Journal of Advanced Mechanical Design, Systems, and Manufacturing

Vol. 6, No. 6, 2012

Evaluation of Process Performance for Sustainable Hard Machining*

Giovanna ROTELLA**,***, Domenico UMBRELLO**,****, Oscar W. DILLON Jr.** and I.S. JAWAHIR**

** Institute for Sustainable Manufacturing, University of Kentucky
413 CRMS Building, Lexington, KY 40506, USA
E-mail: giovanna.rotella@polito.it; giovanna.rotella@uky.edu

*** Department of Production Systems and Business Economics, Politecnico di Torino,
Corso Duca degli Abruzzi 24, Torino (TO) 10129, Italy

**** Department of Mechanical Engineering, University of Calabria
Ponte P. Bucci Cubo 45/C, Rende (CS) 87036, Italy

Abstract

This paper aims to evaluate the sustainability performance of machining operation of through-hardening steel, *AISI 52100*, taking into account the impact of the material removal process in its various aspects. Experiments were performed for dry and cryogenic cutting conditions using chamfered cubic boron nitride (CBN) tool inserts at varying cutting conditions (cutting speed and feed rate). Cutting forces, mechanical power, tool wear, white layer thickness, surface roughness and residual stresses were investigated in order to evaluate the effects of extreme in-process cooling on the machined surface. The results indicate that cryogenic cooling has the potential to be used for surface integrity enhancement for improved product life and more sustainable functional performance.

Key words: Hard Machining, Cryogenic Cooling, Sustainable Production

1. Introduction

All over the world, machining operations such as turning, milling or drilling produce considerable amounts of waste requiring lots of money and energy to be employed. Whereas in the past the manufacturing processes were systematically developed in order to achieve, through innovation, a maximum efficiency for increasing profit; present trends push manufacturers to develop new methodologies incorporating sustainability concepts (1)(2)(3). The traditional practices are being replaced to reduce the energy required by the processes as well as the material used and the generated waste (4)(5). Furthermore, regulations and standards dictate even more healthy and safe environment for workers. For all the above mentioned reasons, a deep analysis of the manufacturing processes performances is needed in order to achieve desired manufacturing sustainability practices.

Sustainable manufacturing processes are those which demonstrate improved environmental impact and energy efficiency, generate minimum quantity of wastes, provide operational safety and personal health maintaining unchanged the quality of the products, or even improving them. In this context, hard turning is becoming competitive because of its ability to properly merge factors of great interest, such as production costs, productivity and especially product quality. However, several issues related to this process require further investigation. Among these, the main ones are associated with heat generation in the machining process which produces high temperatures in the cutting region; subsequently the tool is worn at a faster rate with a negative impact on the surface integrity of the

*Received 16 Jan., 2012 (No. 12-0021)
[DOI: 10.1299/jamdsm.6.989]

machined component. Moreover, the high temperature causes some undesirable microstructural changes, also called white and dark layer [6]. Thus, it is generally believed that to improve surface integrity factors it is necessary to decrease the temperatures; this is mainly done with the application of a coolant and the appropriate choice of the tool geometry [7] and using optimal cutting conditions.

Coolants, or metalworking fluids (MWFs), are considered the most prominent environmental issue for machining processes because they are contaminants, they must be disposed. They also need to be treated at the end of their life cycle and their use is characterized by problems in the immediate working environment and hazards for the worker's health who come in contact with them [8][9][10].

An attractive alternative to conventional cutting fluids is cryogenic cooling. It consists of injecting liquid nitrogen coolant to the exterior surfaces of the tool and the workpiece to maintain the hot-strength and hot-hardness of the tool. This method gives, when combined with tool geometry, the desirable control of cutting temperature and enhancement of tool life without almost any environmental problem, except proper ventilation, as nitrogen constitutes 79% of atmospheric air. However, from a product quality perspective, the convective cooling effect of cutting fluids on hard turning surface integrity has not been yet clarified [11]. Konig *et al* [12] suggested suppression of white layers with coolants, Zurecki *et al* [13] showed that cryogenic nitrogen spray cooling of cutting tool and tool-work contact limits the thickness of white layer, but others [14][15] indicated no effect. For this reason, the main objective of this research is to evaluate the performance of machining operation of through-hardening steel, *AISI 52100*, taking into account the impact of such material removal process in its various aspects and comparing the performance of cryogenic coolant system instead of dry cooling at varying of the cutting conditions (cutting speed and feed rate). Particularly, cutting forces, mechanical power, tool wear, white layer thickness, surface roughness and residual stresses were studied in order to evaluate the effects of extreme in-process cooling on the machined surface and to evaluate the of process performances for sustainable hard machining.

