Machinability of Waspaloy under Different Cutting and Lubri-Cooling Conditions

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Abstract

Nickel-based super alloys are widely employed in critical applications, mainly in aerospace, marine and chemical industries, concerning the production of high performance artifacts. These alloys are considered as hard-to-cut materials, because of their modest machinability, so it is very difficult to implement in an industrial contest, high speed machining processes that can lead to higher quality products, with improved mechanical characteristics and higher dimensional accuracy, and increase productivity. Among these alloys stands out Waspaloy, thanks to its very high mechanical properties, such as stiffness and strength to weight ratio. In order to implement effective machining processes, it is important to analyze the behavior of the material during machining in terms of variables of industrial interest (forces, tool wear, etc.). The aim of this paper is to disclose the results of an experimental investigation aimed to determine the effects of different cutting parameters on cutting forces, chip morphology, tool wear and temperature at tool-chip interface, during orthogonal machining of Waspaloy (45 HRC). Experiments were performed in different lubri-cooling conditions (dry, wet and cryogenic) and at varying cutting conditions (cutting speed and feed rate).

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1. Introduction

Nickel-based super alloys are widely employed in applications where fatigue strength, thermal stability and corrosion resistance are required. These alloys are mainly used in aerospace industry and in other critical applications where the materials have to exhibit high performances, such as petrochemical plants, marine equipment and nuclear reactors [1]. In particular, due to their high creep resistance, nickel based super alloys are the base material for parts of aircraft engines, both static parts as well as the rotating elements, operating at high temperatures under the effect of mass forces. These parts of aircraft engines are manufactured by materials from the family of nickel and cobalt alloys; these are the precipitation-hardened alloys in which a specific type of macrostructure is produced. In general, the superior strength retention capability of super alloys is directly attributable to the presence of finely dispersed γ' precipitates in the austenitic γ phase. The mechanical integrity of components is therefore dependent on the size and distribution of γ' precipitates. Typically, these alloys resist to high operating temperatures, until 50–90% of melting temperature, while in service. In general, approximately 25–45% of these alloys are manufactured by using casting techniques, the remaining part of them are then finished by machining methods [2, 3]. Furthermore, machining represents one of the most important manufacturing processes, because it allows to obtain the required surface qualities for components operating in the above mentioned critical conditions. This clause is proving true also in the case of the components obtained by additive manufacturing processes: although they allow obtaining directly products close to the final shape, also defined as near-net-shape. Therefore, finishing or semi-finishing operations are necessary to achieve the surface quality and tolerance requirements, allowing machining to dominate among all manufacturing processes [4]. Obtaining feedback information during the cutting process is of fundamental importance to choose the optimum machining parameters to decrease process costs and time and allowing to obtain dimensional accuracy and ideal surface quality values [5-7]. Nickel super alloys are classified as hard-to-cut materials, because of the excessive heat generation during machining operations, high friction between tool-chip interface, tendency for Built-Up-Edge (BUE) formation and catastrophic failure of cutting edge [8].

During machining, a hardened layer due to induced thermo-mechanical loading, could form in the surface and subsurface of the workpiece, this latter could strongly affect the mechanical characteristics of the material [9]. Furthermore, due to the low thermal conductivity, the heat generated during the process cannot be rapidly dissipated and temperature in the cutting edge region can easily reach 1000 °C. This leads to excessive tool wear compromising tool life and surface quality [10-13]. Since nickel super alloys have been extensively used in the industrial context, different cooling techniques have been investigated to improve their machinability.

Thakur et al. [14] studied on dry machining of nickel-based super alloy using TiN/TiAlN coated tool as a sustainable alternative to the conventional cooling techniques. Ding et al. [15] investigated on the possibility to improve the machinability of Waspaloy via laser-assisted machining, through a more efficiently heat localization in order to soften the workpiece material prior to material removal and machining it with a conventional single-point cutting tool.

Kaynak [16] evaluated the process performance in cryogenic machining of Inconel 718 and compared his results with dry and MQL machining; machinability of Inconel 718 in turning processes can be improved by using cryogenic cooling and MQL with suitable cutting parameters. Cryogenic machining meets the actual needs of the industries to minimize their waste streams, in accordance with the governmental pollution-preventing initiatives, that focused the attention on the role of cutting fluids in machining, machine tool energy efficiency and the impact of process wastes on the environment. The advantages of the cryogenic coolant, when machining Inconel 718, have been widely presented and discussed in literature [17-20]. However, the benefits of the cryogenic coolant on machining of Waspaloy have not yet been demonstrated. Waspaloy is a nickel-based super alloy developed in the 1950s by Pratt and Whitney, mainly used for parts in turbines such as compressor discs, shafts and turbine cases [21]. During machining of this alloy, a particular high wear rate on the tool is observed, probably due to the high mechanical properties sustained at elevated temperatures, high work hardening and thermal properties that generate high cutting forces and temperatures [22]. Therefore, the study of the effectiveness of coolants and lubricants, such as oils, aqueous emulsions and cryogenic coolants, represents an important aspect that permits to control and reduce the high temperatures developed during Waspaloy machining [23]. For these reasons, the main objective of the present work is to give a contribute in this direction by comparing mechanical and thermal influence of cutting conditions (dry, wet and cryogenic) on cutting forces, tool wear, chip morphology and cutting temperatures at varying cutting parameters (cutting speed and feed rate) during orthogonal cutting of Waspaloy (45 HRC). Therefore, the machinability results of an extensive experimental activity will be presented and discussed.

2. Experimental Plan

Waspaloy disks of outer diameter 127 mm and thickness of 3 mm were bolted to a shaft and used as workpiece material. Orthogonal turning trials were performed in a random order, in order to get reliable results, three repetitions for each analyzed case were carried out (also randomized), using a MAZAK stiff high speed CNC turning center, by means of a radial facing operation. Test were performed using S quality rhomboidal 55° coated carbide tool with ISO code DNMG 15 06 12 - SMR S05F quality, mounted on a DDJNR 2525M 15 tool holder. The tool holder was held on a Kistler 9257 piezoelectric dynamometer, for forces detection: Fc (Cutting Force) and Ft (Thrust Force). A K-type thermo-couple, set in a slot behind the cutting tool, has been used to detect the local value of the cutting temperature beneath the cutting tool. Moreover, an infrared thermo-camera was used during the experiments to detect, having a known value of emissivity, the whole thermal field. In order to have a known and homogenous value of emissivity, the disks were painted using a black thermal-resistant paint. Taking into account that in wet conditions the lubricant could dilute the black paint on disks or affect the emissivity, the local temperature measured by thermocouple has been used to determine, by inverse numerical methodology, the temperature at the tool cutting edge as in [24]. Temperatures in cryogenic machining tests have been measured using both methodologies, avoiding the possibility that evaporating cryogenic vapors could affect the thermal fields measured by thermo-camera. Fig. 1 shows the experimental set up.

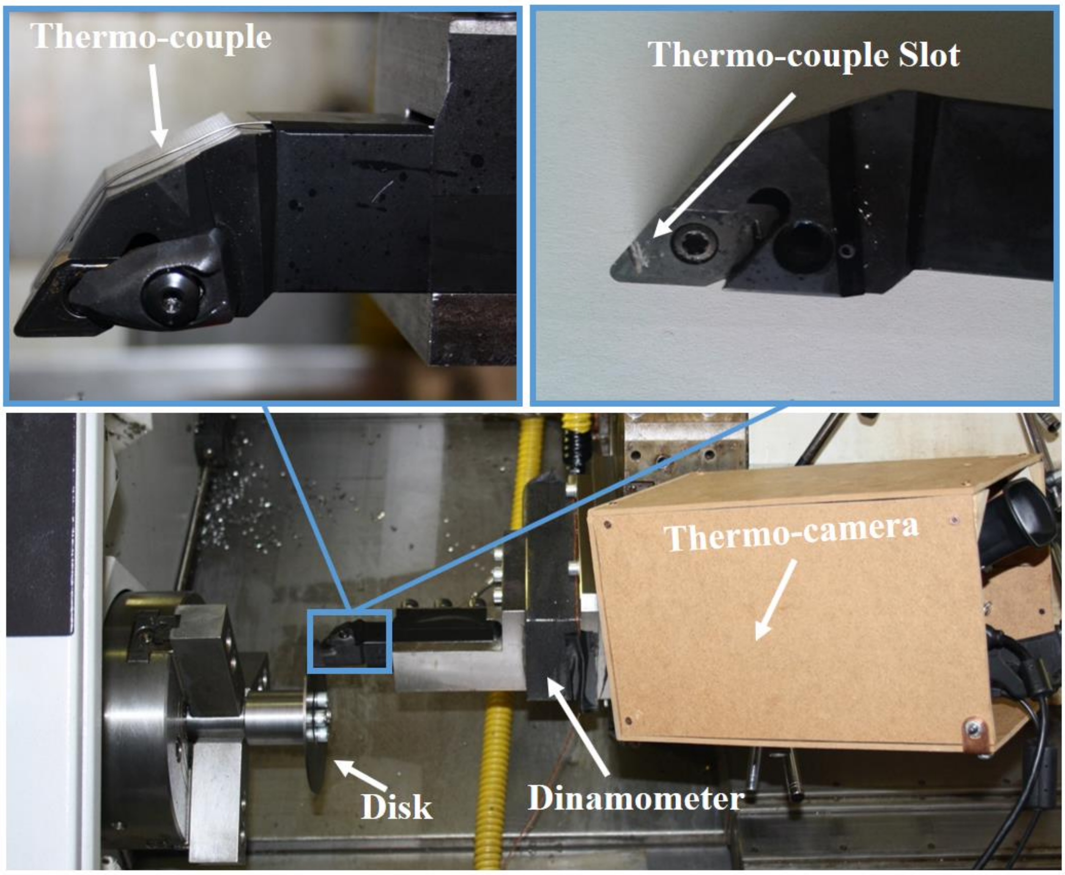
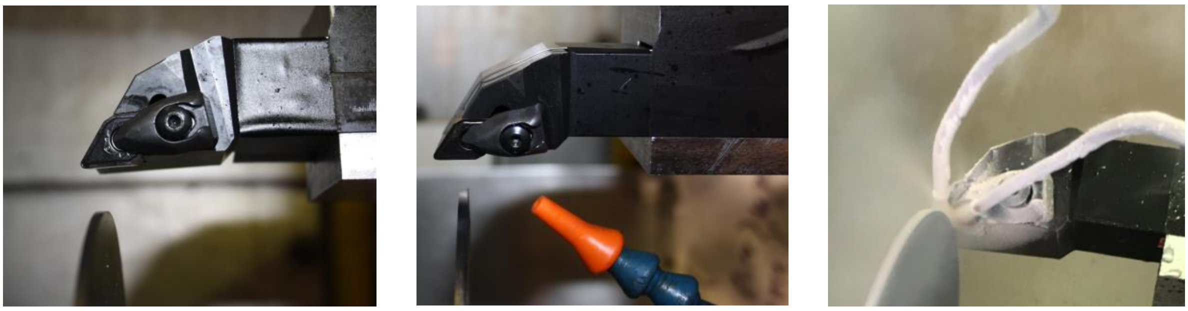


Fig. 1 Experimental set-up: orthogonal cutting with disk, dynamometer, thermo-couple and thermo-camera position.

