

Machinability of Waspaloy under different cutting and lubri-cooling conditions

S. Rinaldi¹ · S. Caruso¹ · D. Umbrello¹  · L. Filice¹ · R. Franchi² · A. Del Prete²

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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 context 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).

Keywords Waspaloy · Cutting · Lubri-cooling conditions · Machinability

✉ D. Umbrello
domenico.umbrello@unical.it

¹ Department of Mechanical, Energy and Management Engineering, University of Calabria, Cubo 45c Ponte Pietro Bucci, 87036 Rende, CS, Italy

² Department of Engineering for Innovation, University of Salento, Via per Monteroni, 73100 Lecce, Italy

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, these 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 parts 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 abovementioned 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 [5, 6]. Furthermore, the feedback data obtained from experimental tests allows the process designers to take into account the various mechanisms that may lead the machining process to a dynamically unstable status, which results in unsatisfactory workpiece surface quality [7].

Nickel super alloys are classified as hard-to-cut materials, because the chips of these alloys do not easily dissipate the heat away from the tool contact zone, thus causing large temperature loading of the tools, high friction between tool-chip interface, and catastrophic plastic failure of cutting tool [8].

During machining, a hardened layer due to induced thermo-mechanical loading could form in the surface and sub-surface 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 disks, 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 and

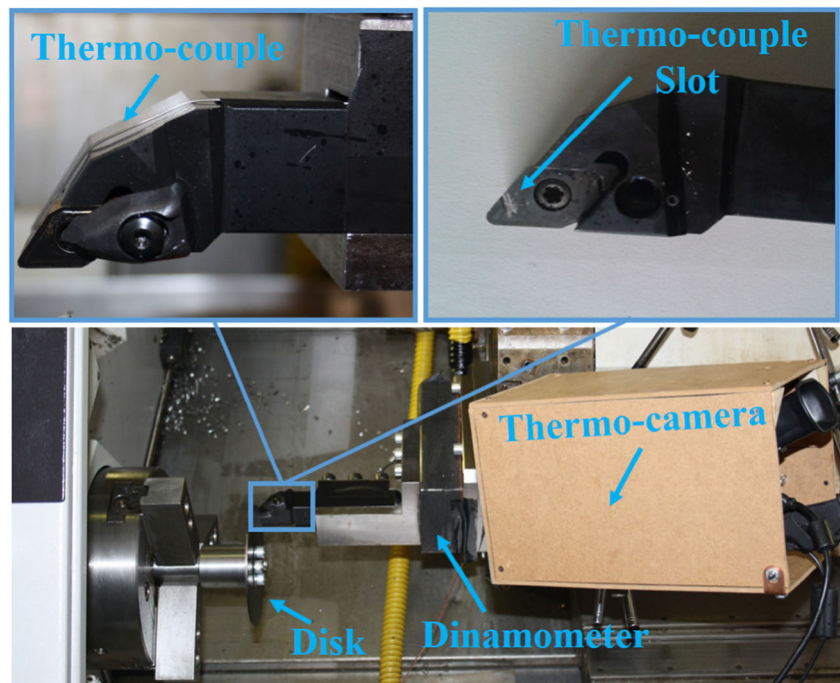
high work hardening and thermal properties that generate high cutting forces and temperatures [22]. Therefore, the study of the effectiveness of coolants and lubricants, such as oils, aqueous emulsions, and cryogenic coolants, represents an important aspect that permits to control and reduce the high temperatures developed during Waspaloy machining [23]. For these reasons, the main objective of the present work is to give a contribution 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 have been bolted to a shaft and used as workpiece material. Orthogonal turning trials were performed in a random order, in order to get reliable results. For each analyzed case, three repetitions for each analyzed case study were carried out (also randomized), using a MAZAK stiff high-speed CNC turning center, by means of a radial facing operation. Tests 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 force detection: cutting force (F_c) and thrust force (F_t). 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 thermo-couple 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. The experimental setup is shown in Fig. 1.

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

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



from 50 to 60 ml/s. As shown in Fig. 2c, in cryogenic cutting condition, a couple of nozzles was positioned reproducing the experimental setup 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.

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.

