Dry and Cryogenic Machining: Comparison from the Sustainability Perspective

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Abstract

Modern manufacturing processes continue to demand high quality products and processes at reduced costs and with greater environmental compliance. This has led to a critical consideration of the use of conventional cutting fluids used in most machining processes. Continued use of cutting fluids poses major problems as they they are hazardous for the operating personnel on the shop floor. They are also carcinogenic, harmful to the environment and cause high costs. The major focus of the proposed paper is the analysis of experimental work on machining under dry and cryogenic conditions in turning of *Al 7075–T651* alloy to achieve environmental and economic benefits and improved surface integrity and fatigue life of the machined product, thus aiming at a more sustainable product. In particular, a preliminary evaluation of the fatigue life of the component is presented based on a microstructure-based model, which varies with the used manufacturing process. The overall results show that cryogenic cooling has the potential to improve the product and process through its superior performance in terms of the machined surface and sub-surface characteristics and the related environmental and economic performance.

Keywords:

Fatigue life, Machining, Sustainable processes.

INTRODUCTION

Considerable amount of waste is produced by machining operations such as turning, milling or drilling in world-wide product manufacture. In the past, the manufacturing processes were systematically developed in order to achieve, through innovation, maximum efficiency for increased profit, and the present trends push manufacturers to develop new methodologies incorporating a variety of sustainability concepts for improved performance and competitive advantage [1, 2]. Sustainable manufacturing processes are those which generate minimum quantity of wastes demonstrating improved environmental impact and energy efficiency while providing operational safety and personal health. In this context, numerous concerns are in place for machining operations. Among these, metalworking fluids (MWFs), are considered the most prominent environmental issue for machining processes. Nowadays, cutting fluids have changed dramatically due to recent regulations on environment, health and safety issues, which identify some of the ingredients in cutting fluids as problematic. In fact, the detection of a variety of illnesses and environmental hazards, that these ingredients cause, has lead to their reduced use, or their elimination.

Generally speaking, MWFs are contaminants, they must be treated and disposed 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 when they come in contact with them [3-4].

The metalworking fluids also play an important role in machining processes in terms of lubrication and cooling [5]. For this reason, we cannot ignore the fact that a sustainable process must consider the final performance of the process, and above all, maintain the product quality and/or improved, during its service life.

It is well known that manufacturing processes significantly influence the type of surface being produced. The quality of the surface dictates the functional performance and service-life of engineered components. Surface characteristics of machined products such as roughness, residual stresses or microstructure are some of the important constituents determining the performance of a product. The aircraft industry is one of the most relevant examples where the final products must be produced in order to ensure the most desirable performance and lifetime.

Since there is no active feedback on how to correct the manufacturing process to achieve the desired surface integrity in the manufactured parts, expensive post-operations are used. Hence, knowledge about factors that cause microstructural improvements will contribute to a better fundamental understanding of manufacturing process mechanics and improved knowledge-driven manufacturing process planning, as well as better prediction of the component's lifetime.

For all the above-mentioned reasons, this paper preliminarily addresses an evaluation of the machined product in terms of surface quality and fatigue life. In particular, the relationship between the coolant action and final product characteristics are addressed when the machining process is carried out under dry and cryogenic machining conditions. The flood cooling and the Minimum Quantity of Lubrication (MQL) methods are ignored in this work due to the environmental concerns involved. In fact, an attractive alternative to conventional cutting fluid applications is cryogenic cooling. It consists of injecting liquid nitrogen coolant onto the exterior surfaces of the tool and the workpiece to maintain the strength and hardness of the cutting tool and workpiece. This method, when combined with tool geometry, gives the desirable control of cutting temperature and tool-life enhancement with no adverse environmental effects.

Liquid nitrogen is the most abundant gas - composes about the 78% by volume of the atmosphere, it is a colorless, odorless, tasteless and non-toxic gas and it is the commonly used element in cryogenics. It is produced industrially by fractional distillation of liquid air and its main functions in metal cutting were shown as removing heat effectively from the cutting zone, hence lowering cutting temperatures, modifying the frictional characteristics at the tool/chip interfaces, thereby changing the properties of the tool material and the workpiece [6].