Depending on the cutting parameters, the cutting time of the experiments ranged from 60 to 300 s in order to reach the steady state conditions and to avoid final outer diameter of the disks too close to the shaft. The experimental tests were performed under three different cutting conditions: dry, wet and cryogenic (cryo). In wet condition the lubri-coolant was applied by a nozzle to the area of interest, influencing all primary, secondary and tertiary shear zones. The lubri-coolant used in wet cutting condition was “Brugarolas Cutting Oil 4010062” at a flow rate ranging from 50 to 60 ml/s.

As shown in Fig. 2 (c), in cryogenic cutting condition a couple of nozzles was positioned reproducing the experimental set up used in [25]. The inner diameter of both nozzles in cryogenic lubri-cooling system was 2 mm and the pressure of liquid nitrogen was regulated at 9 bar. The nozzles were oriented to spray on the workpiece and not on the tool in order to have a consistent improving on surface quality of the machined part.



(a) (b) (c)

Fig. 2 Experimental set-up: a) dry orthogonal cutting, lubri-cooling nozzle position for b) wet and c) cryogenic experiments.

The experimental plan was based on nine different combinations of three levels of cutting speed and three levels of feed rate, either for dry, wet and cryogenic cooling conditions (Table 1), with a repeatability of three experiments for each test. For each test is reported the average value and the standard deviation (as error bar) of the three repetitions for each measured value.

Table 1. Experimental test conditions.

Cutting Speed [m/min]	**Feed Rate [mm/rev]**	**Cutting Condition**
40	0.05/0.10/0.15	Dry/Wet/Cryogenic
55	0.05/0.10/0.15	Dry/Wet/Cryogenic
70	0.05/0.10/0.15	Dry/Wet/Cryogenic

Chips have been mounted and processed for chip micro-morphology (peak, valley and pitch) analysis. Furthermore, tool wear analysis was carried out on the cutting tools. In particular, ten measurements were performed on each insert and the average tool wear rate was evaluated.

It is worth to point out that, the analysis on tool wear and chip morphology were performed using a LEICA DFC 320 optical microscope (1000x).

3. Experimental Results and Discussion

3.1. Cutting Forces

Fig. 3 shows the influence of cutting parameters (cutting speed and feed rate) on thrust (F_t) and cutting (F_c) forces during machining tests at feed rate of 0.05 mm/rev and 0.10 mm/rev. It is noted that, when the cutting speed raises from 40 m/min to 70 m/min in dry machining, an evident decrease of both cutting forces is registered up to 12%. In fact, with the increase of the cutting speed, higher temperatures are reached in the cutting zone, resulting in lower cutting forces for the material thermal softening phenomenon. In contrast the presence of the lubri-coolant, during wet and cryogenic cutting conditions, involves a slighter variation of the cutting forces with the increasing of the cutting speed, as visible from Fig. 3 (c) to Fig. 3 (f), since the lower is the temperature variation between the slighter and the severer cutting conditions. Detailed informations about temperature variation will be reported in Paragraph 3.4.

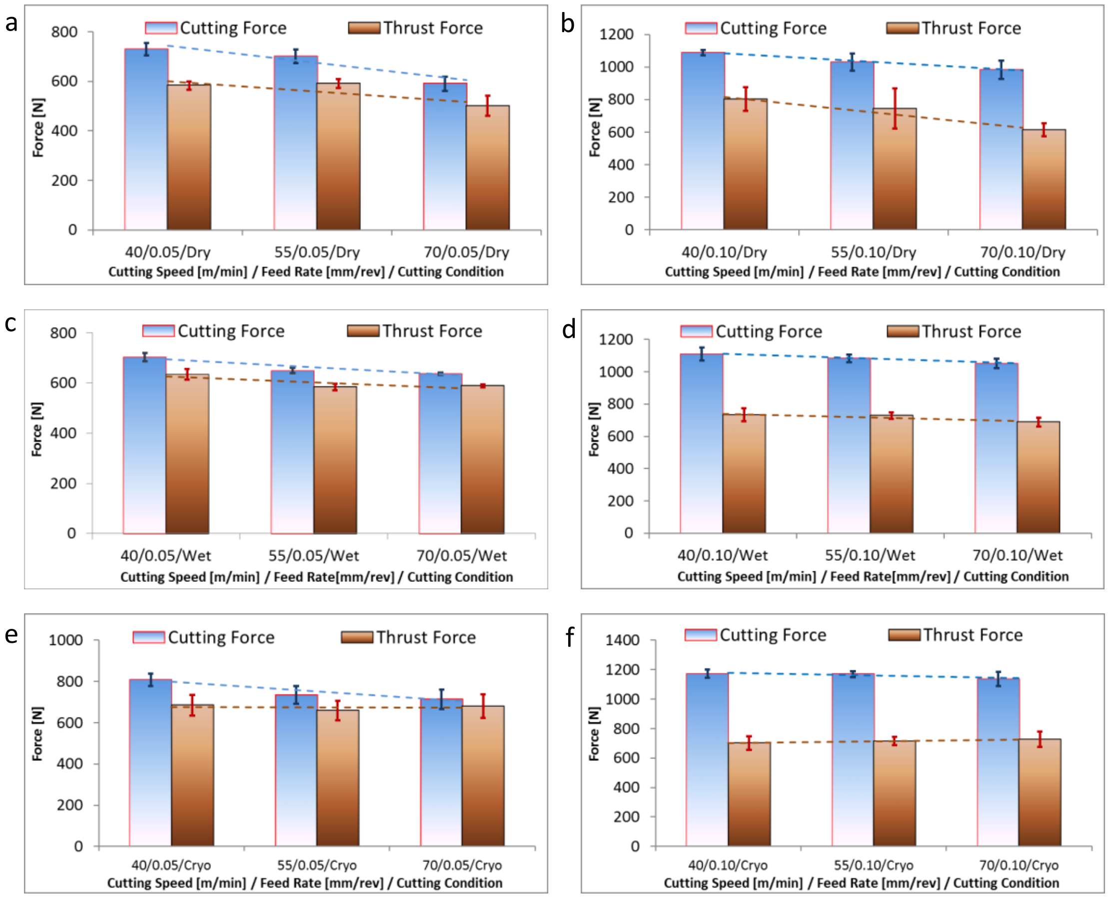
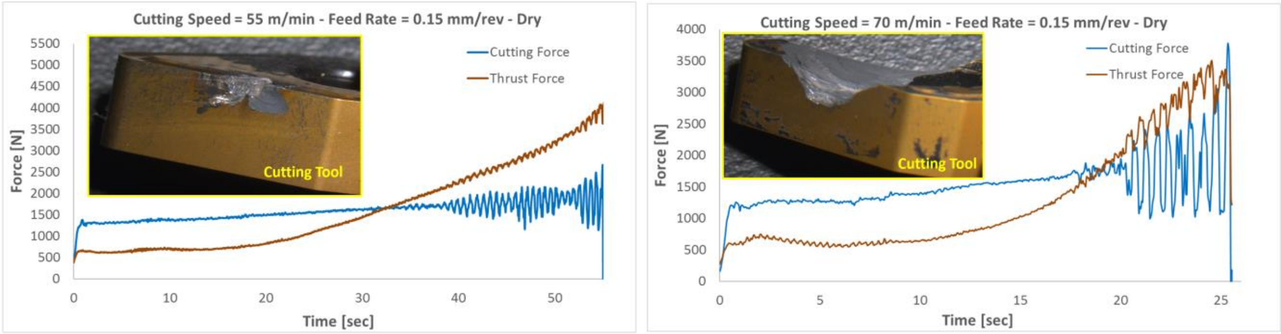


Fig. 3 Variation of cutting and thrust forces at varying cutting speed and feed rate of 0.05 rev/min a), c) and e) and 0.10 rev/min b), d) and f).

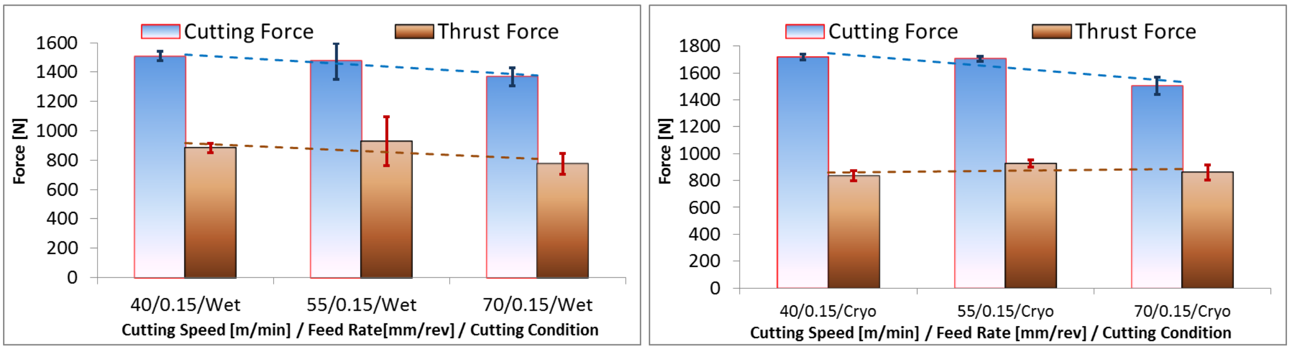
For what concern the dry machining tests at feed rate of 0.15 mm/rev and cutting speed of 55 and 70 m/min, these specific case studies shown an excessive wear that caused a premature catastrophic failure of the cutting tools, so they are not involved in any comparison of the different variables that have been analyzed in this research. The force recording of the experimental tests and the relative worn tools are reported in Fig. 4.



(a) (b)

Fig. 4 Forces registered during dry machining tests at feed rate of 0.15 mm/rev and at cutting speed of (a) 55 m/min and (b) 70 m/min.

In Fig. 5 cutting and thrust forces in wet and cryogenic machining condition at varying cutting speeds and at feed rate of 0.15 mm/rev are shown, as for the previous cases a decreasing trend is visible with the increasing of the cutting speed.



(a) (b)

Fig. 5 Variation of cutting and thrust forces at varying cutting speed and feed rate of 0.15 rev/min in (a) wet and (b) cryogenic condition.