Depending on the cutting parameters, the cutting time of the experimental tests 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.

In order to avoid effects on the machined surface due to transient condition (in both feed rate or cutting speed) due to

the orthogonal machining configuration, the experimental tests were executed in the following sequence:

1. The tool was aligned and moved close to the rotating workpiece by single stepping through the CNC program (i.e., only one block/line of program code is executed with each press of the button by the operator).
2. All the instruments are set to “record” mode, and the CNC program is taken out of single-step mode.
3. With the next press of the button, the rest of the program is executed uninterrupted—i.e., the tool enters into the workpiece and continues cutting at the prescribed feed rate until the prescribed end-of-cut diameter and then instantaneously retracts at maximum feed. This insures that the rubbing of the tool against the final machined workpiece surface is minimal (though it may not be zero) and, equally importantly, invariant/constant for all the experimental conditions. Further, since the feed rate employed is in the low range (0.050–0.150 mm/rev) according to the tool makers, and due to the large workpiece diameter (127 mm at start and 60 at the end) the revolution per

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



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

minute corresponding to the cutting speeds employed are also low/moderate (100–370 rpm), it is possible for the CNC machine's hardware to change from radially inward feed to outward extraction almost instantaneously for all practical purposes. Hence, the transient effects were minimal, and this was confirmed from the force signals recorded during the cutting.

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 was performed using a LEICA DFC 320 optical microscope ($\times 1000$).

3 Experimental results and discussion

3.1 Cutting forces

Figure 3 shows the influence of cutting parameters (cutting speed and feed rate) on thrust (F_t) and cutting (F_c) forces