As far as the latter is concerned, cryogenic cooling can potentially improve the service lifetime of the product. For example, quality is the major issue in aircraft industry because the product has to have a long life and it is subject to fatigue and corrosion effects. Hence, the work material of interest is *7075-T651* aluminum alloy, which is predominantly used in aerospace applications. Its major applications include welded parts, aircraft fittings, meter shafts, gears and shafts, missile parts, and numerous other components in aerospace and defense applications.

FATIGUE LIFE IN ENGINEERED COMPONENTS

A fatigue crack is the result of localized plastic deformation during cyclic straining which causes the failure of a component in service. “Crack initiation” is defined as number of cycles required to generate, nucleate, or form the smallest crack that is detectable by any means [7]. On this basis, assuming a homogenous and free of initial crack component, initiation sets the limit on the minimum size of a small fatigue crack [8].

The resistance of metals and alloys to fatigue crack initiation and propagation is known to be influenced significantly by grain size, and it is widely recognized that an increase in grain size generally results in a reduction in the fatigue endurance limit while a coarse grain structure can lead to an increase in the fatigue crack growth threshold stress intensity factor range and a decrease in the rate of crack growth [9].

In commercial materials, fatigue cracks often start at metallurgical stress concentrations such as inclusions and pores. The crystallographic anisotropy, i.e., texture, of a material also has a strong influence. In some alloys, fatigue cracks nucleate within a local region where a number of adjacent grains of nearly the same orientation have the slip characteristics of a single large grain. Furthermore, many cracks initiate from the surface of a component which is stressed when cyclic loads are applied.

In this paper the number of cycles before the crack initiates is evaluated. The calculation focuses solely on the surface microstructural effect on the fatigue crack initiation under uniaxial cycling loading.

2.2 Microstructure-based model

Many models have been proposed for predicting the fatigue crack initiation mechanism [10-12]. Basically, each model is based on stress or strain and some of the models also contain parameters which take into account the role of microstructure in crack initiation. Since most of the variation in useful lifetimes is in the initiation stage, we use a model incorporating that aspect for comparison purposes.

In this paper, the model proposed by Chan [8] is applied as follows:

$$(\Delta\sigma - 2Mk)N_i^{\alpha} = \left[\frac{8M^2\mu^2}{\lambda\pi(1-\nu)}\right]^{\frac{1}{2}}\left(\frac{h}{d}\right)\left(\frac{c}{d}\right)^{\frac{1}{2}} \qquad (1)$$

where $\Delta\sigma$ is the applied loading stress, N_i is the number of high cycles fatigue to start the crack initiation mechanism, α is an exponent and its values range from 0 to 1, *2Mk* represents the fatigue limit below which fatigue-crack initiation does not occur; μ is the shear modulus of the considered material, ν is the Poisson's ratio and *d* is its grain size; *M* is the Taylor factor equal to 2, the crack depth *c* and the slip band width *h* in the equation have been evaluated by the author for the used material respectively while λ is a parameter with a universal value of 0.005 [8]. Table 1 shows the calculated values for the Equation 1.

μ MPa	α	***2Mk*** MPa	***c*** µm	***h*** µm
25800	0.225	100	524	0.012

Table 1: Parameters for the Eq. 1 as proposed by Chan [8].

Equation (1) is utilized here in order to have a preliminary estimation of the fatigue life of final components in order to compare the effect of the two machining processes (dry and cryogenic conditions) on fatigue life via the surface microstructure.

EXPERIMENTAL PROCEDURE

The experimental tests were performed under dry and cryogenically-assisted conditions. The initial material is *Al 7075-T651* which is artificially aged and then stress relieved. More precisely, the T651 process involves a 1.5% stretch prior to 24 hours at 121℃ followed by air cooling. The initial bars were obtained by extrusion and their chemical composition and the mechanical properties of the material are given in Tables 2 and 3.