An opposite trend is shown when the influence of the feed rate on cutting forces is considered, as reported in Fig. 6. In fact, with the increase of the feed rate, a considerable increase of both cutting forces is registered under all different cooling conditions. In particular, an increase of the 100% is registered for the cutting force (F_c) when feed rate increases from 0.05 mm/rev to 0.15 mm/rev. In this case the mechanical aspect, related to the increased removed material thickness and the increasing the tool wear (as shown in the next paragraph), is more influent than the thermal aspect.

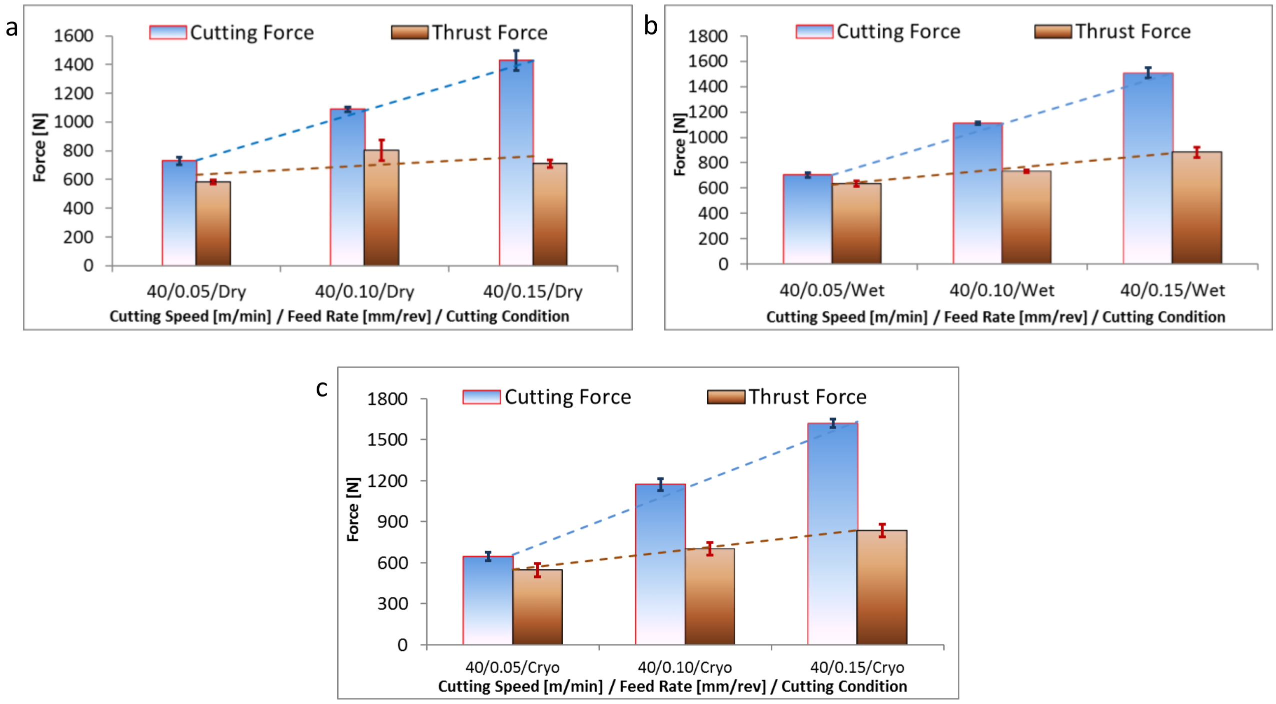
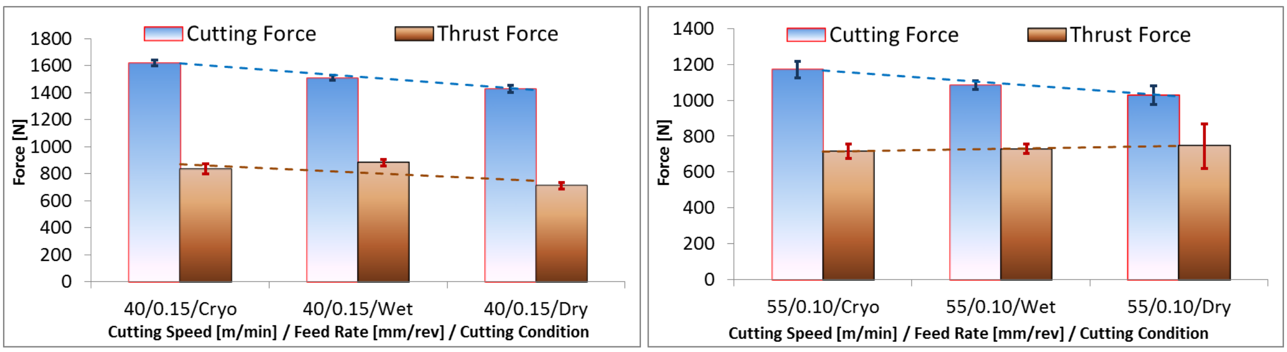


Fig. 6 Variation of cutting and thrust forces at varying feed rate in (a) dry, (b) wet and (c) cryogenic cutting condition.

Finally, the experimental results show that the application of lubricant (Fig. 7) has an important influence on cutting and thrust forces with an increment of about 10% for both cutting forces mainly due to the lower heat concentration at the tool-chip interface.



(a) (b)

Fig. 7 Variation of cutting and thrust forces at varying cutting conditions: (a) V=40 m/min and f= 0.15 mm/rev; (b) V=55 m/min and f= 0.10 mm/rev.

3.2. Tool Wear

Fig. 8 shows the wear length measurement, obtained by optical microscope, while Fig. 9 reports the influence of cutting speed, feed rate and cooling conditions on the tool wear rate. The results show a slight influence of the cutting speed on the tool wear rate for the cutting parameters and lubri-cooling conditions which have not showed catastrophic tool failure. This is strictly related to the small increase of consecutive cutting speed values (only 15 m/min) that do not allow a significant change in thermal field as reported in Paragraph 3.4, especially when lubri-coolants are used. On the contrary the results report an evident influence of feed rate for all the investigated cooling conditions, showing a considerable increase, of about 4-5 times, in the tool wear rate when feed rate increases from 0.05 mm/rev to 0.15 mm/rev. This is mainly due to the increase of the contact area between cutting tool and disks and to the increase of the thickness of the removed material, since orthogonal cutting was performed. Finally, the use of wet cooling systems produces a benefit, reducing the tool wear rate when compared with dry machining condition, as visible in Fig. 9 (d), because of minute capillaries of lubricant, formed at the tool-chip interface, resulting in gentle frictional conditions and consequently reduced cutting temperatures. While in cryogenic cutting condition the high tool wear rate is related to the excessive lower temperature reached by the workpiece due to cryogenic lubri-coolant, that contemporary reduces the cutting temperatures but increases the mechanical resistance of the material. Furthermore, the nozzles configuration was mostly oriented on the workpiece and on the machined surface instead of the tool, since in future analysis the effects of lubri-cooling conditions on the surface integrity will be investigated. This has not permitted to the cryogenic fluid to operate as usually happens when it is sprayed directly on the tool [20].

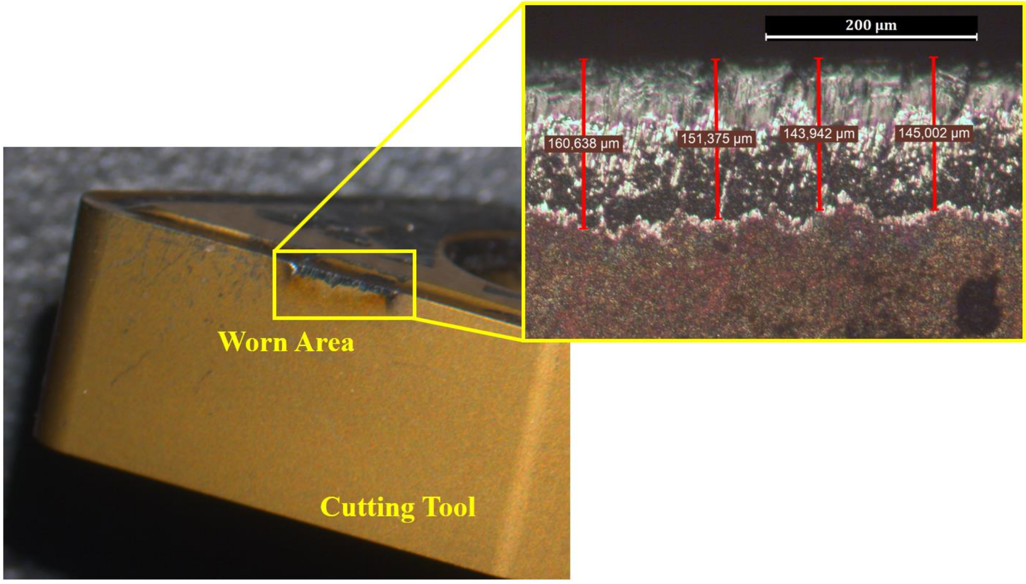


Fig. 8 Wear length measurement (V = 40 m/min - f = 0.15 mm/rev - Dry).

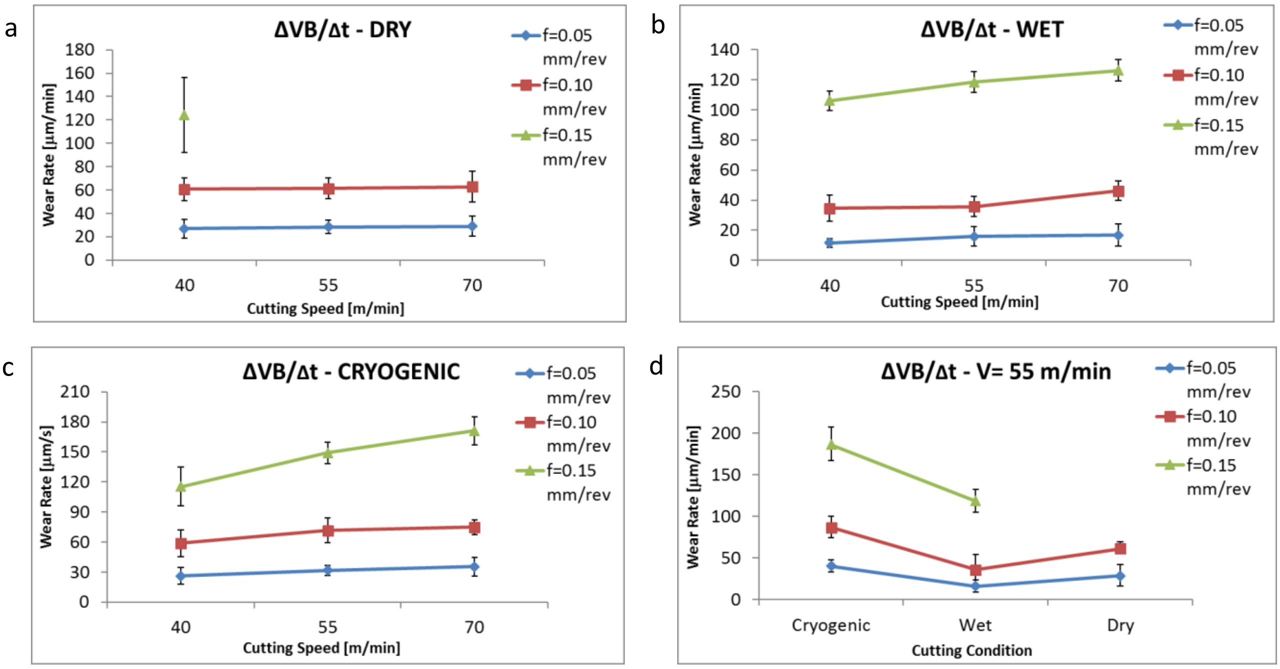


Fig. 9 Variation of tool wear rate at varying a), b) and c) cutting speed and feed rate, d) cooling condition.