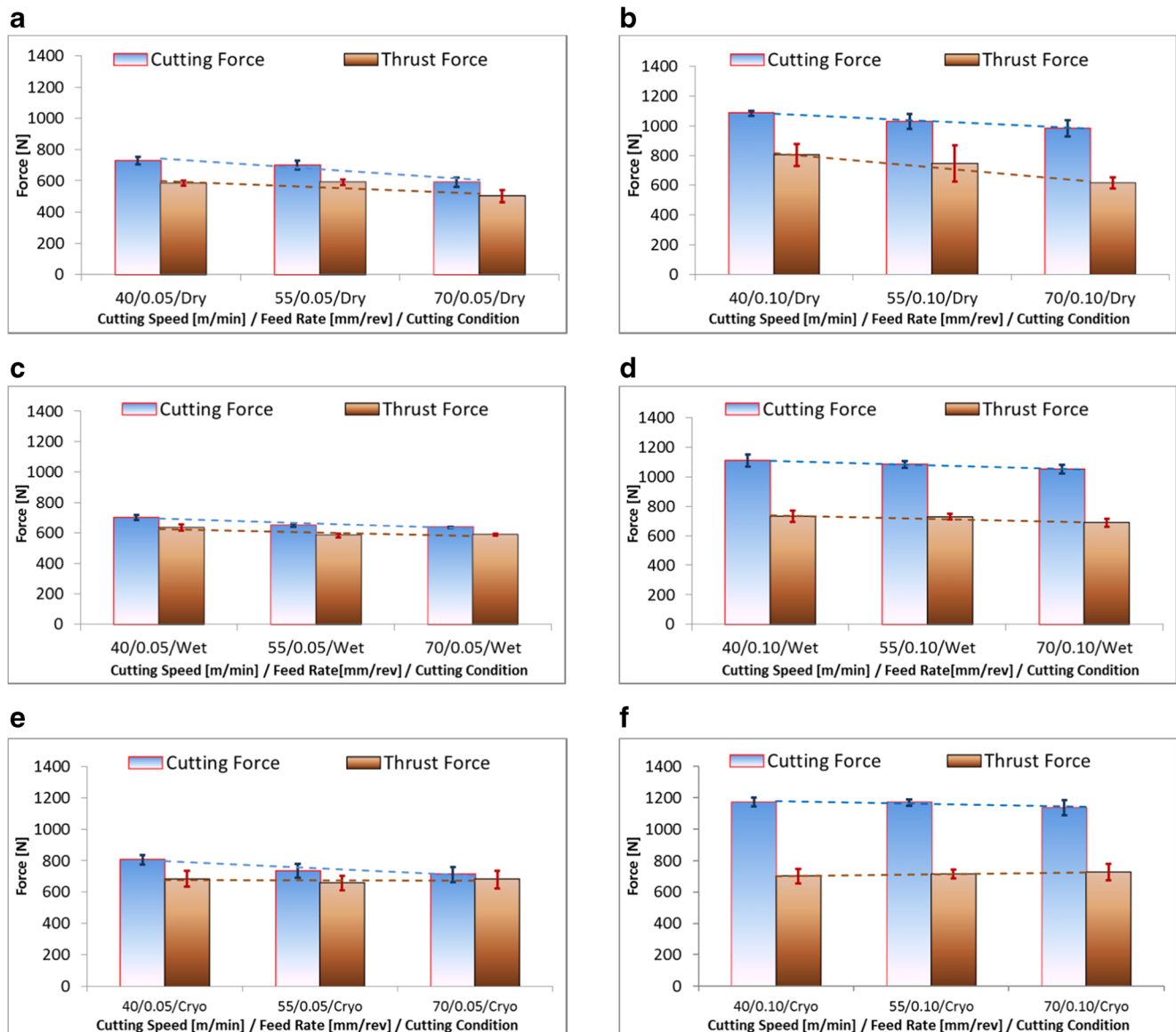


Fig. 3 Variation of cutting and thrust forces at varying cutting speeds and feed rate of 0.05 rev/min (a, c, e) and 0.10 rev/min (b, d, f)

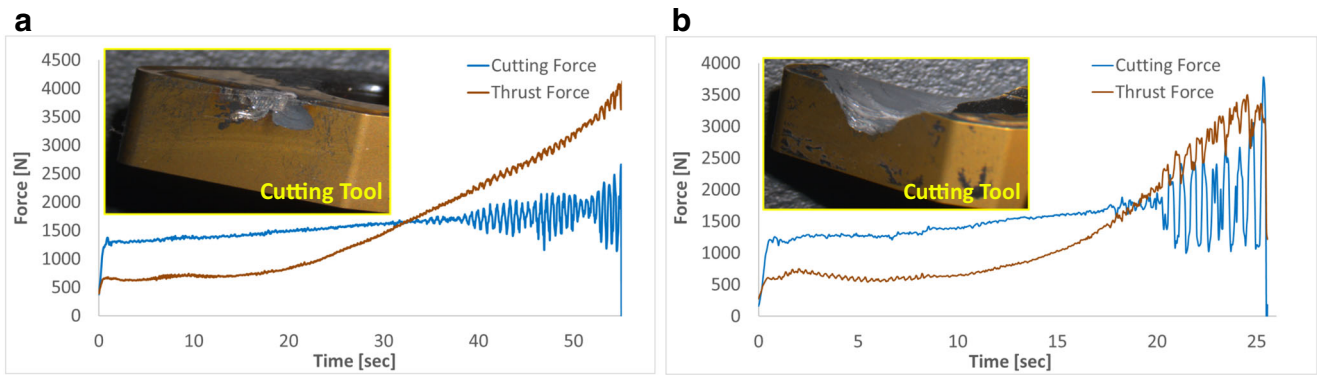


Fig. 4 Forces registered during dry machining tests at feed rate of 0.15 mm/rev and at cutting speeds of **a** 55 m/min and **b** 70 m/min

during machining tests at feed rates of 0.05 and 0.10 mm/rev. It is noted that, when the cutting speed raises from 40 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. 3c–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 Sect. 3.4.

For what concern the dry machining tests at feed rate of 0.15 mm/rev and cutting speeds of 55 and 70 m/min, these specific case studies showed 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 is reported in Fig. 4.

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.

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 to 0.15 mm/rev. In this case, the mechanical aspect, related to the increased removed material thickness and the increased tool wear (as shown in the next paragraph), is more influent than the thermal aspect.

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.