The machining tests were conducted on a stiff high speed Mazak CNC lathe in an external turning operation using uncoated carbide tools (KENNAMETAL grade: K313 with a clearance angle of 11°) with triangular shape mount ed on a CTGPL164C tool holder providing a lead angle of 0°. The turning tests were executed in both dry and cryogenic conditions and the tool holder was held in a Kistler 9121 three-component piezoelectric dynamometer for measuring forces (consequently the mechanical power being consumed during the machining process).

Physical properties	
Ultimate Tensile Stress [MPa]	612.9
Yield Tensile Stress [Mpa]	552.9
Elongation %	11
Hardness HV	160

Table 2: Physical properties of the as received material.

The turning experimental set-up is shown in Figure 1. Table 4 shows the experimental plan.

Table 3: Chemical composition of the *Al 7075 T651* material.

Chemical composition WT%										
	Si	***Fe***	***Cu***	***Mn***	***Mg***	***Cr***	***Zn***	***Ti***	**Other each**	**Other total**
Actual	0.08	0.17	1.4	0.03	2.7	0.19	5.8	0.02		
max	0.40	0.50	2.0	0.30	2.9	0.28	6.1	0.20	0.05	0.15
min			1.2		2.1	0.18	5.1			

Cryogenic machining presents a method of rapidly cooling the cutting tool or/and workpiece during machining. More particularly, it delivers the cryogenic cooling media to the tool, which normally experiences high temperature during the machining process, or to the workpiece to change the material characteristics and improve machining performance. In the current experimental work, the liquid nitrogen was applied by a nozzle to the tool flank face as indicated in Figure 1. After each test, the properties of the machined samples were evaluated. The roughness of each machined surface was measured by a Zygo®7300 optical interferometry-based surface profilometer. The final surface microstructure has been analyzed by means of a stereo microscope NIKON L-IM (with 1000X magnification), after each cutting test. In particular, the grain size of each machined sample, as well as the “as received” material was measured at different distances from the machined surfaces.

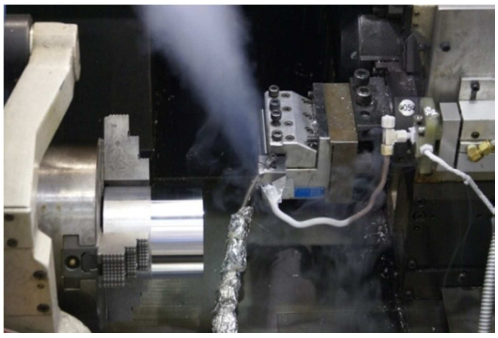


Figure 1: Experimental setup for cryogenic machining.

Test	Tool geometry – tool nose radius [mm]	Cutting speed [m/min]	Cooling method
1	TPG 431 - 0.4	320	Dry
			Cryogenic
2	TPG 432 - 0.8	180	Dry
			Cryogenic
3	TPG 432 - 0.8	320	Dry
			Cryogenic
4	TPG 433 – 1.2	320	Dry
			Cryogenic
5	TPG 432 - 0.8	720	Dry
			Cryogenic

Table 4: Experimental plan: depth of cut = 0.5mm and feed rate = 0.1mm/rev.

EXPERIMENTAL RESULTS AND DISCUSSION

As previously mentioned, the average cutting force components have been acquired when mechanical steady-state condition was reached for each test. As shown in Figures 2-4, the application of liquid nitrogen has a significant influence on all three force components acting during the turning process. In particular, the measured cutting and thrust forces for the cryogenic condition were found to be less than those measured during dry cutting in almost all test cases. As far as the radial force is concerned, the cryogenic cooling generates forces comparable to the dry machining case.