3.3. Chip Morphology

As visible in Fig. 10, the chip results more fragmented when the cutting parameters (cutting speed and feed rate) increase, while considering the different lubri-cooling conditions, the chip fragmentation increases from dry to cryogenic conditions. These results are in accordance with the literature [26] and to those experimentally found by Pusavec et al. [18] on similar difficult to cut materials.

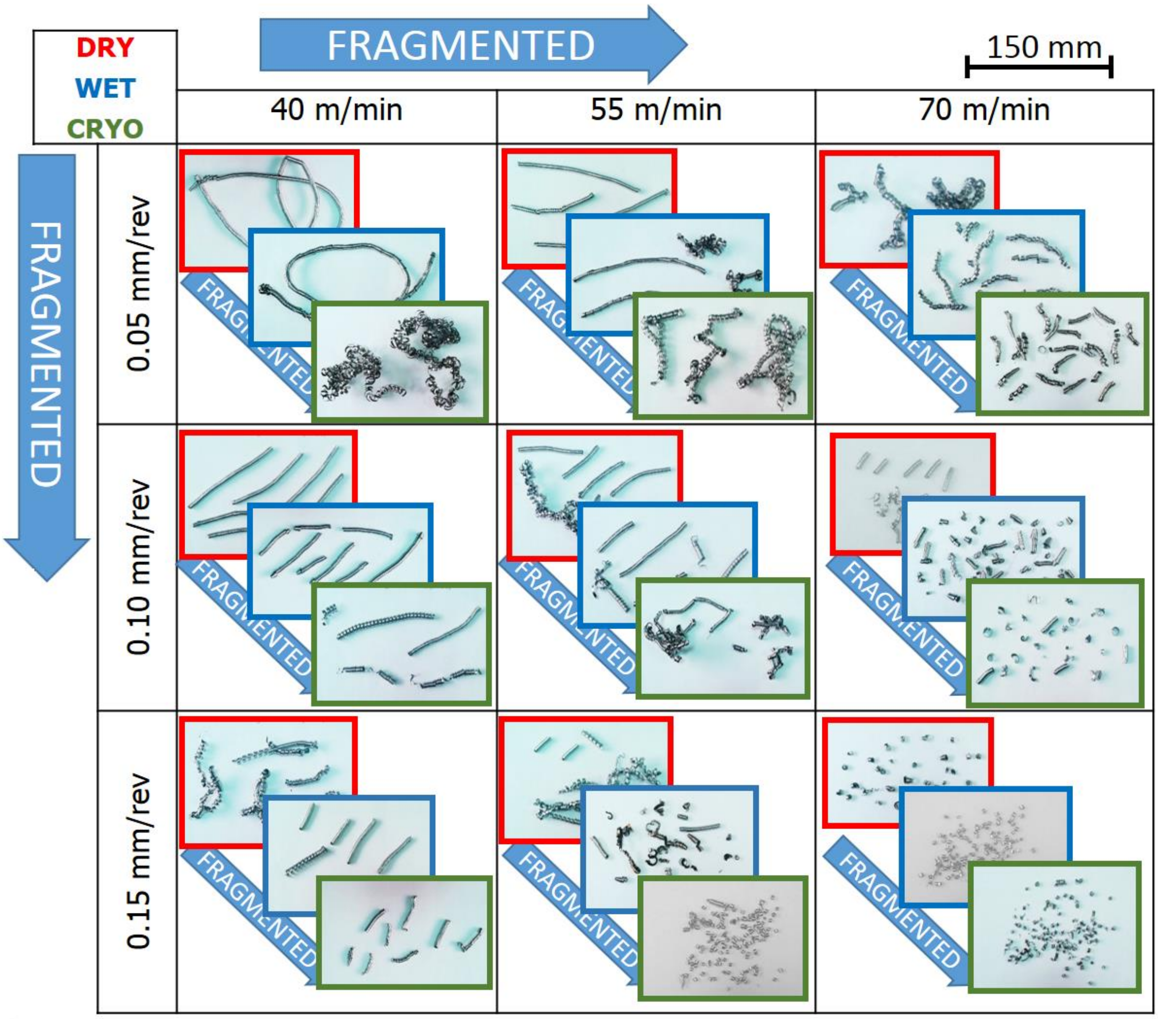


Fig. 10 Chip fragmentation at varying cutting speed, feed rate and at different lubri-cooling conditions.

Fig. 11 shows the influence of cutting speed, feed rate and cooling conditions on chip micro-morphology, in terms of peak, valley and pitch. For all the investigated cooling conditions with the increase of feed rate an increase of chip peak, valley and pitch is registered. In particular, with the increase of feed rate from 0.05 mm/rev to 0.15 mm/rev an increase of about 100 μm for both chip peak and chip valley is reported, while an increment of 60 μm is reported when chip pitch is considered. On the contrary, with the increase of cutting speed a slight decrease of about 20 μm for chip peak, valley and pitch is registered in all the investigated cooling conditions.

Taking into account lubri-cooling condition, the experimental results show the highest and the lowest chip peak, valley and pitch values respectively for cryogenic and dry machining.

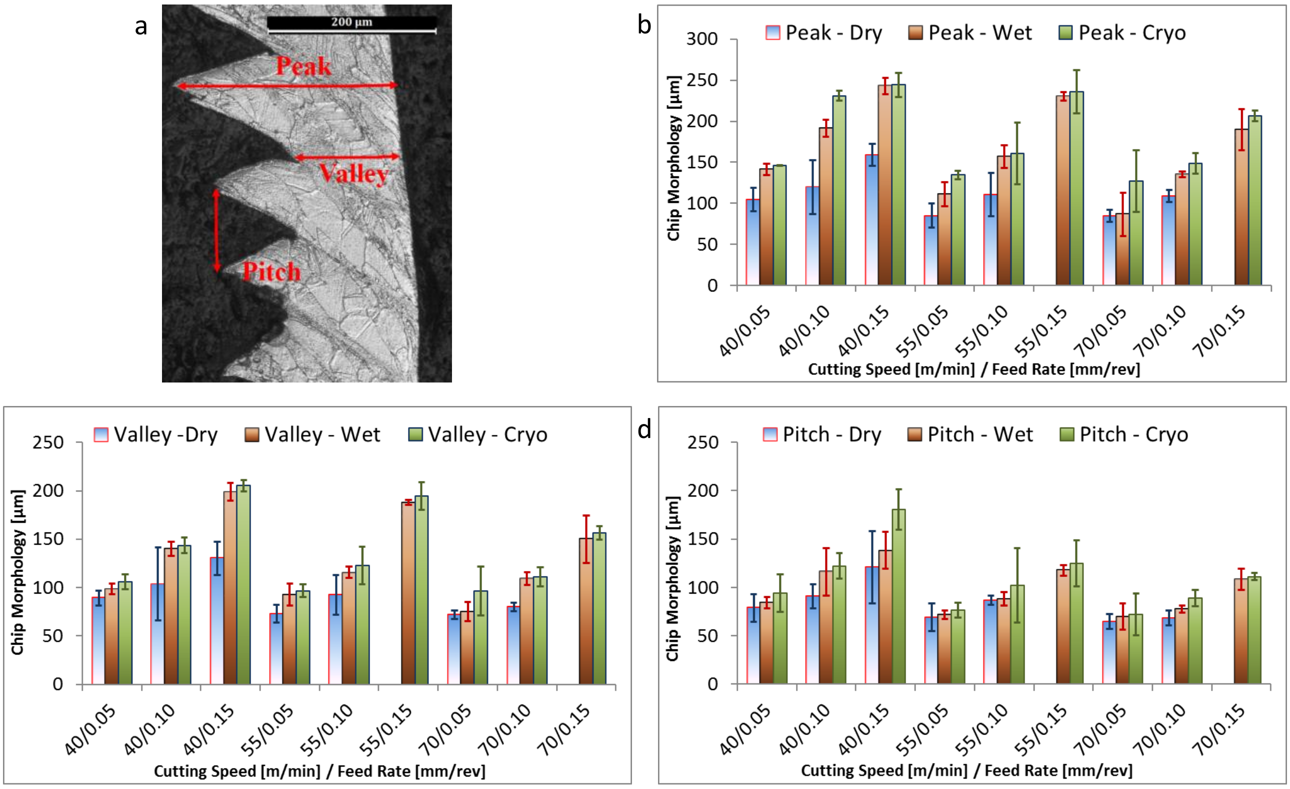


Fig. 11 Chip micro-morphology parameters (V=70 m/min - f=0.15 mm/rev - Cryo) (a) and variation of peak (b), valley (c) and pitch (d) at varying cutting parameters and cooling conditions.

The increasing of the cutting speed and the decreasing of the cooling effects cause the increasing of cutting temperatures, causing thermal softening on the worked material. This phenomenon promotes heat concentration on the local shear effect during chip formation [27], that is the cause of peak, valley and pitch decreasing trends.

3.4. Cutting Temperatures

Comparison of temperatures is often based upon the maximum temperatures measured on the tool rake face [28].

In Fig. 12 the temperature fields at the tool-chip interface, recorded by thermo-camera in dry and cryogenic machining conditions, are shown. Furthermore, the reference areas for temperature measurements are highlighted.