3.2 Tool wear

Figure 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/

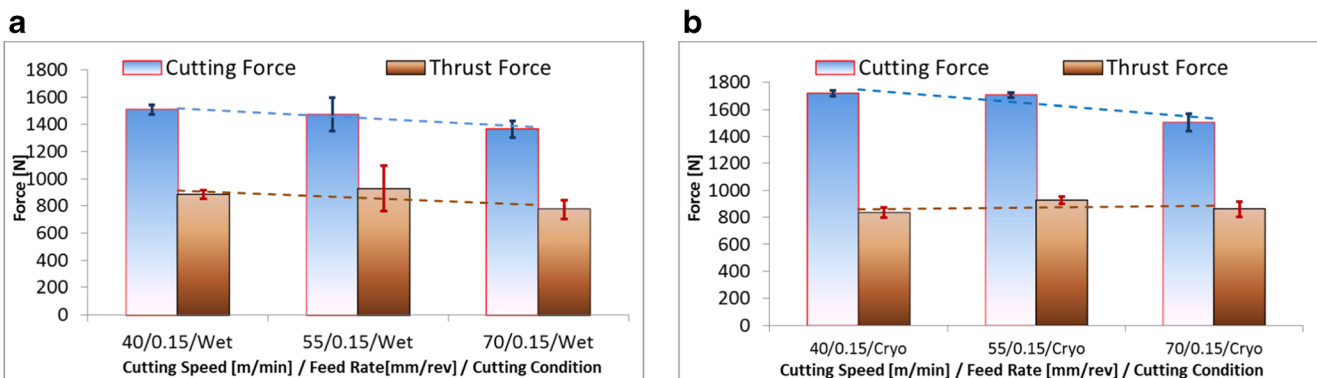


Fig. 5 Variation of cutting and thrust forces at varying cutting speeds and feed rate of 0.15 rev/min in **a** wet and **b** cryogenic condition