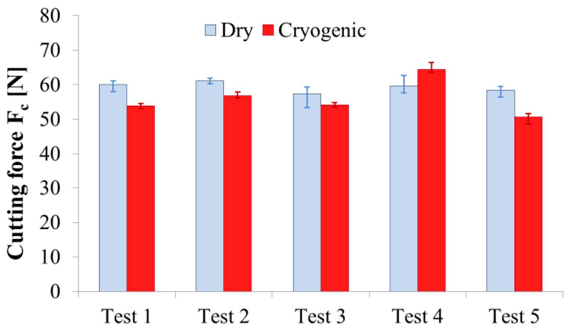


Figure 2: The comparison of the measured cutting force *(F_c)* during machining under dry and cryogenic cooling conditions at varying cutting speeds and tool nose radii.

It is important to emphasize that the direction of flooding of the liquid nitrogen was the same as the tool flank face so that the radial forces would not be much influenced by its cooling effect. As expected, the cutting forces have also been influenced by the cutting parameters and the tool geometry.

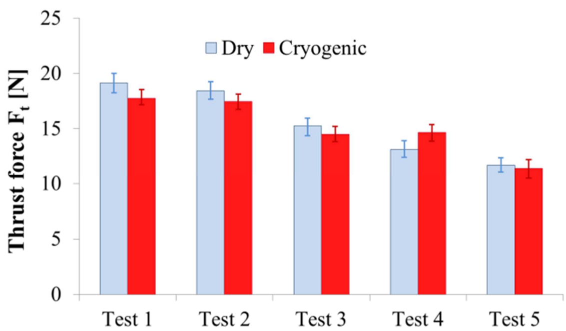


Figure 3: The comparison of measured thrust force *(F_t)* during machining under dry and cryogenic cooling conditions at varying cutting speeds and tool nose radii.

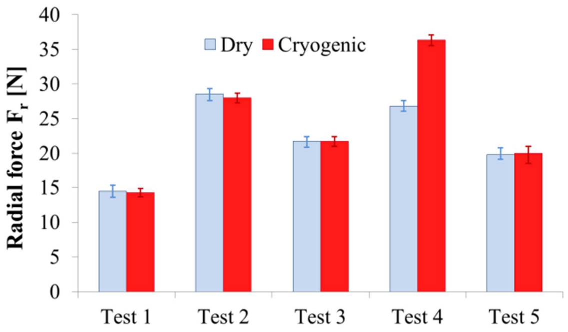


Figure 4: The comparison of the measured radial force *(F_r)* during machining under dry and cryogenic cooling conditions at varying cutting speeds and tool nose radii.

The mechanical power required by the process shows the same trend as previously stated for the forces. In fact, as shown in Figure 5, in almost all the cases, the cryogenic machining process requires less power than dry machining. More specifically, the forces decrease with increasing cutting speed while they increase with decreasing tool nose radius.

Assuming that the finish-machined component will be employed in an aerospace or automotive application, it is important to evaluate its performances in terms of surface quality and fatigue life under service conditions. It is well known that the crack initiation in a component starts from the surface. Therefore, it is very important to keep the surface as smooth as possible and not to induce tensile residual stresses on the surface.

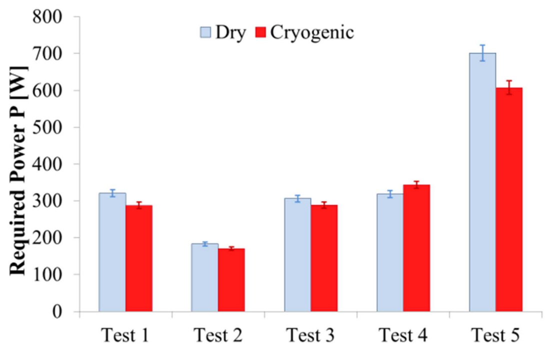


Figure 5: The comparison of the "measured" mechanical Power, *P,* in dry and cryogenic machining.

The mean average surface roughness, R_a, was measured on all machined samples in order to evaluate the surface quality of the final product (Figures 6-7). The obtained results highlight that the cryogenic condition improves the surface quality of the product. The roughness of the machined samples can be slightly improved by increasing the tool nose radius. Also, the known trend of improved surface roughness by increasing the cutting speed was verified.