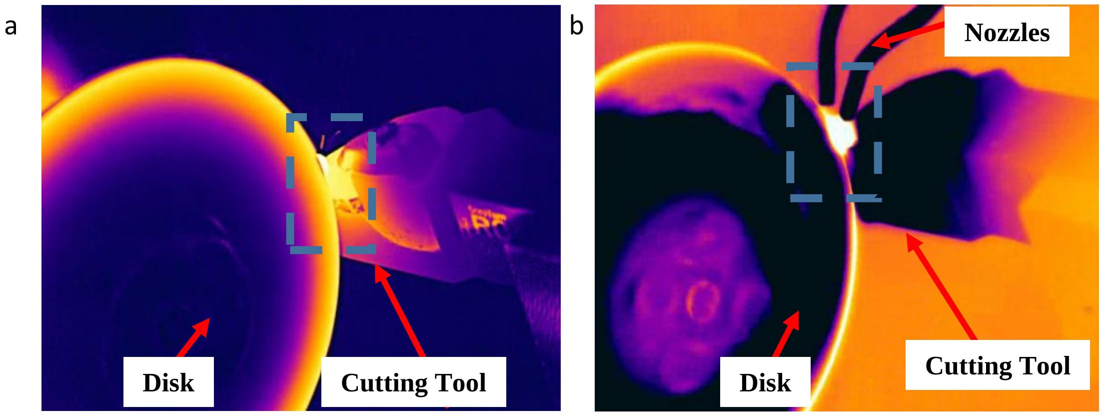


Fig. 12 Temperature fields in the reference area for a) dry machining and b) cryogenic machining condition.

In Fig. 13 the obtained results for all the investigated cutting conditions are shown. By comparing wet cutting conditions with dry machining a low reduction of cutting temperatures is shown at the tool-chip interface, ranging from 6% up to 16%, due to minute capillaries of lubricant formed at the tool chip interface that reduce the friction contribution. While during cryogenic machining, a high cutting temperatures reduction, ranging from 64% to 76%, is registered if compared with dry machining. As overall, an increase of cutting temperatures is observed with the increase of cutting speed and feed rate.

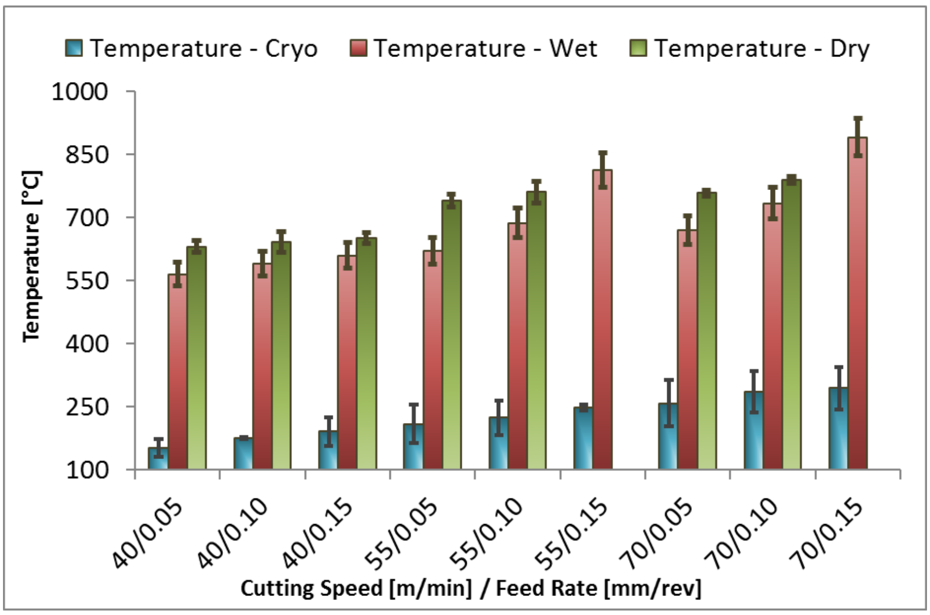


Fig. 13 Measured temperatures at tool-chip interface.

4. Conclusions and Future Works

Experimental observations reported in the present work suggest that the correct choice of cutting parameters and lubri-cooling condition in orthogonal cutting of Waspaloy significantly affects the studied aspects, leading to following major conclusions:

- Cutting forces are slightly influenced by cutting speed, while the employing of lubri-coolants and the increasing of feed rate cause a substantial rising.

- Tool wear rate is weakly influenced by cutting speed variation, while it is critically affected by feed rate. Wet lubri-cooling conditions cause a reduction in tool wear rate, while the employment of cryogenic fluid, causes an increasing in mechanical resistance of the workpiece, badly affecting the tool wear rate. This effect is mainly due to the lubri-coolant that was sprayed directly on the workpiece instead of the cutting tool, in order to have a significant improving in surface quality that will be meticulously studied.

- An increasing trend in chip morphology (in terms of peak, valley and pitch) has been showed with the decreasing of cutting speed and the increasing of feed rate. Similarly, different lubri-cooling conditions cause an increasing trend, a slighter trend is observed in wet conditions, while a broader one is shown in cryogenic conditions. Concerning chip breakability, severer machining conditions improve this phenomenon; similar effect is visible in lubri-cooling conditions going from dry to cryogenic.

- Temperatures at tool-chip interface are weakly influenced by the increasing of cutting speed, while a broad increasing trend is visible with the increasing of feed rate. Lubri-coolants influence the cutting temperatures, a weaker influence was detected in wet condition, while in cryogenic conditions the influence was stronger.

Concerning machinability, while wet and cryogenic conditions allow machining using all the studied combinations of cutting parameters, in dry cutting some combinations are not possible. In particular, except for the cutting speed of 40 m/min, the other speeds (55 and 70 m/min) exhibited catastrophic tool failure at a feed rate of 0.15 mm/rev. Therefore, in order to implement the analysed manufacturing process at higher cutting parameters, a lubri-cooling technique must be employed.

References

[1] Thakur A, Gangopadhyay S (2016) State-of-the-art in surface integrity in machining of nickel-based super alloys. International Journal of Machine Tools & Manufacture 100 25–54

[2] Ezugwu EO, Bonney J, Yamane Y (2003) An overview of the machinability of aero-engine alloys. J. Mater. Process. Technol. 134 233–253

[3] Del Prete A, Primo T, Franchi R (2013) Super-Nickel Orthogonal Turning Operations Optimization. Elsevier Publication Procedia CIRP, Volume 8, pp 163-168

[4] Del Prete A, De Vitis A, Filice L, Caruso S, Umbrello D (2012) Tool Engage Investigation in Nickel Superalloy Turning Operations. Key Engineering Materials, 504-506 pp 1305-1310

[5] Del Prete A, De Vitis A, Anglani A (2010) Roughness Improvement in Machining Operations Through coupled Metamodel and Genetic Algorithm Technique. International Journal of Material Forming

[6] Devillez A, Schneider F, Dominiak S, Dudzinski D, Barrouquere D (2007) Cutting forces and wear in dry machining of Inconel 718 with coated carbide tools. Wear 262, pp 931–942

[7] Motorcu AR, Kus A, Durgun I (2014) The evaluation of the effects of control factors on surface roughness in the drilling of Waspaloy superalloy. Measurement 58 pp 394–408

[8] Venkatesan K, Ramanujam R, Kuppan P (2014) Laser Assisted Machining of difficult to cut materials: Research Opportunities and Future Directions - A comprehensive review. Procedia Engineering 97 pp 1626 – 1636

[9] Ulutan D, Ozel T (2011) Machining induced surface integrity in titanium and nickel alloys: A review. International Journal of Machine Tools & Manufacture 51, pp 250–280

[10] Zhu D, Zhang X, Ding H (2013) Tool wear characteristics in machining of nickel-based superalloys. International Journal of Machine Tools & Manufacture 64, pp 60–77

[11] Cantero JL, Dìaz-Àlvarez J, Miguélez MH, Marìn NC (2013) Analysis of tool wear patterns in finishing turning of Inconel 718. Wear 297, pp 885–894

[12] Khan SA, Soo SL, Aspinwall DK, Sage C, Harden P, Fleming M, White A, M’Saoubi R (2012) Tool wear/life evaluation when finish turning Inconel 718 using PCBN tooling. Procedia CIRP 1, pp 283-288

[13] Del Prete A, De Vitis A, Franchi R (2012) Numerical-experimental correlation of distortions induced by machining process on thin-walled nickel super alloy forged components. Key Engineering Materials Vols. 504-506, pp 1299-1304

[14] Thakur A, Gangopadhyay S (2016) Dry machining of nickel-based super alloy as a sustainable alternative using TiN/TiAlN coated tool. Journal of Cleaner Production 129, pp 256-268

[15] Ding H, Shin YC (2013) Improvement of machinability of Waspaloy via laser-assisted machining. International Journal of Advanced Manufacturing Technology 64, pp 475–486

[16] Kaynak Y (2014) Evaluation of machining performance in cryogenic machining of Inconel 718 and comparison with dry and MQL machining. International Journal of Advanced Manufacturing Technology 72, pp 919–933

[17] Pusavec F, Deshpande A, Yang S, M'Saoubi R, Kopac J, Dillon OWJ, Jawahir IS (2014) Sustainable machining of high temperature Nickel alloy e Inconel 718: part 1 - predictive performance models. Journal of Cleaner Production 81, 255-269

[18] Pusavec F, Deshpande A, Yang S, M'Saoubi R, Kopac J, Dillon OWJ, Jawahir IS (2014) Sustainable machining of high temperature Nickel alloy e Inconel 718: part 2 - chip breakability and optimization. Journal of Cleaner Production 87, pp 941-952

[19] Ezugwu EO (2005) Key improvements in the machining of difficult-to-cut aerospace superalloys. International Journal of Machine Tools & Manufacture 45, pp 1353–1367

[20] Jawahir IS, Attia H, Biermann D, Duflou J, Klocke F, Meyer D, Newman ST, Pusavec F, Putz M, Rech J, Schulze V, Umbrello D (2016) Cryogenic manufacturing processes. CIRP Annals - Manufacturing Technology 65, pp 713–736

[21] Olovsjö S, Nyborg L (2012) Influence of microstructure on wear behavior of uncoated WC tools in turning of Alloy 718 and Waspaloy. Wear 282–283

[22] Reed RC (2006) The Superalloys. Cambridge University press, Cambridge

[23] Pusavec F, Kopac J, (2011) Sustainability assessment: cryogenic machining of Inconel 718. J. Mech. Eng. 57, pp 637-647

[24] Umbrello D, Filice L, Rizzuti S, Micari F, Settineri L (2007) On the effectiveness of Finite Element simulation of orthogonal cutting with particular reference to temperature prediction. Journal of Materials Processing Technology 189, pp 284–291

[25] Umbrello D, Yang S, Dillon OWJ, Jawahir IS (2012) Effects of cryogenic cooling on surface layer alterations in machining of AISI 52100 steels. Material Science and Technology 28, pp 1320–1331

[26] Grzesik W (2008) Advanced Machining Processes of Metallic Materials. Theory, Modelling and Applications. Elsevier p 108.