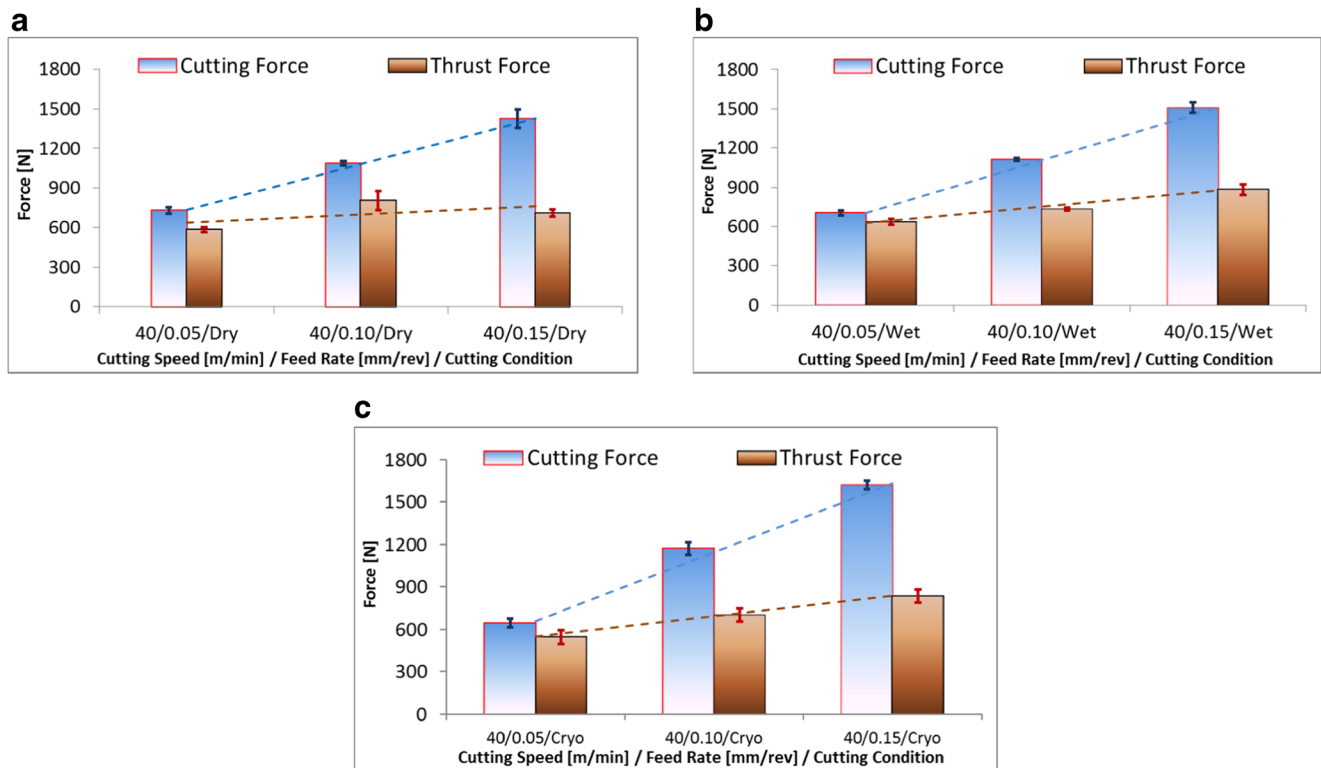


Fig. 6 Variation of cutting and thrust forces at varying feed rates in **a** dry, **b** wet, and **c** cryogenic cutting condition

min) that do not allow a significant change in thermal field as reported in Sect. 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 four to five