The grain size of each machined surface has been measured, and, in all investigated cases, the recrystallization occurs. More precisely, all examined samples present a refinement of the mean grain diameter from the bulk to the surface. Due to recrystallizaion, the cryogenic machining has some positive effects as it helps to keep the surface grains smaller after the recrystallization phase than the initial size.

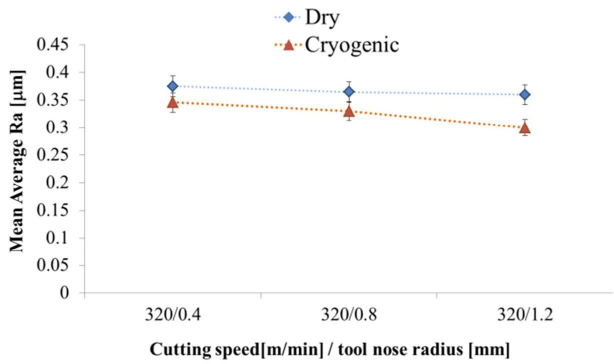


Figure 6: Measured R_a data obtained during machining under dry and cryogenic cooling conditions with varying nose radii.

The results highlight a strong surface grain refinement for the cryogenically machined samples as shown in Table 5. As observed, the grain recrystallization takes place in all the performed tests but the cryogenic cooling allows the final surface grain size small. Figure 8 shows two different surface structures obtained from dry and cryogenic machining. The micro-hardness, Vickers $HV_{0.05}$, of each sample was also measured in order to verify the microstructural changes in the machined samples. The results shown in Figures 9 and 10 demonstrate that hardness increases when liquid nitrogen is applied on the tool flank face and compares with results from dry machining.

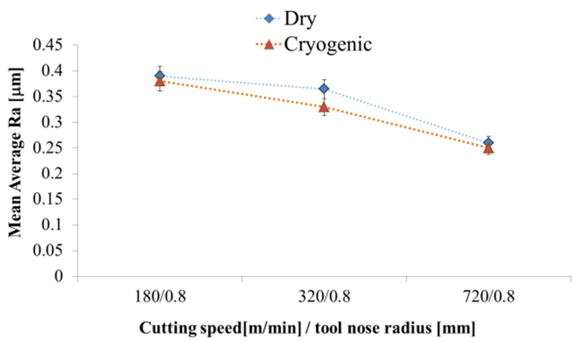
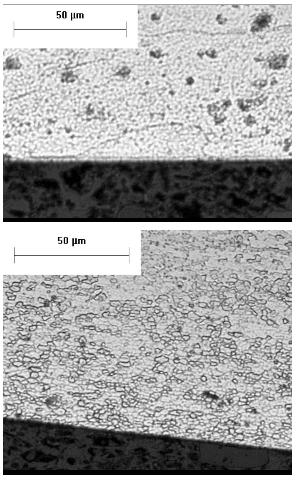


Figure 7: Measured R_a data obtained during machining under dry and cryogenic cooling conditions
with varying cutting speeds.

Also, each cryogenically machined sample presents a higher surface hardness when compared with the dry-machined samples. The larger nose radius seems to generate a higher hardness value on the surface. Once again, the cutting speed has a greater influence on the generated hardness, and combined with cryogenic machining, it almost always results in a better surface hardness and quality.



(a)

(b)

Figure 8: Micrograph of the dry machined surface (a), and the cryogenically machined surface (b).

Test N	Surface mean grain size [µm]	Cooling method
1	12.30	Dry
	5.36	Cryogenic
2	12.33	Dry
	5.60	Cryogenic
3	10.10	Dry
	5.01	Cryogenic
4	7.73	Dry
	4.50	Cryogenic
5	4.05	Dry
	1.79	Cryogenic

Table 5: Grain size refinement at varying cooling conditions and tool nose radii.