2. Experimental Procedure

Disks of hardened *AISI 52100* steel (outer diameter: 150 mm, disk thickness: 1.4 mm) were prepared, machined and heat-treated. Afterwards a gentle grinding was required to restore flatness and parallelism after the distortion caused during quenching. The heat treatments were performed in order to through-harden the disks to 54±1 HRC. Dry and cryogenic orthogonal cutting tests were conducted on a stiff high speed CNC lathe by means of a radial facing operation using low CBN content cubic boron nitride tools (Seco grade: CBN 100) with chamfered geometry (ISO TNGN 110308S with a chamfer of 20°x0.1 mm) mounted on a CTFNR3225P11 tool holder (providing rake and clearance angles of -8° and 8°, respectively). The tool holder was held in a Kistler 9121 three-component piezoelectric dynamometer for measuring forces. Disks were machined at varying cutting speed (75 m/min, 150 m/min and 250 m/min) and feed rate (0.075 mm/rev, 0.1 mm/rev and 0.125 mm/rev) either for dry and cryogenic conditions; the cutting time of each test was 18-20 sec in order to reach the mechanical and thermal steady state conditions. An ICEFLY™ cryogenic equipment was used to provide liquid nitrogen as a cryogenic coolant during cryogenic cutting tests. In particular, cryogenic coolant was applied by a nozzle perpendicular to the disc where chip formation mechanism takes place, as indicated in Fig. 1 (a), to provide the cooling effect at the primary, secondary and tertiary shear zones and on the tool flank face. After machining, samples of 5x5 mm were sectioned by wire-EDM for microstructure analysis and microhardness measurements. Then, the samples were polished and etched for about 5 s using 5% Nital solution to observe white layer using a light optical microscope (1000X) and scanning electron microscope (SEM).

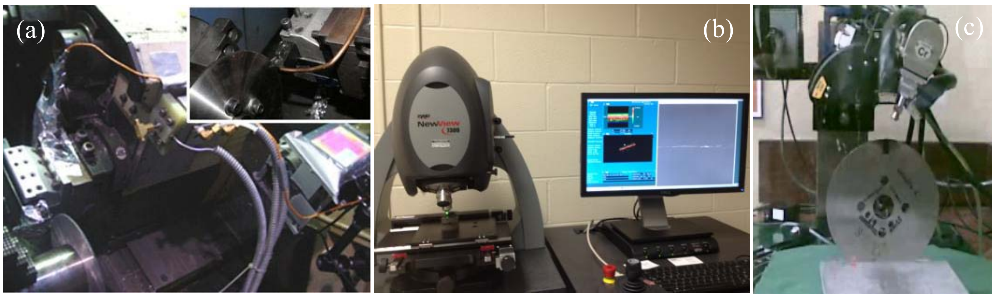

Fig. 1 (a) Experimental set-up for cutting tests and nozzle position for cryogenic delivery; (b) surface roughness measurement by Zygo optical interferometry, (c) residual stresses measurement by X-ray diffraction technique.

Tool wear analysis was carried out on the CBN inserts using an optical microscope; for each cutting tool, ten measurements were performed and the average value was evaluated.

Finally, constituents related to the surface integrity, such as surface roughness, residual stresses, etc., were also taken into account. In particular, the surface roughness values of the machined workpieces were measured using a Zygo® optical interferometry-based surface profilometer (Fig. 1 (b)). The residual stress state in machined disk surfaces was analyzed by X-ray diffraction technique (Fig. 1 (c)) using the $\sin^2\psi$ method [16]. The parameters used in the X-ray analysis are shown in Table 1.

It is important to underline that although both axial and circumferential residual stresses can be measured by the XRD technique, only the latter (parallel to the cutting direction) were considered for this research since they are more critical for part performance in service. To determine the in-depth residual stress profiles, successive layers of material were removed by electro-polishing to avoid the modification of machining-induced residual stress. Further corrections to the residual stress data were made due to the volume of material removed.

Table 1: XRD factors for residual stress measurement.