times, in the tool wear rate when feed rate increases from 0.05 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. 9d, 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 nozzle 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].

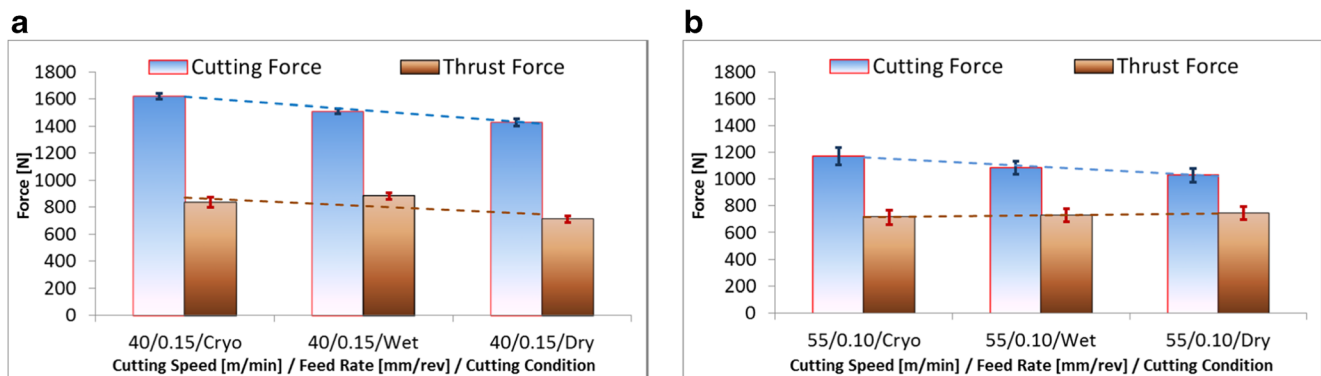
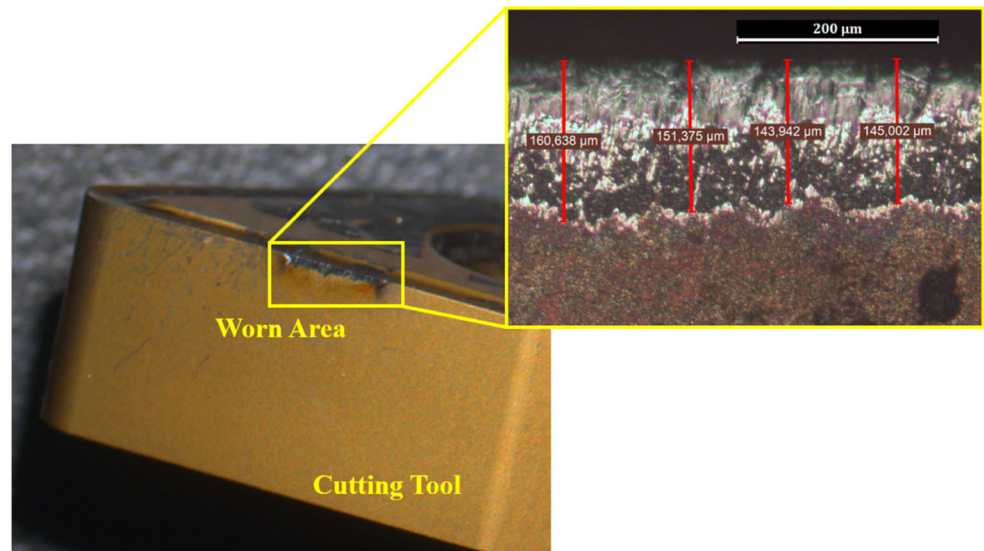