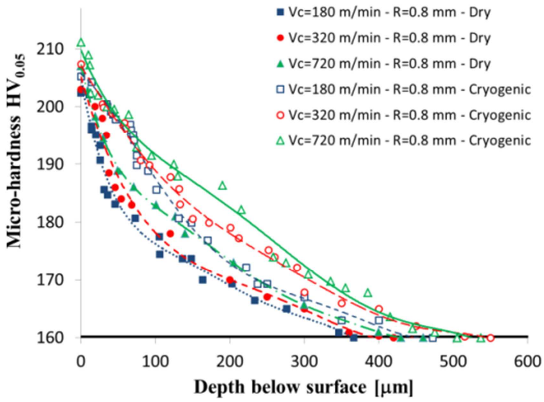


Figure 9: Measured micro-hardness for specimens machined under dry and cryogenic cooling conditions at varying cutting speeds.

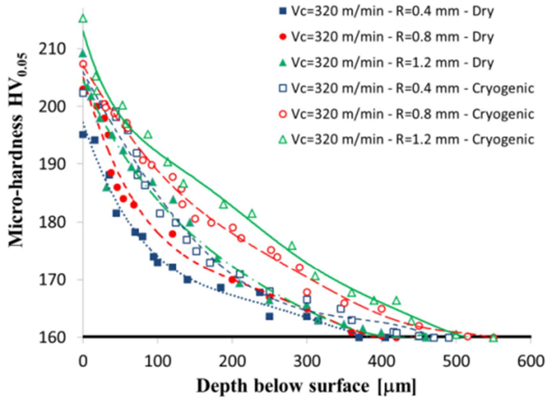


Figure 10: Measured micro-hardness for specimens machined under dry and cryogenic cooling conditions at varying of nose radii.

4.2 Fatigue Life Prediction

Figures 11 and 12 show the fatigue life prediction, using Equation (1), for the investigated cases using the measured grain size data as reported in Table 5.

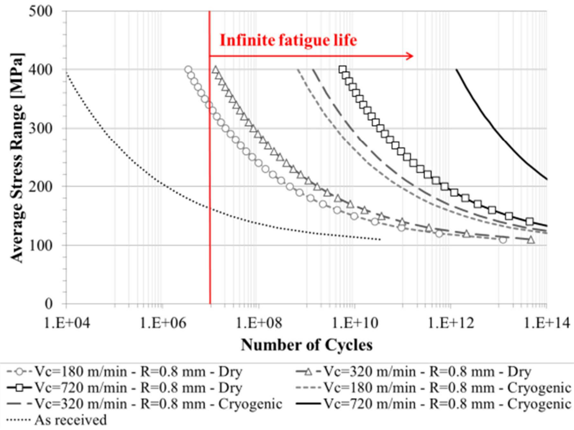


Figure 11: Calculated fatigue life for the measured surface grain size at varying cutting speeds and cooling conditions.

As seen from Figures 11 and 12, all machined samples move from the High Cycle Fatigue- HCF- range (usually defined as run-out at 10^7 cycles) to a Ultra High Cycle Fatigue regime. It means that the surface theoretically exhibits an infinite fatigue life under a reasonable loading range. The meaning of these values is that the fatigue life of the component greatly benefits from the refined surface grains and it moves from a failure occurring on the surface to predominantly internal fatigue failure usually characterized by micro crack growth and fish eye formation [10]. Furthermore, due to the better surface resistance, the sub surface might fail rather than the void/ particle internal mode generating a new failure mode. It is important to note that the cutting speed plays a very important role in reducing the size of the grain and consequently to extending the life of the component, while the use of cryogenic machining, usually associated with hard cutting conditions, allows the grains to maintain their small size.

It is worth pointing out that for the present experiments, the considered value of c was set equal to 524 µm while the slipband width h has been kept constant at the suggested value of 0.012. The model proposed by Chan [9] is dependent upon the slip band width and the initial crack length, which change with the variation of the initial grain size. Ultimately, they should be measured in order to obtain a more accurate prediction of fatigue life.