X-Ray Radiation	Cr-Kα
Young's Modulus	210 GPa
Poisson ratio	0.3
Bragg Angle 2θ	156.3°
Lattice plane	{2 1 1}
Number of ψ angles (±40°)	15

3. Experimental Results and Discussions

3.1 Cutting Forces and Mechanical Power

Fig. 2 shows the trend of the average cutting forces for each experiment evaluated when mechanical and thermal steady-state conditions were reached, while the error bars represents the standard deviations of the signal. The results highlight that the application of liquid nitrogen only has a slight influence on both cutting and thrust forces. On the other hand, the increase of cutting speed shows a decrease of the cutting forces for both dry and cryogenic conditions; this is due to the increased thermal softening at the higher temperatures reached when the cutting speed rises. In contrast, the increase of feed rate shows a considerable increase in cutting forces, under both dry and cryogenic cooling conditions. Fig. 3 illustrates the mechanical power variation for the selected cutting conditions for both dry and cryogenic cooling conditions (in this research only the amount required by the lathe was considered). The results do not highlight substantial differences in terms of power consumption at varying of cooling conditions. In contrast, the mechanical power is drastically influenced by the material removal rate (i.e., cutting conditions) as clearly evidenced in the Fig. 3: higher material removal rate requires more mechanical power. It is interesting to note as the ratio between the highest power consumption (at 150 m/min and 0.075 mm/rev) and the lowest one (at 75 m/min and 0.075 mm/rev) is 3.12 although, for the given cutting conditions, the material removal rate (MRR) ratio is only 2.

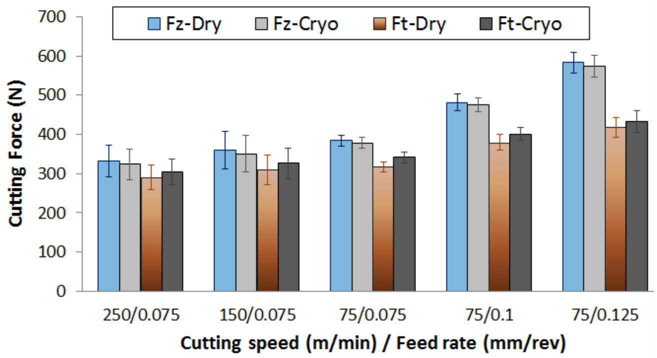

Fig. 2 Variation of cutting (F_z) and thrust (F_t) forces during machining under dry and cryogenic cooling conditions at varying cutting speeds and feed rates.

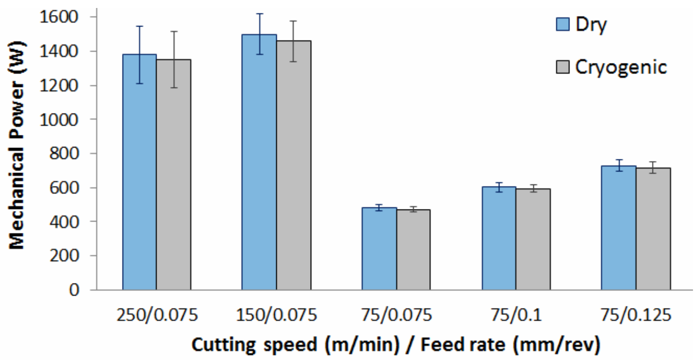

Fig. 3 Required mechanical power for machining operation under dry and cryogenic cooling conditions at varying cutting speeds and feed rates.

3.2 Surface Roughness

The average surface roughness, R_a, of the machined sample was measured for each set of cutting process parameters and cooling conditions in order to evaluate the characteristic of the machined surface (Fig. 4 (a)). The obtained R_a measurements evidence as the surface quality in machining with cryogenic coolant is superior to that in dry cutting. Additionally, using the cryogenic cooling system, the values of the surface roughness permit to achieve the so called "*cutting replace grinding*" operation.

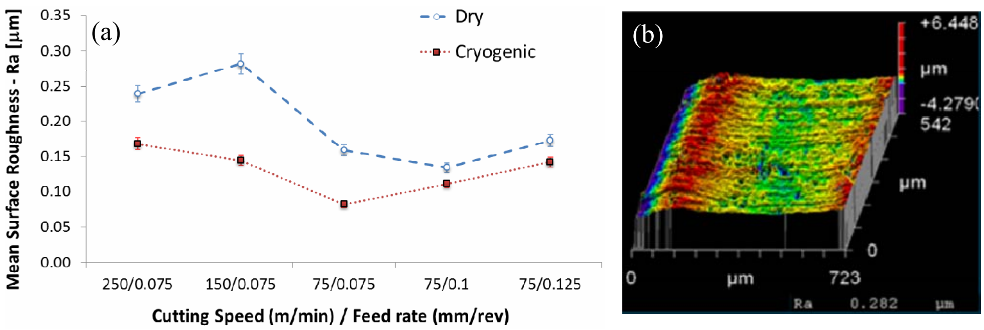

Fig. 4 (a) Mean surface roughness on machined samples under dry and cryogenic cooling conditions for all five test conditions; (b) surface roughness profile acquired by a Zygo® interferometry-based surface profilometer.