Fig. 7 Variation of cutting and thrust forces at varying cutting conditions. **a** $V = 40$ m/min and $f = 0.15$ mm/rev. **b** $V = 55$ m/min and $f = 0.10$ mm/rev

Fig. 8 Wear length measurement ($V = 40 \text{ m/min}$ — $f = 0.15 \text{ mm/rev}$ —dry)



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.

Figure 11 shows the influence of cutting speed, feed rate, and cooling conditions on chip micromorphology, 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 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

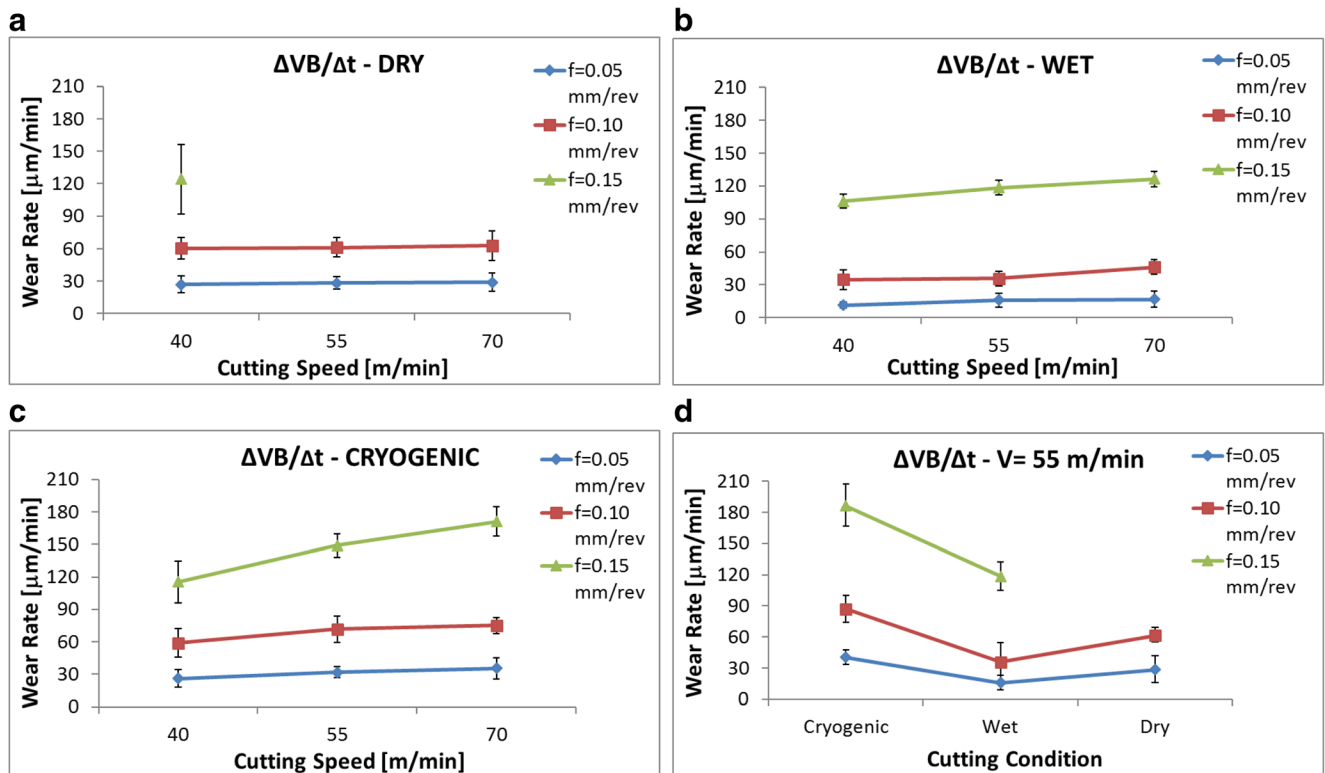
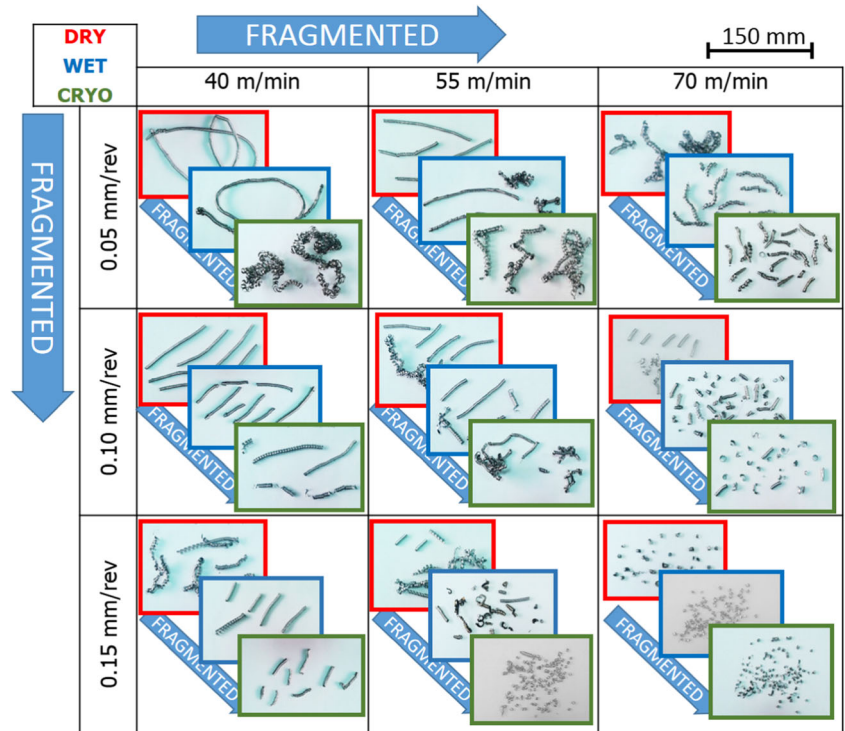
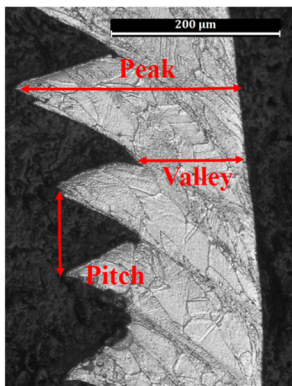