[27] Poulachon G, Moisan A, Jawahir IS (2001) On modelling the influence of thermo-mechanical behavior in chip formation during hard turning of 100Cr6 bearing steel. Annals of the CIRP 50 (1), pp 31-36

[28] Davies MA, Cooke AL, Larsen ER (2005) High bandwidth thermal microscopy of machining AISI 1045 steel. Annals of the CIRP 54 (1), pp. 63-66

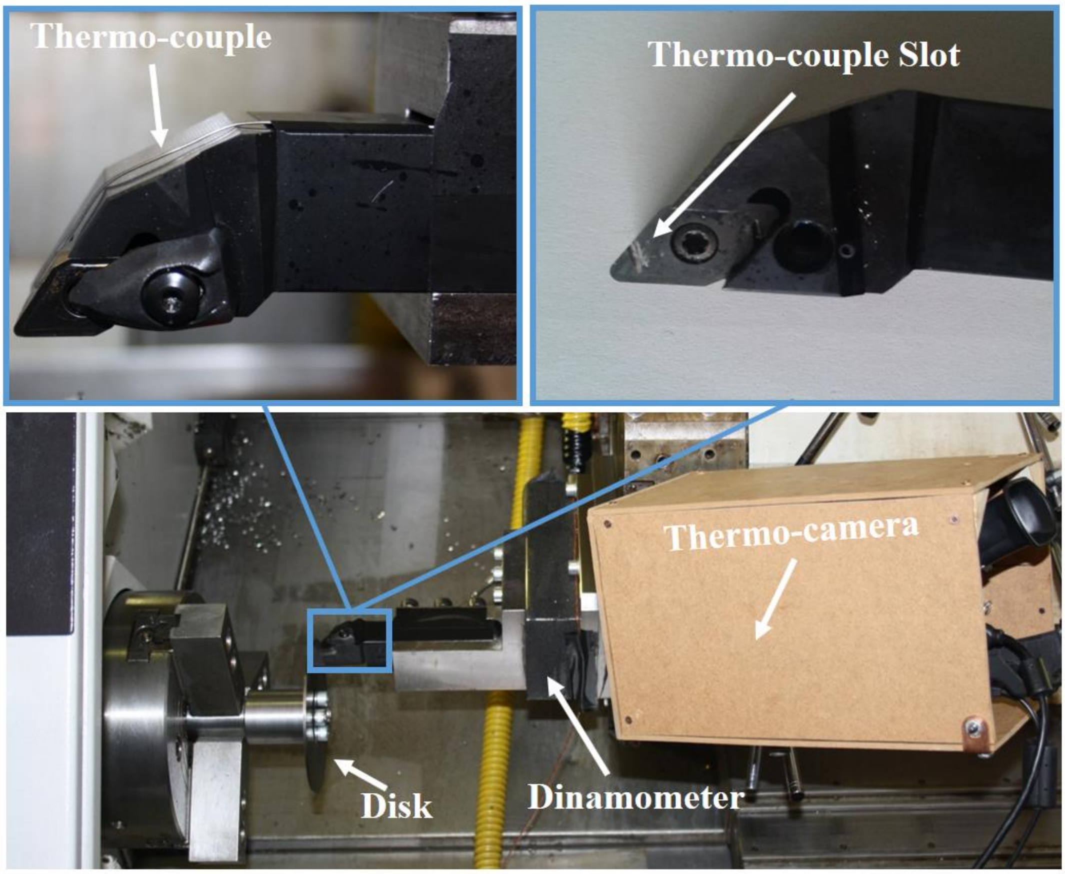
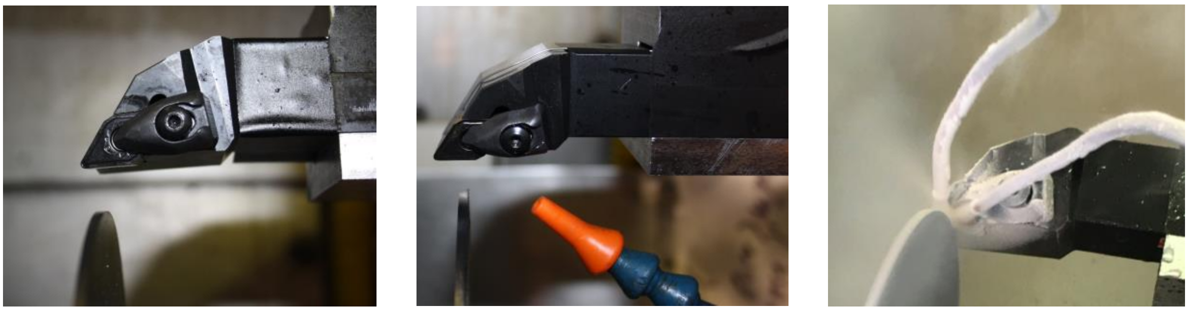


Fig. 1 Experimental set-up: orthogonal cutting with disk, dynamometer, thermo-couple and thermo-camera position.



(a) (b) (c)

Fig. 2 Experimental set-up: a) dry orthogonal cutting, lubri-cooling nozzle position for b) wet and c) cryogenic experiments.

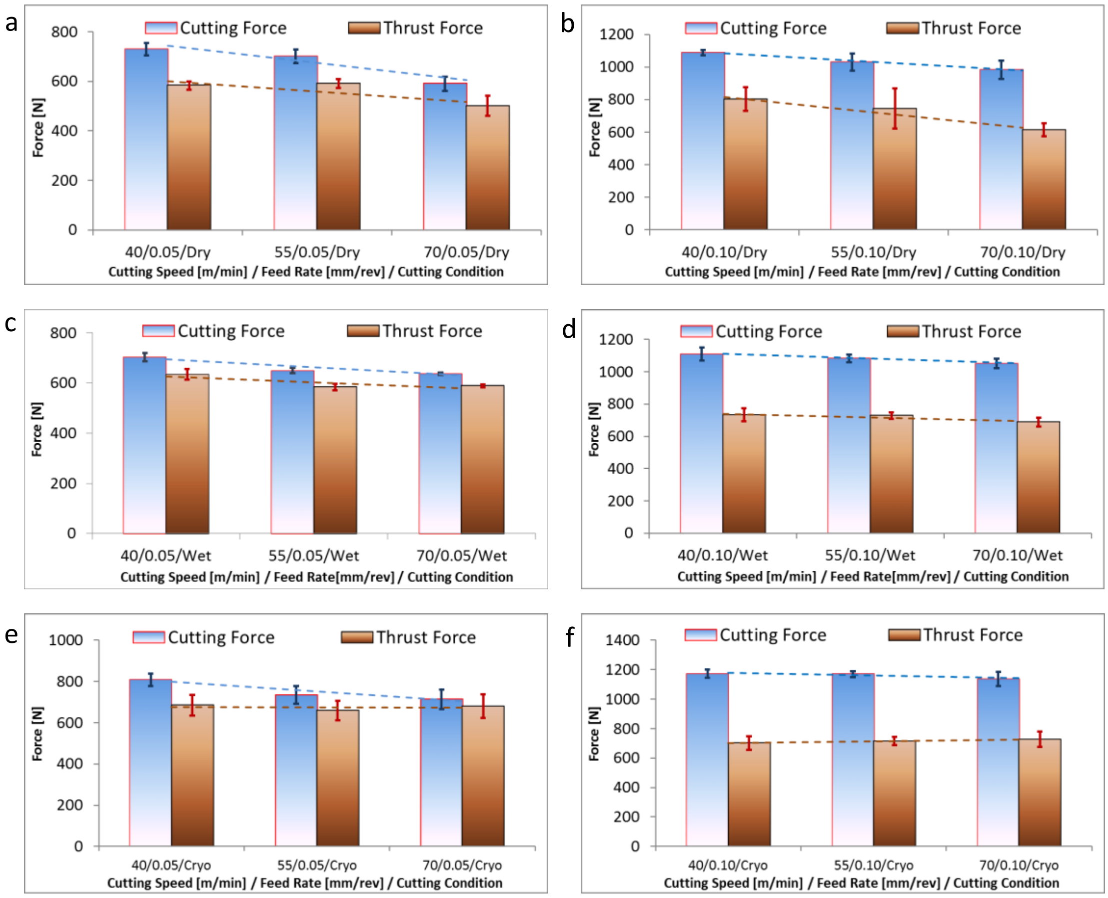
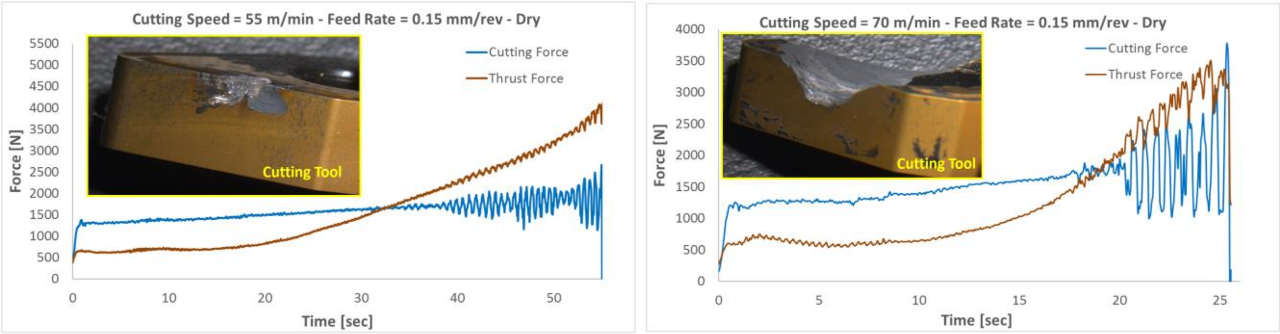
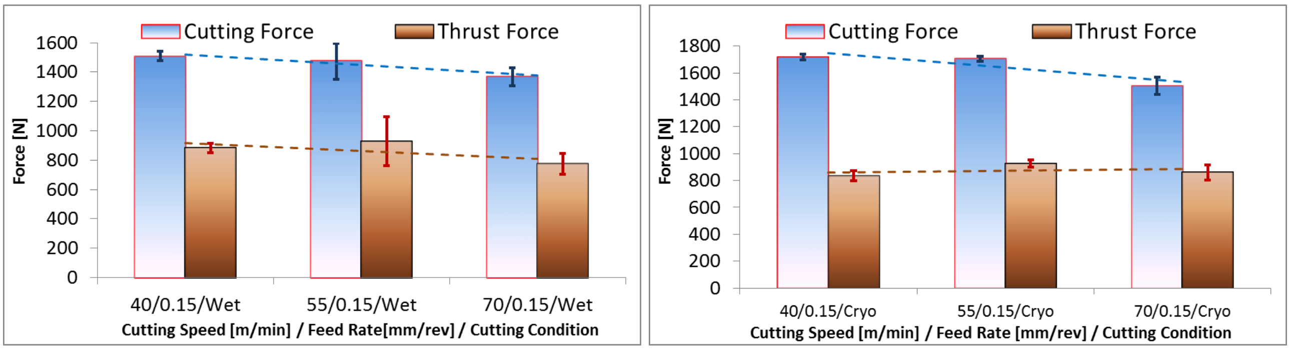


Fig. 3 Variation of cutting and thrust forces at varying cutting speed and feed rate of 0.05 rev/min a), c) and e) and 0.10 rev/min b), d) and f).