Moreover, for both the cooling conditions used the increase of the feed rate shows a general worsening of the surface roughness. In contrast, experiments do not show trends normally expected as the R_a decrease with the increasing of the cutting speed. This discrepancy might be related to the cutting conditions employed in this research which are higher than those suggested by the tool makers for finish hard machining (usually 0.05-0.075 mm/rev, 150-200 m/min and depth of cut less than 0.5 mm). Consequently, the insufficient spindle rigidity can lead, in certain conditions, to the vibration of the machining system, influencing the surface quality as depicted in Fig. 4 (b).

3.3 Tool Wear

Fig. 5 illustrates how the process cutting parameters and the cooling condition influence the flank wear rate. As expected, the wear rate increases with the increasing of both feed rate and cutting speed. What is more, the influence of cutting speed on flank wear rate is higher than that of feed rate; in fact, an evident increase of the wear rate of about two times is recorded when cutting speed ranges from 75 m/min to 250 m/min are used. In addition, the use of cryogenic cooling system does not produce any significant tool wear benefits under the conditions employed since its use increases wear rate, especially when feed rate increases (a rise of about 21% is revealed).

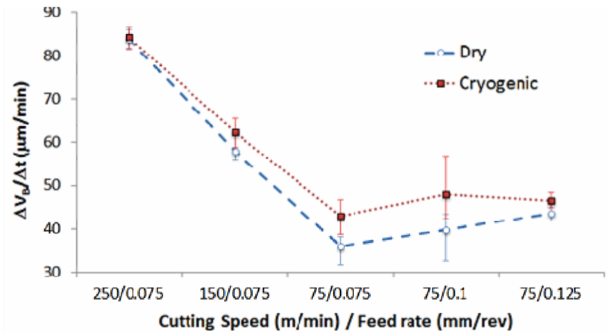

Fig. 5 Effects of dry and cryogenic cooling conditions on flank wear rate at varying cutting speeds and feed rates.

The results reported in Fig. 5 are in disagreement with those previously published [17][18], where a reduction in tool wear is recorded when the cryogenic technique is used. The reason of this discordance is due the nozzle position for cryogenic delivery, which in this research was adjusted to cool the workpiece while, normally, it is applied on the tool rake face or from the bottom of the flank side. Thus, the “unusual” nozzle position in combination with the short cutting time produce more abrasive wear between tool and workpiece than the one observed in the dry condition.

3.4 Whyte Layer Thickness

Fig. 6 shows the experimental white layer thickness created by varying feed rate, cutting speed and cooling condition. In particular, the white layer ranges from less than 1 μm, when cryogenic cooling is employed, to 6 μm during dry cutting. Moreover, the white layer observed in the dry condition decreases with decreasing values of both the cutting speed and the feed rate. Similar trends are revealed when machining was carried out under cryogenic condition although the difference on white layer thickness are less noticeable. However, what is new is that the white layer depth obtained using cryogenic cooling is much smaller than the white layer thickness measured when dry machining was performed. Similar results was found by Zurecki *et al* [13]. Also, the white layer formation in dry machining is mainly due to a rapid heating and quenching which results in phase transformation (i.e., generation of martensitic structure); in contrast, the use of cryogenic cooling limits or avoids the martensitic phase changes. This is due to the lower temperatures reached during the material removal process [(19)].

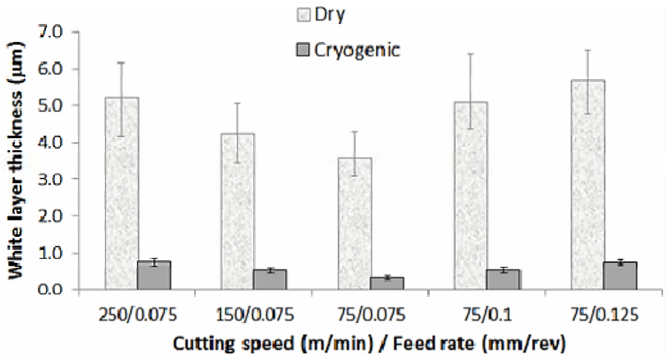

Fig. 6 Experimentally obtained white layer thickness.