Fig. 9 Variation of tool wear rate at varying **a, b, c** cutting speeds and feed rates and **d** cooling conditions

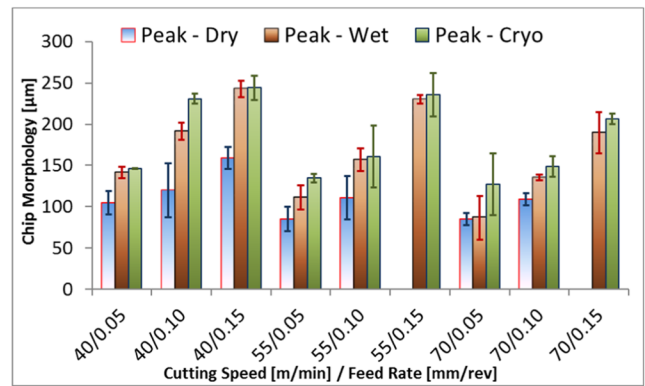
Fig. 10 Chip fragmentation at varying cutting speeds and feed rates and at different lubri-cooling conditions



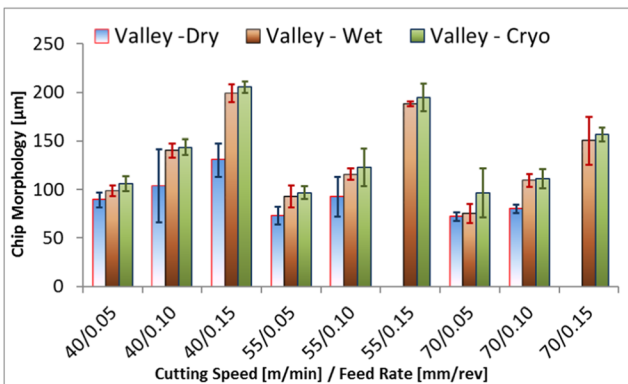
a



b



c



d

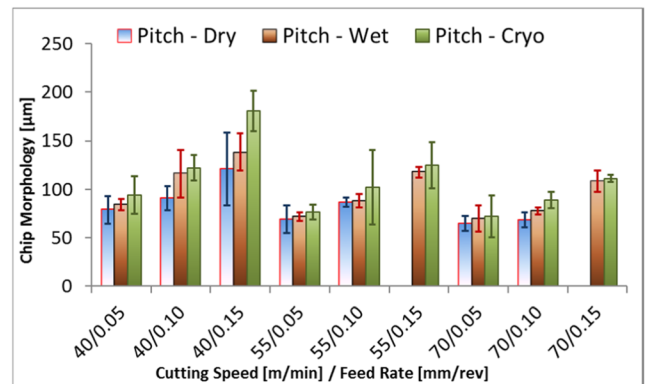
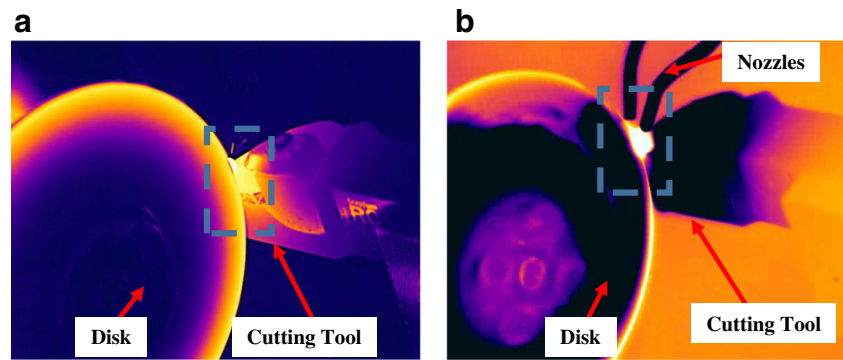


Fig. 11 Chip micromorphology parameters ($V = 70 \text{ m/min} - f = 0.15 \text{ mm/rev} - \text{cryo}$) (a) and variation of peak (b), valley (c), and pitch (d) at varying cutting parameters and cooling conditions

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



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.

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.

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

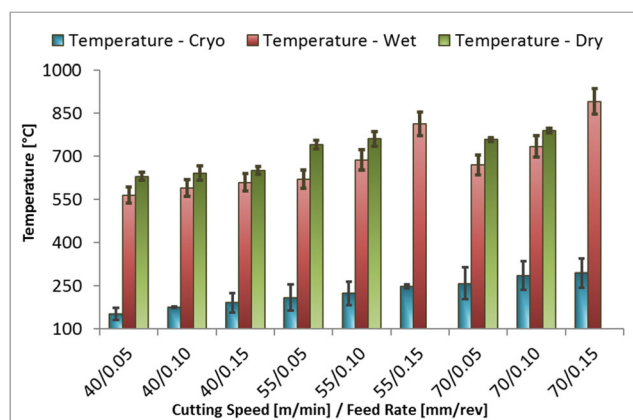


Fig. 13 Measured temperatures at tool-chip interface

interface that reduce the friction contribution. While during cryogenic machining, a high cutting temperature 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.

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 in future works, involving FEM simulation and microstructure evolution during the machining process.
- An increasing trend in chip morphology (in terms of peak, valley, and pitch) has been shown 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 of the material, while wet and cryogenic conditions allow machining using all the studied combinations of cutting parameters, in dry cutting, some parameters 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 analyzed manufacturing process involving severe cutting parameters, a lubri-cooling technique must be employed.

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