(a) (b)

Fig. 4 Forces registered during dry machining tests at feed rate of 0.15 mm/rev and at cutting speed of (a) 55 m/min and (b) 70 m/min.



(a) (b)

Fig. 5 Variation of cutting and thrust forces at varying cutting speed and feed rate of 0.15 rev/min in (a) wet and (b) cryogenic condition.

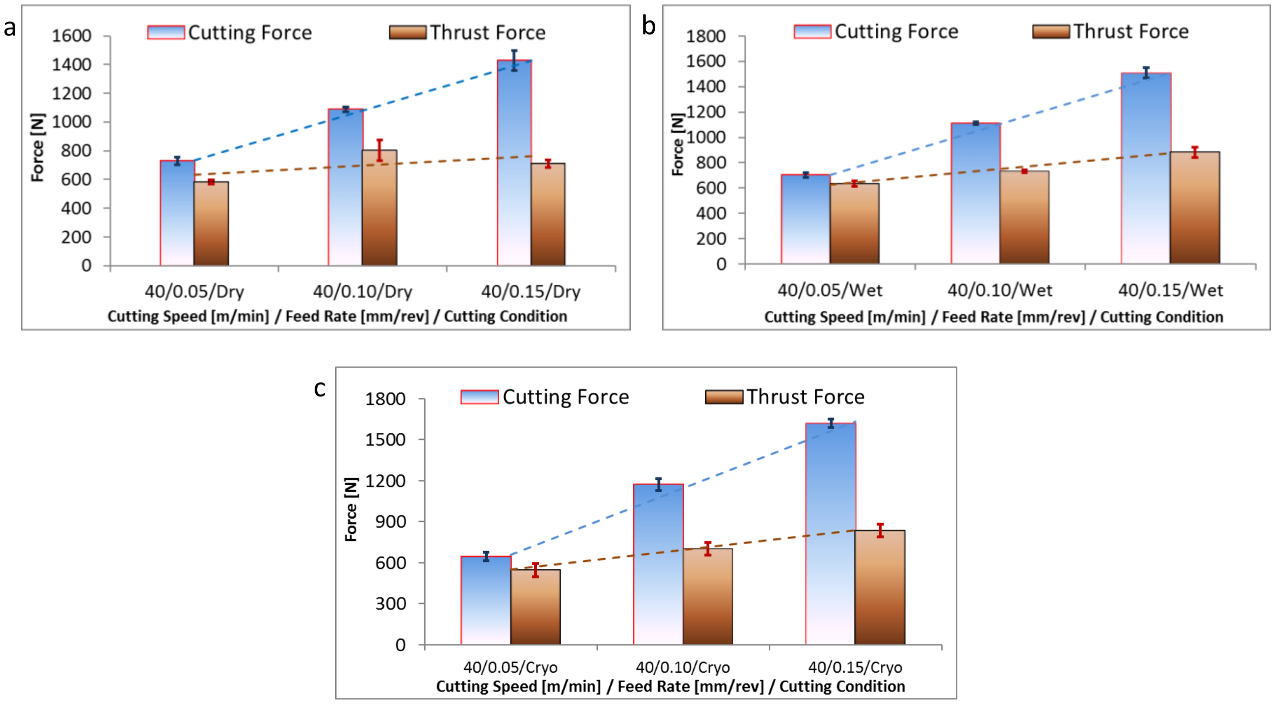
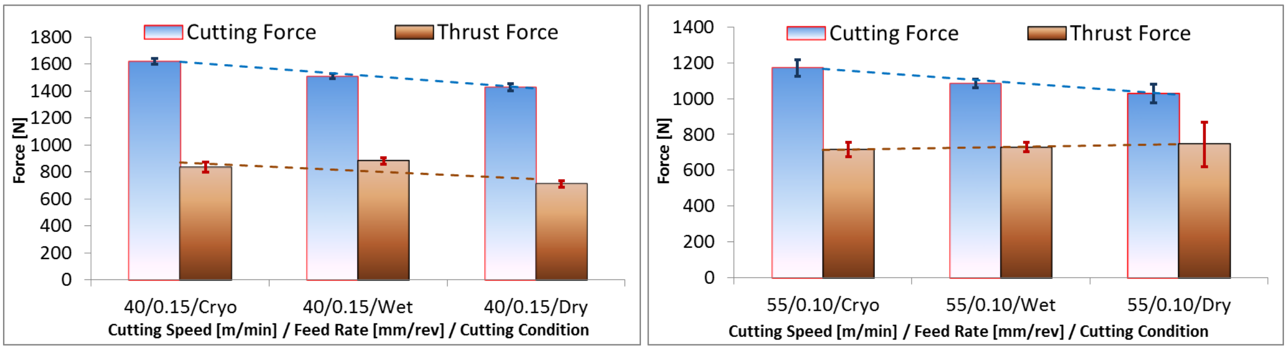


Fig. 6 Variation of cutting and thrust forces at varying feed rate in (a) dry, (b) wet and (c) cryogenic cutting condition.



(a) (b)

Fig. 7 Variation of cutting and thrust forces at varying cutting conditions: (a) V=40 m/min and f= 0.15 mm/rev; (b) V=55 m/min and f= 0.10 mm/rev.

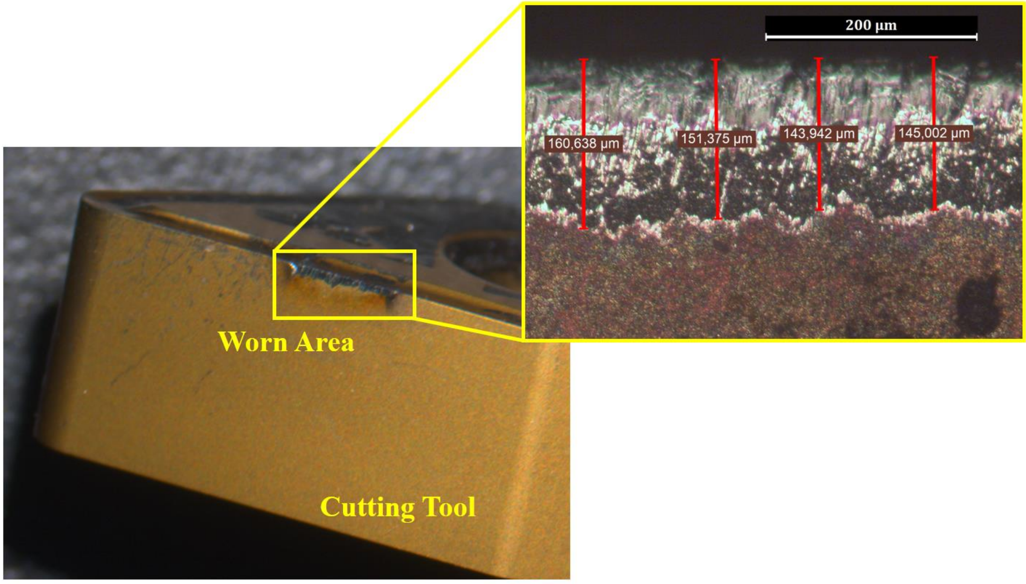


Fig. 8 Wear length measurement (V = 40 m/min - f = 0.15 mm/rev - Dry).

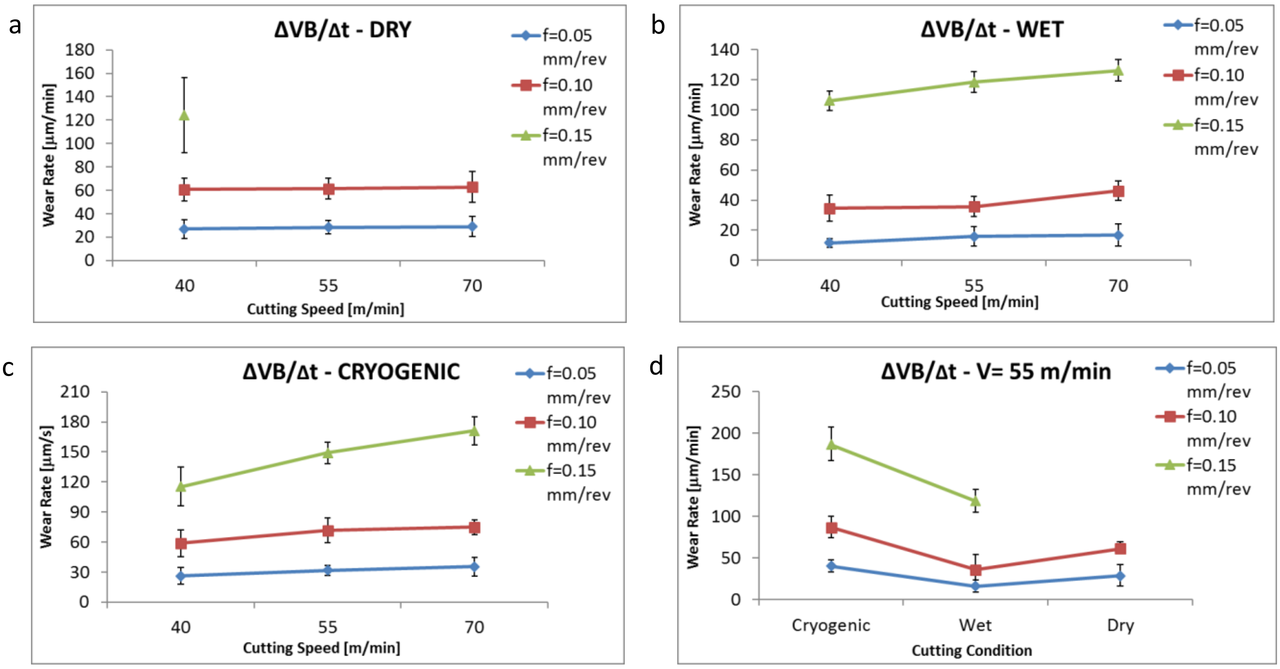


Fig. 9 Variation of tool wear rate at varying a), b) and c) cutting speed and feed rate, d) cooling condition.