Fig. 7 clarifies the above-mentioned aspects; in particular, Fig. 7 (a) shows that only a thin layer (less than 1 µm) is subjected to phase change during machining, while Fig. 7 (b) depicts the mechanical deformation effect as dominant when cryogenic coolant is applied – a zone of severe plastic deformation showing a superficial layer having different microstructure due to plastic deformation is clearly observed.

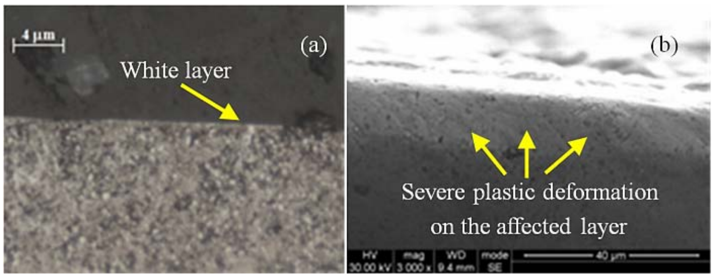

Fig. 7 Optical observation (a) and SEM image (b) of cross-section of machined workpiece surface for test at 150 m/min 0.075 mm/rev using cryogenic coolant.

3.5 Surface Residual Stress and Compressive Area

Fig.8 shows the surface residual stress for all the investigated cases conducted in this research. These results show that in dry machining the surface residual stress is always compressive and it becomes thicker (i.e., deeper profile) as cutting speed increases, while it has a minor influence from the feed rate; in fact, it then slightly reduces or remains constant. In contrast, when machining under cryogenic cooling condition was carried out, the surface residual stress in all the investigated cases becomes tensile and it increases with the feed rate, while it slightly decreases when cutting speed rises.

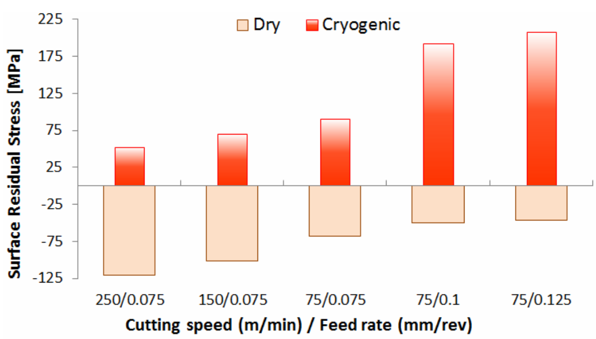

Fig. 8 Effect of dry and cryogenic cooling conditions on surface residual stresses.

Another factor of cardinal interest, related to the fatigue life of any machined component, is the compressive area which represents the compressive portion of the residual stress profile [20]. Fig. 9 highlights the effects of the cooling conditions and process parameters on the compressive area. In particular, it can be noted, as general trend, that the compressive areas obtained in dry machining are higher than those observed when cryogenic cooling was applied. Moreover, it becomes larger (i.e., deeper profile) when both cutting speed and feed rate increase. In contrast, the compressive area measured under cryogenic cooling condition is strongly affected by the cutting speed (it increases with increasing of the cutting speed), while it is slightly influenced by the feed rate.

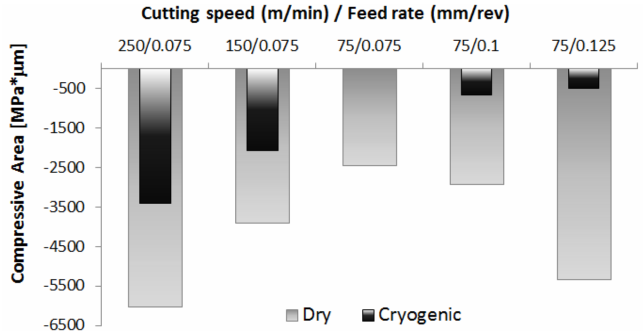

Fig. 9 Compressive area at varying cutting speed, feed rate and cooling condition.

