeiro, D. Meyer, D. Umbrello and A.D. Jayal, 2011. Surface integrity in material removal processes: Recent advances. CIRP Annals - Manufacturing Technology, 60(2): 603-626.

Jerold, B.D. and M.P. Kumar, 2011. Experimental investigation of turning AISI 1045 steel using cryogenic carbon dioxide as the cutting fluid. Journal of Manufacturing Processes, 13(2): 113-119.

Kakinuma, Y., S. Kidani and T. Aoyama, 2012. Ultra-precision cryogenic machining of viscoelastic polymers. CIRP Annals - Manufacturing Technology, 61(1): 79-82.

Khan, A.A. and M.I. Ahmed, 2008. Improving tool life using cryogenic cooling. Journal of Materials Processing Technology, 196(1-3): 149-154.

Kumar, K.V.B.S.K. and S.K. Choudhury, 2008. Investigation of tool wear and cutting force in cryogenic machining using design of experiments. Journal of Materials Processing Technology, 203(1-3): 95-101.

Larbi, A.B.C., A. Cherif and M.A. Tarres, 2005. Improvement of the adhesive wear resistance of steel by nitriding quantified by the energy dissipated in friction. Wear, 258(5-6): 712-718.

Leskovšek, V. and B. Podgornik, 2012. Vacuum heat treatment, deep cryogenic treatment and simultaneous pulse plasma nitriding and tempering of P/M S390MC steel. Materials Science and Engineering: A, 531: 119-129.

Li, J.G., M. Umemoto, Y. Todaka and K. Tsuchiya, 2007. A microstructural investigation of the surface of a drilled hole in carbon steels. Acta Materialia, 55(4): 1397-1406.

Liu, Y., S. Shao, C. Xu, X. Yang and D. Lu, 2012. Enhancing wear resistance of Mg–Zn–Gd alloy by cryogenic treatment. Materials Letters, 76: 201-204.

Meng, F., K. Tagashira, R. Azuma and H. Sohma, 1994. Role of eta-carbide precipitations in the wear resistance improvements of Fe-12Cr-Mo-V-1.4 C tool steel by cryogenic treatment. ISIJ Int., 34(2): 205-210.

Meyer, D., 2012. Cryogenic deep rolling – An energy based approach for enhanced cold surface hardening. CIRP Annals - Manufacturing Technology, 61(1): 543-546.

Meyer, D., E. Brinksmeier and F. Hoffmann, 2011. Surface hardening by cryogenic deep rolling. Procedia Engineering, 19: 258-263.

Nageswara rao, P. and R. Jayaganthan, 2012. Effects of warm rolling and ageing after cryogenic rolling on mechanical properties and microstructure of Al 6061 alloy. Materials & Design, 39: 226-233.

Nalbant, M. and Y. Yildiz, 2011. Effect of cryogenic cooling in milling process of AISI 304 stainless steel. Transactions of Nonferrous Metals Society of China, 21(1): 72-79.

Panigrahi, S.K. and R. Jayaganthan, 2011. Development of ultrafine grained high strength age hardenable Al 7075 alloy by cryorolling. Materials & Design, 32(6): 3150-3160.

Paul, S. and A.B. Chattopadhyay, 1995a. A study of effects of cryo-cooling in grinding. International Journal of Machine Tools and Manufacture, 35(1): 109-117.

Paul, S. and A.B. Chattopadhyay, 1995b. Effects of cryogenic cooling by liquid nitrogen jet on forces, temperature and surface residual stresses in grinding steels. Cryogenics, 35(8): 515-523.

Podgornik, B., F. Majdic, V. Leskovsek and J. Vizintin, 2012. Improving tribological properties of tool steels through combination of deep-cryogenic treatment and plasma nitriding. Wear, 288: 88-93.

Pu, Z., J.C. Outeiro, A.C. Batista, O.W. Dillon, D.A. Puleo and I.S. Jawahir, 2012. Enhanced surface integrity of AZ31B Mg alloy by cryogenic machining towards improved functional performance of machined components. International Journal of Machine Tools and Manufacture, 56: 17-27.

Ravi, S. and M.P. Kumar, 2011. Experimental investigations on cryogenic cooling by liquid nitrogen in the end milling of hardened steel. Cryogenics, 51(9): 509-515.

Salleh, S.H., M.Z. Omar, J. Syarif and S. Abdullah, 2009. Carbide formation during precipitation hardening of SS440C steel. European Journal of Scientific Research, 34(1): 83-91.

Shimojo, M., K. Takashima, Y. Higo, T. Inamura and T.H. Myeong, 2001. Formation of nanosized martensite particles in stainless steels. Metallurgical and Materials Transactions A, 32A(February): 261-265.

Stanford, M., P.M. Lister, C. Morgan and K.A. Kibble, 2009. Investigation into the use of gaseous and liquid nitrogen as a cutting fluid when turning BS 970-80A15 (En32b) plain carbon steel using WC–Co uncoated tooling. Journal of Materials Processing Technology, 209(2): 961-972.

Tamura, I., 1982. Deformation-induced martensitic transformation and transformation-induced plasticity in steels. Metal Science, 16(May): 245-253.

Umbrello, D., F. Micari and I.S. Jawahir, 2012. The effects of cryogenic cooling on surface integrity in hard machining: A comparison with dry machining. CIRP Annals - Manufacturing Technology, 61(1): 103-106.

Umbrello, D., Z. Pu, S. Caruso, J.C. Outeiro, A.D. Jayal, O.W. Dillon and I.S. Jawahir, 2011. The effects of Cryogenic Cooling on Surface Integrity in Hard Machining. Procedia Engineering, 19: 371-376.

Xavier, S.E.D., S. Delijaicov, A.D. Farias, M.S. Filho and G.F. Batalha, 2010. Investigation on the surface integrity and tool wear in cryogenic machining. In the International Conference on Advances in Materials and Processing Technologies: American Institute of Physics, Eds., F. Chinesta, Y. Chastel, and M. El Mansori, pp: 1199-1205.

Yazid, M.Z.A., C.H. CheHaron, J.A. Ghani, G.A. Ibrahim and A.Y.M. Said, 2011. Surface integrity of Inconel 718 when finish turning with PVD coated carbide tool under MQL. Procedia Engineering, 19: 396-401.

Zhang, S., J.F. Li and Y.W. Wang, 2012. Tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions. Journal of Cleaner Production, 32: 81-87.

Zhirafar, S., A. Rezaeian and M. Pugh, 2007. Effect of cryogenic treatment on the mechanical properties of 4340 steel. Journal of Materials Processing Technology, 186(1-3): 298-303.