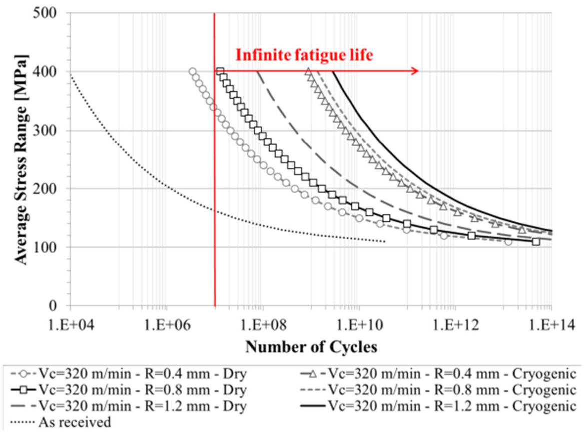


Figure 12: Calculated fatigue life for the measured surface grain size at varying tool nose radii and cooling conditions.

However, the proposed investigation reveals that the cryogenic machining process entails sustainability benefits for both the process and the product. In fact, as far as the product is concerned, the smaller surface grain structure and its better surface quality drive the component to have a longer fatigue life, to improve its performance and to be replaced at a later time. As for the process point of view, the cryogenic effect on the cutting forces reduces the energy consumption of the process and, consequently, the productivity rate can be increased without compromising the energy cost and consumption rate.

CONCLUSIONS

This paper presents results from a preliminary investigation showing the capability of cryogenic cooling to increase the sustainability performance of the product and the process in machining of *Al 7075-T651* alloys.

Cryogenic coolant significantly influences the grain refinement of the final product which results in a better surface hardness and fatigue life performance. From a process perspective, cryogenic coolant allows one to achieve lower cutting forces and lower mechanical power as compared with the dry process, thereby ensuring benefits from the energy consumption point of view. Furthermore, cryogenic machining is, as previously stated, more environmental friendly when compared with the traditional flood cooling methods which use classical fluids, or MQL machining. Finally, it is important to emphasize that additional experiments should be carried out in order to optimise the process and predict product performances. Finally, a more comprehensive model may be needed for the prediction of the component fatigue life based on the surface microstructure and taking into account also the effect of the initial residual stresses on the life of the component under service.

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REFERENCES

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

[2] F. Jovane, H. Yoshikawa(1), L. Alting(1), C.R. Boër, E. Westkamper, D. Williams, M. Tseng, G. Seliger, A.M. Paci**,** The Incoming Global Technological and Industrial Revolution Towards Competitive Sustainable Manufacturing, CIRP Annals – Manuf. Technol., 57 (2) (2008) 641–659.

[3] A. Munoz, P. Sheng, Analytical Approach for Determining the Environmental Impact of Machining Processes, Journal of Materials Processing Technology, 53 (3) (1995) 736-758.

[4] J. Kopac, Achievements of sustainable manufacturing by machining, Journal of Achievement in Materials and Manufacturing Engineering, 34 (2) (2009) 180-187.

[5] R. Raki, Z. Raki, Tribological aspects of the choice of metalworking fluid in cutting processes, Journal of Materials Processing Technology, 124 (1-2) (2002) 25-31.

[6] S.Y. Hong, Z. Zhao, Thermal aspects, material considerations and cooling strategies in cryogenic machining, Clean Products and Processes 1 (1999) 107–116.

[7] R. W. Hertzberg, Deformation and Fracture Mechanics of Engineering Materials,

[8] K. S. Chan, A Microstructure-Based Fatigue-Crack-Initiation Model, Metallurgical and Materials Transactions 34 (A) (2003) 43–58.

[9] K. S. Chan, Roles of microstructure in fatigue crack initiation, International Journal of Fatigue 32 (2010) 1428–1447

[10] M.R. Mitchell, Fatigue and Microstructure, M. Meshii, ed., ASM, Metals Park, OH, (1978) 385-437.

[11] L.F. Coffin, Jr., Trans. ASME, 76 (1954) 931-50.

[12] L.FS.S. Manson, 1964, M.H. Hirschberg, Fatigue: An Inter-Disciplinary Approach, Syracuse University, Syracuse, NY, 133-78.