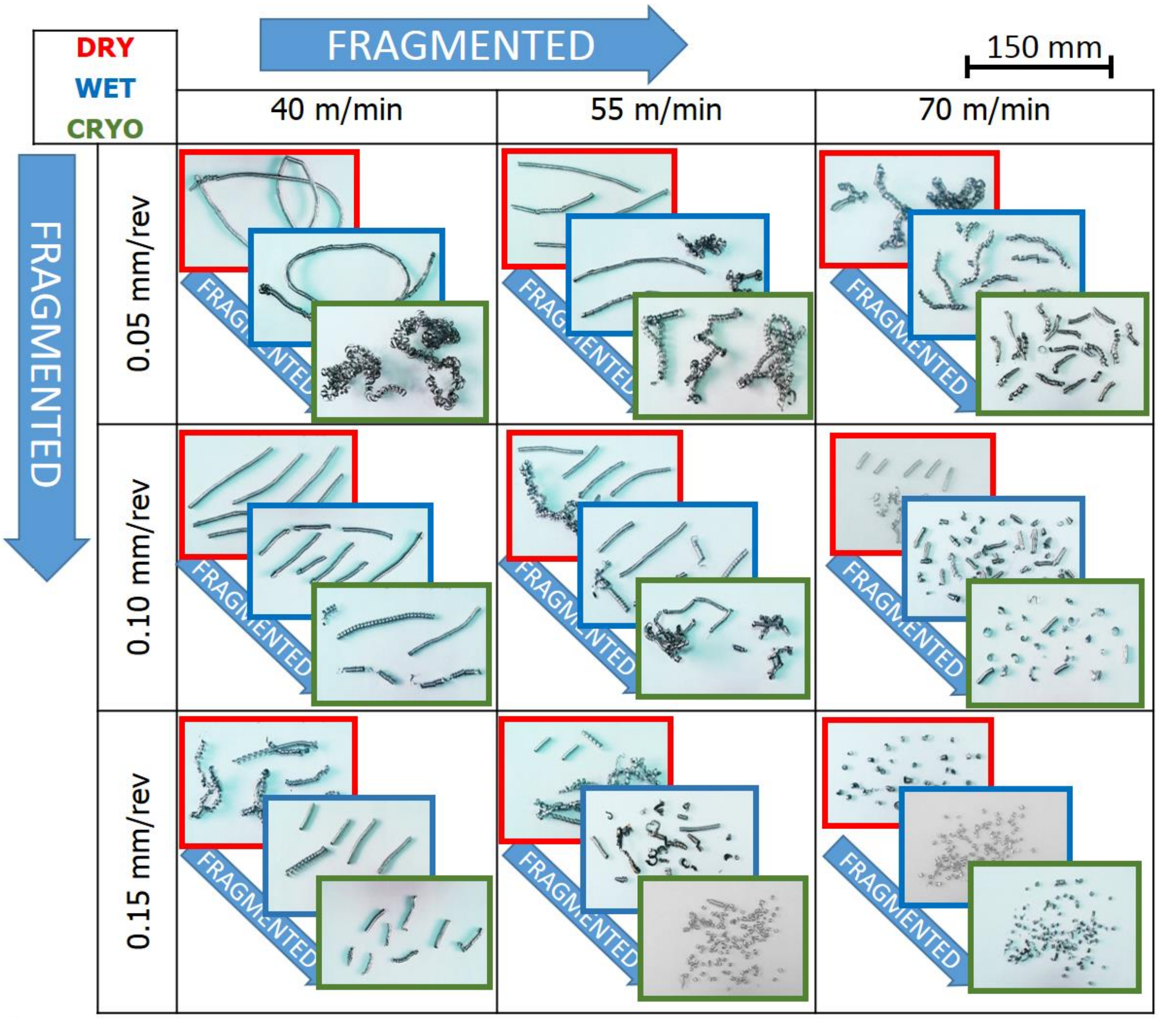


Fig. 10 Chip fragmentation at varying cutting speed, feed rate and at different lubri-cooling conditions.

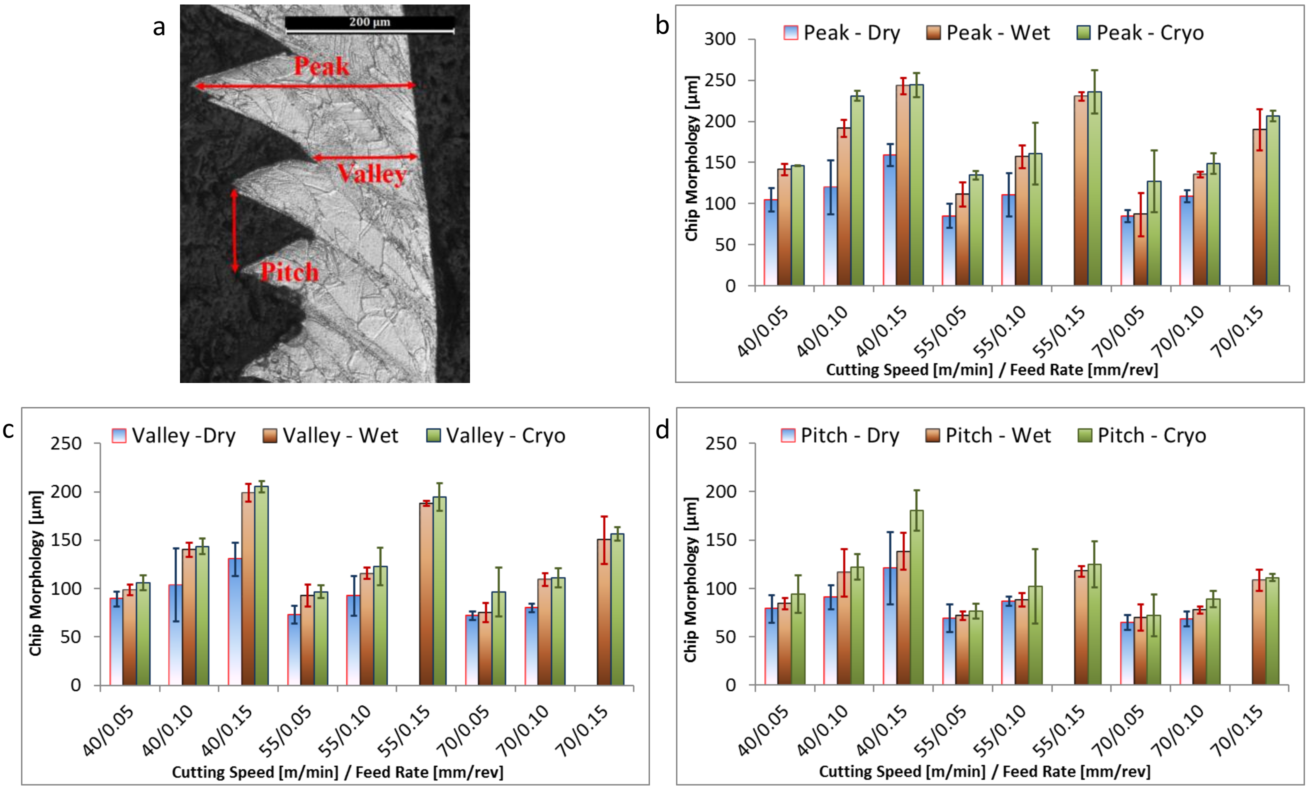


Fig. 11 Chip micro-morphology parameters (V=70 m/min - f=0.15 mm/rev - Cryo) (a) and variation of peak (b), valley (c) and pitch (d) at varying cutting parameters and cooling conditions.

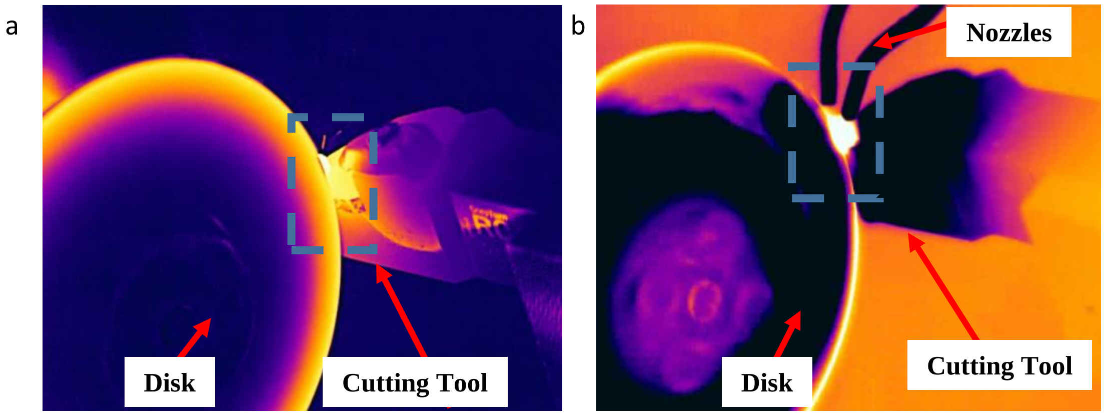


Fig. 12 Temperature fields in the reference area for a) dry machining and b) cryogenic machining condition.

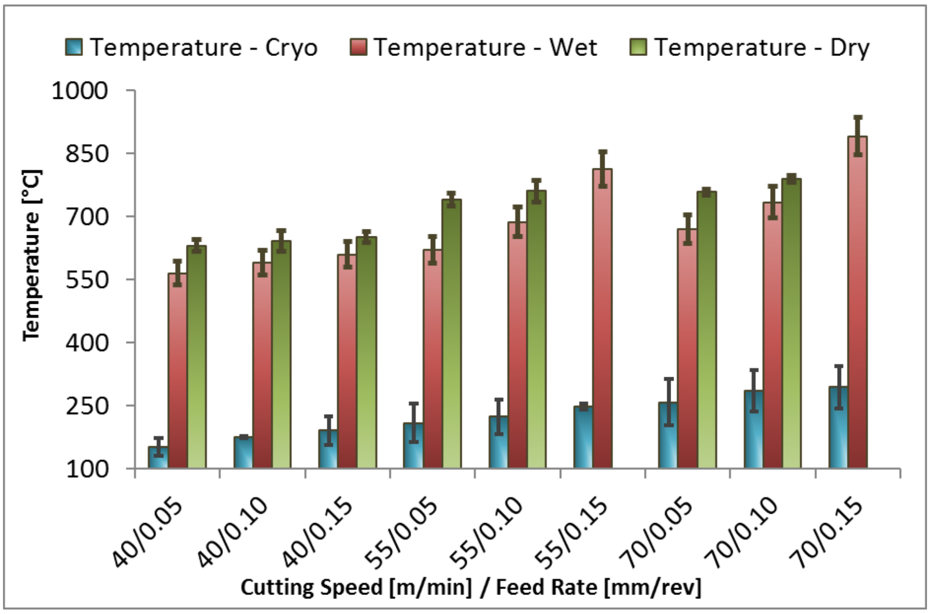


Fig. 13 Measured temperatures at tool-chip interface.

Table 1. Experimental test conditions.

Cutting Speed [m/min]	Feed Rate [mm/rev]	Cutting Condition
40	0.05/0.10/0.15	Dry/Wet/Cryogenic
55	0.05/0.10/0.15	Dry/Wet/Cryogenic
70	0.05/0.10/0.15	Dry/Wet/Cryogenic