What is more, when the cutting speed of 75 m/min is used, the compressive area observed under cryogenic machining becomes very small (feed rates of 0.1 and 0.125 mm/rev) or it is totally absent (0.075 mm/rev). In addition, for the above mentioned process conditions, tensile area are detected due to the partial or total tensile residual stress profiles on the machined surface and sub-surface. In the best cases the values are lower than 100 MPa* µm (0.1 and 0.125 mm/rev) while in the worst case it is 1815 MPa*µm (0.075 mm/rev).

4. Evaluation of Hard Machining Performance

Figs. 10 and 11 report the results of the different process parameters and cooling conditions employed in this research as far as the evaluation of hard machining performance is regarded (in the charts, each parameter has been equally weighted). In dry machining (Fig. 10), higher cutting speeds permit to obtain major benefits in term of the parameters related to the fatigue life (i.e., surface residual stress and compressive area) and productivity (material removal rate). Similar tendency is observed when machining operation is carried out with cryogenic coolant (Fig. 11) although, it is worth to point out that it is dangerous to have tensile residual stresses on the machined surface.

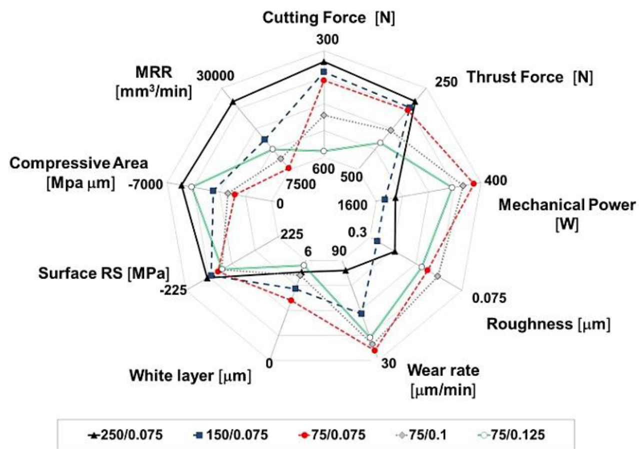

Fig. 10 Machining performance in dry condition for all five experimental tests.

In fact, even in the cases of shallow superficial tensile residual stresses, the presence of tensile area is detrimental for the fatigue life of the machined component.

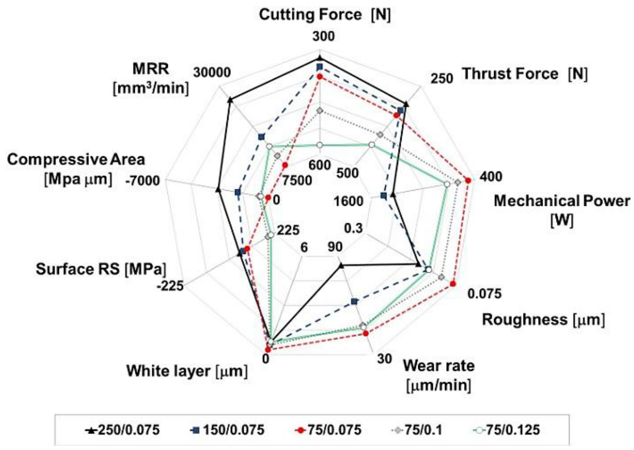

Fig. 11 Machining performance with cryogenic coolant for all five test conditions.

In contrast, for above cutting conditions, other factors related to the surface integrity (white layer thickness and mean surface roughness) are not so good as they are for other cutting speeds and feed rates. Once again, this trend is similar either for dry machining as well as for machining under cryogenic cooling.

Moreover, when parameters related to mechanical power, tool cost and tool substitution policy are taken into account, other cutting conditions offer the best trade-off. Thus, in order to evaluate the performance, it is necessary to define a criterion which considers all the aspects and, consequently, optimises the benefits and the drawbacks for the different combination of the process parameters. Although several optimization algorithms are available, in this research a simple method based on the total area under the curve for each cutting condition was applied. Based on that criterion and taking into account the performance evaluation (surface integrity, productivity and machining cost), two very close major areas were achieved for both the cooling conditions corresponding to the cases: 250 m/min – 0.075 mm/rev and 75 m/min – 0.075 mm/rev.

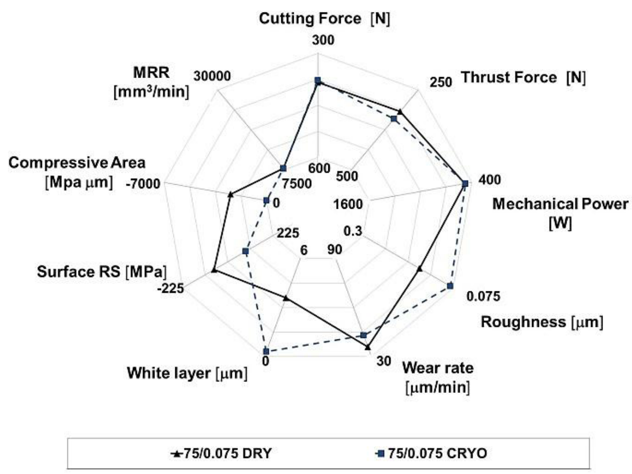

Fig. 12 Process performance in dry and cryogenic condition at 75 m/min and 0.075 m/rev.

What is more, they are referred to the best performance related to the surface integrity and productivity from one side and to the mechanical power, tool cost and tool substitution policy from the other side. In fact, the best trade-off for the surface integrity factors are achieved by 250 m/min and 0.075 mm/rev, while for the mechanical power and tool aspects the cutting speed of 75 m/min with the same value of feed rate represents the best choice. Finally, the comparison between dry machining and cryogenic coolant assisted machining was carried out. As shown in Figs. 12 and 13, taking also into account the evaluation criterion, hard machining under cryogenic cooling for both 75 m/min and 250 m/min shows the higher sustainable functional performance (Fig. 12). Furthermore, although in a minor manner, it represents potential benefit for surface integrity enhancement for improved product life (Fig. 13).

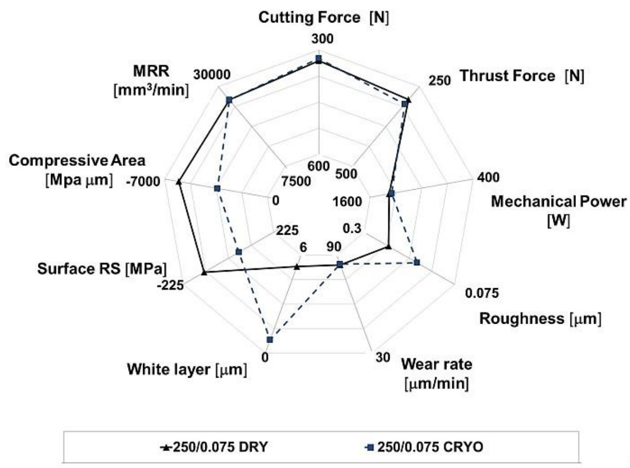

Fig. 13 Process performance in dry and cryogenic condition at 250 m/min and 0.075 m/rev.

5. Conclusions

Experimental observations reported in this study suggest that use of cryogenic coolant in machining of hardened AISI 52100 significantly affects the residual stress, the roughness, the tool wear and the white layer formation. In particular, cryogenic cooling condition permits to limit the white layer thickness and to achieve better surface roughness. In contrast, dry machining offers better performance on residual stress profile and, therefore, to the fatigue life, although it produces higher white layer which is detrimental for the product's performance and relative cost (necessity of secondary operation for removal operation). As overall, it was demonstrated as the hard machining under cryogenic cooling shows higher sustainable functional performance and, moreover, it has the potential to be used for surface integrity enhancement for improved product life although particular attention must be paid in order to avoid the surface tensile residual stress and tensile area which are detrimental for fatigue life. Finally, it should be pointed out that other cutting conditions, initial workpiece hardness and tool shape were not considered at this stage, and a further investigation on this topic, including the optimization, will be necessary to better highlight which cutting parameters, initial workpiece hardness cooling conditions, etc., should be chosen in order to improve the sustainability of the hard machining processes.

Acknowledgements

The authors thank Air Products for their support with the cryogenic cooling system.

References

(1) Jegatheesan, V., Liow, J.L., Shu, L., Kim, S.H. and Visvanathan, C., The Need for Global Coordination in Sustainable Development, *Journal of Cleaner Production*, Vol. 17/7 (2009), pp. 637-643.

(2) Bansal, P., Evolving Sustainably: a Longitudinal Study of Corporate Sustainable Development, *Strategic Management Journal*, Vol. 26 (2005), pp. 197-218.

(3) Jovane, F., Yoshikawa, H., Alting, L., Boer, C., Westkamper, E., Williams, D., Tseng, M., Seliger, G. and Paci, A., The Incoming Global Technological and Industrial Revolution Towards Competitive Sustainable Manufacturing. *CIRP Annals –*

Manufacturing Technology, Vol. 57/2 (2008), pp. 641-659.

(4) Jawahir, Jayal, A.D., Badurdeen, F., Dillon Jr., O.W., Jawahir, I.S., Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels, *CIRP Journal of Manufacturing Science and Technology*, Vol. 2/3 (2010), pp. 144-152.

(5) Gutowski, T., Murphy, C., Allen, D., Bauer, D., Bras, B., Piwonka, T., Sheng, P., Sutherland, J., Thurston D. and Wolff, E., Environmentally Benign Manufacturing: Observations from Japan, Europe and the United States, *Journal of Cleaner Production*, Vol. 13/1 (2005), pp. 1-17.

(6) Lucca, D.A., Brinksmeier, E. and Goch, G., Progress in Assessing Surface and Subsurface Integrity, *Annals of the CIRP*, Vol. 47/2 (1998), pp. 669-693.

(7) Dhar, N.R. and Kamruzzaman, M.,Cutting Temperature, Tool Wear, Surface Roughness and Dimensional Deviation in Turning AISI-4037 Steel Under Cryogenic Condition, *International Journal of Machine Tools and Manufacture,* Vol. 47 (2007), pp. 754-759.

(8) Jayal, A.D. and Balaji, A.K., On a Process Modelling Framework for Sustainable Manufacturing: A Machining Perspective, *Proceedings of ASME IMECE07*, (2007), pp. 301-307.

(9) Kopac, J., Achievements of Sustainable Manufacturing by Machining, *Journal of Achievements in Materials and Manufacturing Engineering*, Vol. 34/2 (2009), pp.180-187.

(10) Rajemi, M.F., Mativenga, P.T. and Aramcharoen, A., Sustainable Machining: Selection of Optimum Turning Conditions based on Minimum Energy Considerations, *Journal of Cleaner Production* Vol. 18/11 (2010), pp. 1059-1065.

(11) Chou, Y.K. and Barash, M.M., Review on Hard Turning and CBN Cutting Tools, *SME Technical Paper MR 95-214, 1st Int. Machining and Grinding Conference*, (1995), pp. 949-962.

(12) König, W., Klinger, M., and Link, R., Machining Hard Materials with Geometrically Defined Cutting Edges-Field of Applications and Limitations, *Annals of the CIRP*, Vol. 39/1 (1990), pp. 61-64.

(13) Zurecki, Z., Ghosh, R. and Frey, J.H., Investigation of White Layer Formed in Conventional and Cryogenic Hard Turning of Steels, *Proceedings of ASME IMECE03,* (2003), pp. 16-21.

(14) Berktold, A., König, W., Liermann, J. and Winands, N., Top-quality components not only by grinding, Industrial Diamond Review, Vol. 54/562 (1994), pp. 127-132.

(15) Tonshoff, H.K., Brandt, D. and Wobker, H.G., Potential and Limitation of Hard Turning, *SME Technical Paper MR 95-215, 1st Int. Machining and Grinding Conference*, (1995), pp. 965-978

(16) Noyan, I.C. and Cohen, J.B., Residual Stress – Measurement by Diffraction and Interpretation, Springer, New York (1987).

(17) Hong, S.Y. and Ding, Y., Cooling Approaches and Cutting temperatures in Cryogenic Machining of Ti–6Al–4V, *International Journal of Machine Tools & Manufacture*, Vol. 41 (2001), pp. 1417-1437.

(18) Bhattacharyya, D., Allen, M.N. and Mander, S.J., Cryogenic Machining of Kevlar Composites, *Materials and Manufacturing. Processes*, Vol. 8/6 (1993), pp. 631-651.

(19) Umbrello, D., Yang, S., Dillon Jr., O.W. and Jawahir, I.S., The Effects of Cryogenic Cooling on Surface Layer Alterations in Machining of AISI 52100 Steels", *Materials Science and Technology*, 2012 in press (DOI 10.1179/1743284712Y.0000000052)

(20) Hashimoto, F., Melkote, S.N., Singh, R. and Kalil, R., Effect of Finishing Methods on Surface Characteristics and Performance of Precision Components in Rolling/Sliding Contact, *Int. J. Machining & Machinability of Materials,* Vol. 6/1-2 (2009), pp. 3-15.